ACHIEVING WATER-ENERGY-FOOD NEXUS SUSTAINABILITY: A SCIENCE AND DATA NEED OR A NEED FOR INTEGRATED PUBLIC POLICY?

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PUBLISHED IN: Frontiers in Environmental Science and
Frontiers in Sustainable Food Systems

frontiers Research Topics

ISSN 1664-8714
ISBN 978-2-88966-105-3
DOI 10.3389/978-2-88966-105-3

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ACHIEVING WATER-ENERGY-FOOD NEXUS SUSTAINABILITY: A SCIENCE AND DATA NEED OR A NEED FOR INTEGRATED PUBLIC POLICY?

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Citation: Lawford, R. G., Mohtar, R., Engel-Cox, J. A., eds. (2020). Achieving Water-Energy-Food Nexus Sustainability: a Science and Data Need or a Need for Integrated Public Policy?. Lausanne: Frontiers Media SA.
doi: 10.3389/978-2-88966-105-3

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frontiers in Environmental Science

EDITORIAL
published: 28 August 2020
doi: 10.3389/fenvs.2020.00132

Editorial: Achieving Water-Energy-Food Nexus Sustainability: A Science and Data Need or a Need for Integrated Public Policy?

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Keywords: water, global change, environmental policy, future sustainability, water-energy-food nexus

Editorial on the Research Topic

Achieving Water-Energy-Food Nexus Sustainability: A Science and Data Need or a Need for Integrated Public Policy?

OPEN ACCESS

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Specialty section:
This article was submitted to Freshwater Science, a section of the journal Frontiers in Environmental Science

Received: *15 November 2019*
Accepted: *16 July 2020*
Published: *28 August 2020*

Citation:
Mohtar R, Lawford RG and Engel-Cox JA (2020) Editorial: Achieving Water-Energy-Food Nexus Sustainability: A Science and Data Need or a Need for Integrated Public Policy? Front. Environ. Sci. 8:132. doi: 10.3389/fenvs.2020.00132

INTRODUCTION

The benefits of addressing the water, energy, and food sectors in an integrated manner are gaining significant recognition. An integrated approach can provide improved resource use efficiencies, more coherent environmental policies, and an overall strategy for achieving sustainability in the three sectors, as outlined in the United Nations Sustainable Development Goals (SDG) 2 (Food), 6 (Water), and 7 (Energy). Societies are concerned with ensuring food security, avoiding wars over water, and creating opportunities by ensuring access to energy. To be effective, however, this approach needs to be adopted by all segments of society including government, the private sector, and civil society and must be reinforced by appropriate management and planning approaches.

This special issue identifies different approaches that are either being conceptualized or tested to support the Water-Energy-Food (WEF) Nexus approach. The articles contribute to answering the question, "Is achieving Water-Energy-Food (WEF) Nexus Sustainability a science and data need or an integrated public policy need?" In either case, both natural and social scientists need to combine their efforts to address interdisciplinary science issues and integrated policy approaches. The papers in this special issue explore the ways in which science, data, and policy development could help define integrative principles and policies for the three sectors. This approach could expand beyond the water, energy, and food sectors to include health, environment, trade, commerce, and international assistance, thereby providing broad support to the SDGs. Moreover, this issue demonstrates that data combined with new technologies (tools and models) can support better decision-making when adopted by governments and the management cadre for each of these sectors.

The issue includes 25 papers each designated as a specific type of paper by their authors. The papers include 3 policy and practice review [PPR] papers, 2 hypothesis and theory [HT] papers, 2 review [R] papers, 1 systematic review [SR] paper, 1 perspective [P] paper, and 16 original research [OR] papers. This editorial provides a summary of main messages in the special issue with a synthesis of the 25 papers and offers a perspective on gaps in the WEF Nexus science and policy domains. Although no one paper answered all aspects of the question posed in the title, when considered together the papers provided an overall perspective. That perspective is summarized in the last paragraph of this editorial.

SYNTHESIS OF SPECIAL ISSUES AND LESSONS LEARNED

The papers all had a primary focus, which allowed them to be grouped into the following four categories in order to better review their findings:

i. Applications and gaps in governance
ii. Availability of new science, observations, and information technologies
iii. Pragmatic solutions to regional WEF Nexus problems
iv. Approaches to effectively moving scientific information and new technologies into governance and public action

The key findings from the papers in each category are summarized below. It should be noted that in addition to their primary focus, some papers also addressed issues in other categories. To keep the review focused, however, we have based our conclusions on what we believe is the primary contribution of each paper.

Applications and Gaps in Governance

Although some approaches are directed from the top, others consider the views and concerns of communities and sectors involved. Wiegleb and Bruns argue for cross-sectoral Nexus approaches for resource governance and Nexus discourse. They conclude that the traditional utilitarian approach to resource governance should be supplemented by a multi-perspective approach that addresses the societal and environmental factors affecting WEF Nexus dynamics.

There are different views of how governance should be implemented to manage integrated resources like water, energy, and food. Often the needs of the WEF Nexus approach are most evident when conflicts exist in management and governance structures. Based on a review of scientific literature related to the WEF Nexus as a framework for resource security, Simpson and Jewitt review interpretations of the WEF Nexus concept and discuss challenges associated with integrating and optimizing its multi-centric components. Liu et al. investigate the competition for the allocation of critical resources among the water, energy, and food sectors in China and conclude that WEF Nexus approaches are needed to lessen conflict among ministries in ways that support sustainable water management and food production while conserving the potential for hydropower generation.

Water's importance in the WEF Nexus and in economic growth more generally is an important policy issue. Markantonis et al. address this in the context of the Mediterranean region, where ongoing water scarcity is further exacerbated by climate change. The authors explore how implementing the WEF Nexus can support economic growth under the anticipated water constraints. Land is another critical resource that constrains WEF Nexus sustainability in many countries. Based on land use issues in South Africa, Simpson et al. highlight the competition over land use (food/water securities vs. mineral rights and extractions) and emphasize the critical need for WEF Nexus science and data to influence integrated public policy and land use decisions.

A number of regional studies demonstrate that similar challenges and issues are resolved very differently in various regions because of governance. Although geography is important, a specific region may face greater problems for different reasons. Hoff et al. found that the absence of a clear definition of the WEF Nexus in the Middle East and North Africa limits the ability to communicate the concept and often hinders the adoption of WEF Nexus principles. Scenario analysis is an important aspect of both policy and technology that support better communication.

Dombrowsky and Hensengerth address the roles of investors, governance, and planning structures (joint vs. individual) for riparian basins. The roles of regional organizations in joint planning and consensus development should be included in the pathways for solutions.

Education will be an important tool for developing and promoting an understanding of the WEF Nexus (or FEW Nexus, in National Science Foundation parlance) and its implications. Rodríguez et al. review options for educational programs, proposing a curriculum outline that includes typical WEF Nexus challenges and toolbox modules for addressing them. The authors emphasize the need for transdisciplinary education and training.

Availability of New Science, Observations, and Information Technologies

Evidence-based decision-making in support of the WEF Nexus relies on scientific understanding and related information, which in turn is based on data and observations, and models and tools for analysis. New capabilities to observe at high resolution over global scales are changing the ability of the science community to support integrated WEF Nexus planning. Giupponi et al. explicitly identify the need to define assessment procedures that go beyond national or regional aggregation. They argue for "zooming in" to local phenomena in order to identify the policies and technologies that will provide solutions at the scales where production occurs and meaningful decisions can be made.

Through a diverse set of case studies using NASA Earth observations, McNally et al. demonstrate the benefits of these observational systems for the Water-Food Nexus. They also demonstrate the value of applying these data to issues in the water-food component of the WEF Nexus and the benefits of stakeholder interactions to data providers to help transform Earth observations into more accurate, timely, and relevant products and information. Bruss et al. demonstrate how Gravity Recovery and Climate Experiment (GRACE) data can be analyzed to provide key predictors that can help inform policies for water management in areas such as water supply and water use. Understanding the context of these policies is important for determining the optimum role of data.

Lawford hypothesizes that readily available data and information can be used to promote integrated resource planning. He proposes a series of steps for designing, implementing, and testing an integrated data and information system in a WEF Nexus decision-making environment. He also emphasizes the critical roles of observations data, information, and modern technology in facilitating the paradigm shifts needed to advance WEF Nexus approaches.

Kurian et al. address the underlying siloes, trade-offs, and synergies of the Nexus and advocate for specialized long-term multi-sector observatories located where specific issues are expected. Local measurements, qualitative observations, and data obtained regularly over a long period can be used in combination with policy instruments (guidelines, notifications, standards, circulars, and directives) to provide information for better decision-making on a local or regional basis and to support the valorization of data and assess methodological assumptions.

Pragmatic Solutions to Regional Wef Nexus Problems

A number of potential practical solutions were elaborated, many of them tailored for specific geographical areas or a specific aspect of the WEF Nexus. Urbanization is often accompanied by the rapid expansion of urban populations in areas without proper infrastructure, urban ecosystems, and burgeoning populations that threaten food security and raise the risk of food crisis events, particularly in the developing world as Davies and Garrett demonstrate. They discuss the role of smart technology and identify 12 innovative technology platforms to promote urban food ecosystems. When linked to value chains, these platforms can lead to both increased entrepreneurial opportunities and greater efficiency of resource use. Schulterbrandt Gragg et al. describe urbanizing socioecological systems from a policy perspective and offer an iterative, multidimensional model that provides new opportunities for solutions and stakeholder involvement in assessing options.

Shumilova et al. discuss water transfer megaprojects and the challenges of using existing hydrological models to assess the impacts of these projects and to recommend design criteria. These hydrological models currently do not explicitly include ecological, social, and economic factors and are therefore of limited value for impact assessment. More comprehensive models should be used to ensure maximum relevance for decision makers and operational managers. A similar conclusion is made by Givens et al. who report on decision-making in the Columbia River basin. Their study, which is based on the physical models typically used in river basin management, identifies limitations with the current approach. The authors call for the inclusion of social aspects (inequality, power, social justice) in the set of models used to address river basin planning.

In additional to traditional approaches, new technologies and methodologies are critical to WEF Nexus security. Haskett et al. discuss the potential use of the decaying leaves of *Faidherbia albida* trees in Ethiopia to fertilize nearby crops. In tropical countries with suitable climates this method could reduce the production and transportation of chemical fertilizers and reduce regional greenhouse gas emissions. Alemneh et al. demonstrate the importance of monitoring cropland conversions in order to quantitatively assess their impacts on the local production of food and water, energy, and food consumption.

Approaches to Effectively Moving Scientific Information and New Technologies Into Governance and Public Action

Trade-offs are an essential aspect of managing WEF resources. The key to future sustainable development in these resource sectors involves balancing supply and demand at all scales and under all environmental conditions. Linking WEF Nexus activities to the relevant SDGs would facilitate the development of joint monitoring and modeling strategies. Efforts in one sector can synergistically benefit the two other sectors. Fader et al. developed and applied a quantitative methodology to provide a replicable way of identifying potential synergies and trade-offs in the implementation of the food, water, and energy SDG targets. By extension, the WEF Nexus could be implemented using a similar assessment tool.

Strategies are needed to address tradeoffs, especially when it is difficult to bring entrenched interests together to discuss compromise. Frameworks such as that discussed by Allam and Eltahir in their study of the Nile River basin use optimization models to produce a range of options for the allocation of land and water resources. These model outputs are analyzed to produce problem-solving scenarios with stakeholders when cooperation is difficult to obtain.

Stakeholder perspectives and interactions are highlighted by Bielicki et al. who conclude that, with regard to WEF Nexus sustainability, the importance and use of science, data, and integrated policy depends on the context in which the stakeholders operate in the WEF Nexus domain. Linking strategies that rely on stakeholder interactions are outlined by Yung et al., who found that the strategic use of the characterization and navigation of Nexus uncertainties could facilitate integrated risk assessment. The authors stress the importance of stakeholder engagement for obtaining local knowledge of cultural and economic considerations that could affect the implementation of broad-scale WEF Nexus policies.

Holistic WEF Nexus frameworks are reviewed by Kulat et al. They show how these models offer insights into sustainable (and unsustainable) scenarios that are critical to developing policies that will preserve WEF resources without disrupting economic well-being and the health of ecosystems. Taniguchi et al. also present a holistic model by assessing the effectiveness of a Japanese government program that subsidizes farmers for ponding water on their fields. Subsidized water ponding leads to groundwater recharge, reduced energy use, and increased food production. This tool is one of a number available for cities, states, and countries to evaluate their policy interventions on WEF Nexus sustainability.

As this special issue demonstrates, there are many tools available to help engage stakeholders. The challenge is to inform stakeholders, and to provide timely and relevant information to enable them to make better decisions for themselves and for WEF Nexus sustainability. Increasingly reliable modeling produces improved scenarios for policy and technology. Discussing with stakeholders outcomes that support long-term sustainability could be a good way to encourage much broader awareness of the WEF Nexus and the importance of its sustainability.

GENERAL FINDINGS AND RESEARCH GAPS

This special issue shows that both the socioeconomic and physical dimensions of the WEF Nexus need to be addressed jointly—but the integration of these approaches requires a considerable amount of work and research. There are many challenges to bridging the social and the physical sciences as they relate to the WEF Nexus. To make progress on the WEF Nexus goals and to support SDG implementation, both communities need to develop mutually beneficial research strategies. Collaborations could be enhanced by exploring opportunities for joint WEF Nexus and SDG monitoring systems and other options.

Other approaches that could advance WEF Nexus implementation include tools and models for the WEF Nexus, relevant interdisciplinary research approaches, indices, and monitoring systems that can support governance and evidence-based decision-making. Addressing siloed resources and expertise—and the current lack of policy coherence—demands "out-of-the-box" thinking and more integrated approaches to planning and management.

Integrated modeling tools are essential to produce relevant outputs, including analyses and scenarios that support the development of policies on sustainable consumption. Such policies are informed by the strong links between issues like fossil fuel extraction and water quality or energy subsidies, which can lead to overexploitation of groundwater for food production. Models play a key role in the generation of scenarios, but their scientific underpinnings must be sound for the resulting scenarios to be credible. While integrated models can help clarify and quantify the trade-offs of various scenarios, the limitations and appropriate applications and uncertainties of models must be understood.

Currently, modeling tools are not optimally used by policy makers because there is a lack of interactions among scientists, engineers, and practitioners in the water, energy, and agricultural sectors to develop an appreciation for the value of integration. Siloed science and governance approaches contribute to the lack of informed and optimized multi-sector decisions. This challenge can be overcome, at least in part, with interdisciplinary work and convergent scientific and applications infrastructure. In particular, collaborative efforts among experts from each sector to increasingly integrate sector-specific models into comprehensive WEF Nexus models could be an important step in overcoming these siloed effects.

As a result of their complexity, WEF Nexus issues present interconnected challenges where the best solutions to problems in one sector often are achieved by working collaboratively with the other sectors. For example, some water issues can only be solved through collaboration with the food and energy sectors, and vice versa. Only interdisciplinary collaboration can result in truly encompassing discussions that identify common goals for the various consumers, experts, and policy makers. These collaborations should be based on an understanding of the science and short- and long-term policy implications of each option involved in WEF Nexus sustainability.

Better systems for acquiring and processing data, and rapidly disseminating data products and information for planning and decision-making, are essential. Many of the components for such a system are available "off the shelf," but each system needs to be co-designed or at least coordinated with careful attention to the needs, perceptions, and assessments of product utility by stakeholders and users.

This special issue demonstrates that there are a large number of innovative applications of special techniques, local practices, and sophisticated tools and models that are all available for addressing the WEF Nexus issues. There is no single framework to structure and disseminate this information. It would be beneficial to have an inventory for the many users that would benefit from this information. Some of the papers in this collection emphasize two-sector interactions such as water and food or energy and food. These papers generally addressed the WEF Nexus as a conceptual framework rather than an analytical approach to sustainability. Joint research that engages the expertise and information available for all three sectors is needed.

As part of efforts to develop stronger commitments for the implementation of WEF Nexus principles, national meetings feeding into an international strategy for the WEF Nexus could advance collaboration and integrated approaches to development and applications. One or more high-profile events with policy engagement could advance the development of a WEF Nexus planning approach by many nations. Such an event could focus on the development and endorsement of a roadmap or implementation plan for the WEF Nexus as one of its principal outputs. A model for this event could be the 1993 Dublin International Conference on Water and the Environment.

Human security and ecosystem services need to be included in WEF Nexus decision-making. New measures and data streams could be developed for agricultural and ecosystem services outputs so that statistics such as tons of produce per hectare would be supplemented with other measures such as concentrations of nutrients, proteins, water and energy footprints, energy production/use, and other environmental parameters. People may be more supportive of WEF Nexus principles if they see how important aspects of each sector are changing.

The papers raised a number of science questions that also relate to developing new paradigms. Some of these questions include the following:

- Given the capabilities of satellites to provide the spatial distribution of water quality variables such as phytoplankton, why are measures of ambient water quality not having a greater role in decision-making? For example, non-point source pollution from nitrogen and phosphorus arising from fertilizers and enhanced by irrigation is a critical problem that needs to be monitored regularly in the WEF Nexus. How can end-point measurements be supplemented by ambient measures to develop indicators that can assess WEF interlinkages?
- How can hydrological models incorporate more energy, food, environmental, and socioeconomic factors to produce scenarios that inform the public and motivate action?
- In many areas, one or more components of the WEF Nexus will be very sensitive to climate change. Several papers referenced hydropower, a major source of clean energy, that nonetheless is vulnerable in areas where prolonged dry periods can persist. In a similar way agricultural irrigation is under high risk and uncertainty due to climate change impacts on water availability in certain regions. How will climate change impact the WEF Nexus and water-stressed regions?
- In the context of meeting water needs, including those outlined in SDG 6, how can we ensure that recycled water fully alleviates water supply deficits without affecting irrigation water quality and food security and safety? In turn, how can we make better use of energy recovery systems in wastewater facilities?

Although the title of this paper suggests WEF Nexus sustainability could be achieved solely by either a policy approach or the use of science and technology, papers in this special issue have shown that both public policy and science/data are necessary for WEF Nexus sustainability. This assessment concludes that a blend of monitoring data, coordinated research, public policy, and governance are needed at the national and global scales to help set goals to encourage the sectors to work together to address broader integration as needed. Scientific understanding and data are needed to support evidence-based decision making to address these problems within the context of the rules set out by governance decisions. Policy must be adopted that not only reflects regional priorities, but also supports global public policy such as sustainable development. When coordinated, data and science can provide support for decisions at all scales from local transient problems to macroscale research and the observational systems needed to monitor the overall status of the WEF Nexus on a global basis.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

FUNDING

RL acknowledged the support he received while working on this publication from USRA Cooperative Agreement 05700-01-02.

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Environmental Science

ORIGINAL RESEARCH
published: 19 September 2018
doi: 10.3389/fenvs.2018.00104

Incorporating Social System Dynamics in the Columbia River Basin: Food-Energy-Water Resilience and Sustainability Modeling in the Yakima River Basin

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OPEN ACCESS

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Specialty section:
This article was submitted to Freshwater Science, a section of the journal Frontiers in Environmental Science

Received: 25 June 2018
Accepted: 24 August 2018
Published: 19 September 2018

Citation:
Givens JE, Padowski J, Guzman CD, Malek K, Witinok-Huber R, Cosens B, Briscoe M, Boll J and Adam J (2018) Incorporating Social System Dynamics in the Columbia River Basin: Food-Energy-Water Resilience and Sustainability Modeling in the Yakima River Basin. Front. Environ. Sci. 6:104. doi: 10.3389/fenvs.2018.00104

In the face of climate change, achieving resilience of desirable aspects of food-energy-water (FEW) systems already strained by competing multi-scalar social objectives requires interdisciplinary approaches. This study is part of a larger effort exploring “Innovations in the Food-Energy-Water Nexus (INFEWS)” in the Columbia River Basin (CRB) through coordinated modeling and simulated management scenarios. Here, we focus on a case study and conceptual mapping of the Yakima River Basin (YRB), a sub-basin of the CRB. Previous research on FEW system management and resilience includes some attention to social dynamics (e.g., economic and governance systems); however, more attention to social drivers and outcomes is needed. Our goals are to identify several underutilized ways to incorporate social science perspectives into FEW nexus research and to explore how this interdisciplinary endeavor alters how we assess innovations and resilience in FEW systems. First, we investigate insights on FEW nexus resilience from the social sciences. Next, we delineate strategies for further incorporation of social considerations into FEW nexus research, including the use of social science perspectives and frameworks such as socio-ecological resilience and community capitals. Then, we examine a case study of the YRB, focusing on the historical development of the FEW nexus and innovations. We find that a resilience focus applied to the FEW nexus can inadvertently emphasize a status quo imposed by those already in power. Incorporating perspectives from the social sciences, which highlight issues related to inequality, power, and social justice, can address these shortcomings and inform future innovations. Finally, we use causal loop diagrams to explore the role of the social in the FEW nexus, and we suggest ways to incorporate social aspects into an existing stock and flow object-oriented modeling system. This project represents a starting point for a continued research agenda that incorporates social dynamics into FEW system resilience modeling and management in the CRB.

Keywords: resilience, sustainability, social science, Food-Energy-Water Nexus, INFEWS, Columbia River Basin, Yakima River Basin

INTRODUCTION

The Columbia River Basin (CRB) in the Pacific Northwest Region of the United States is home to a network of food production systems, hydroelectric dams, and tributaries and watersheds that shape the food-energy-water (FEW) nexus. The region is currently attempting to plan for projected changes in climate and precipitation, extremes in flood, and the renegotiation of the Columbia River Treaty (Cosens, 2010, 2016; Vano et al., 2010; Cosens and Fremier, 2018). Within the CRB, the Yakima River Basin (YRB) in particular provides more than $3 billion in agricultural products (Yoder et al., 2017), $3.4 million in power generation to local and regional grids (USBR, 2011a,b), and instream flows for endangered salmon and steelhead (Cosens et al., 2018). Over the past century the YRB has experienced a veritable food-energy-water transformation, from one dominated by Native American tribes and fishing, to a multicultural, highly managed, highly profitable agricultural center. This transformation was made possible by innovative developments and massive investments in infrastructure for irrigated agriculture, reservoir storage, railroad and highway connectivity, and fish ladders and screens (Meinig, 1962; Jarosz and Qazi, 2000; Vano et al., 2010; 98 Stat. 1333, Public Law 98–381; 98 Stat. 1379, Public Law 98–396). Not all transformations have been beneficial, nor have the benefits and costs been distributed evenly. For example, health concerns for farmworkers and consumers due to pesticide usage (Jarosz and Qazi, 2000), civil unrest over wage disputes (McMahon, 2002), protests over rangeland parcelization (Olson, 1980), and decades of litigation over declining fish resources available for Yakama Nation communities (Cosens et al., 2018) are inexorably tied to the development of the FEW nexus in this region.

In order to address FEW nexus sustainability in the YRB, CRB, and beyond, we need research that incorporates not only biophysical feedbacks and tradeoffs into proposals for innovation, but also socio-cultural *drivers* and *outcomes* of these interactions. According to the (World Commission on Environment Development, 1987), "a world in which poverty is endemic will always be prone to ecological and other disasters" (Lockie, 2016). However, divides between social and natural sciences sometimes hinder interdisciplinary work, in part because disciplines have developed independently with their own methodologies, epistemologies (Miller et al., 2008; Stuart, 2016), and ontologies. To address FEW nexus sustainability, we draw upon the concept of resilience. This offers one promising way forward, but it is not without issues. Numerous scholars address why resilience as a concept is unappealing to social sciences (Olsson et al., 2015) or how it has important limitations (Davidson, 2010; Cote and Nightingale, 2012; Hatt, 2013). Many of these issues are also relevant to discussions of sustainability. The puzzle we tackle in this paper is how to address these issues and incorporate considerations of the social, including political, economic, and cultural issues, into FEW nexus resilience research. We argue that incorporating considerations of social-ecological resilience along with other insights, frameworks, and indicators from the social sciences will improve research by making it more just, more accurate, and more likely to produce desired advances, such as innovation adoption, and avoid unintended negative consequences.

In what follows, we first discuss several issues in bringing social science, and social considerations, into FEW nexus resilience research. We then discuss opportunities in this area and identify a set of possibly useful frameworks and indicators, while also acknowledging limitations and data needs. The strategies we suggest for incorporating the social into FEW nexus resilience emphasize process, metrics, and modeling. After this, to provide real-world context, we examine a case study of the YRB focusing on the historical development of the FEW nexus and current FEW nexus challenges and innovations. We also use this case study to explore some of the issues and opportunities that arise when incorporating social considerations into FEW nexus research. Finally, we discuss our conceptual mapping approach, the goal of which is to advance incorporation of the social into FEW nexus resilience research and facilitate later efforts at system dynamic (SD) modeling. We examine how social insights inform research based on an object-oriented river basin modeling system already in use (RiverWare^{TM}, Carron et al., 2000; Zagona et al., 2001), and we discuss implications for future research. This paper represents an interdisciplinary approach—while engineers may not be aware of some of the social science frameworks we discuss, sociologists may not be as familiar with system dynamics modeling—therefore our work aims to facilitate collaboration between diverse audiences.

BRINGING SOCIAL SCIENCE INTO FEW NEXUS RESILIENCE RESEARCH

Growing concern has been expressed over food, energy, water resources, and their deep connection to income inequality, economic instability, and urban expansion (Middleton et al., 2015; Howarth and Monasterolo, 2016). Importantly, researchers are questioning how FEW nexus frameworks can be operationalized (Liu et al., 2017), whether critical issues such as labor, human capital, health, and welfare are absent (Wichelns, 2017), and what perspectives/institutions should be prioritized for integration (Al-Saidi and Elagib, 2017). Here we discuss concepts and issues related to these questions in an effort to bring social science perspectives more explicitly into FEW nexus resilience research.

Concepts

Many have studied the water-energy-food (WEF) nexus and have used this specific abbreviation to investigate the complex interactions between these resources (Lawford et al., 2013; Biggs et al., 2015; Middleton et al., 2015; Larcom and van Gevelt, 2017; Liu et al., 2017). We use the FEW (food-energy-water) abbreviation for consistency with recent initiatives and projects funded by the National Science Foundation (2015) and Mohtar and Lawford (2016). These projects emphasize a systems-based approach to understanding Innovations at the Nexus of Food, Energy, and Water Systems (INFEWS). D'Odorico et al. (2018) recently discuss these emerging initiatives and parallel growing literatures in their thorough review of the Global Food-Energy-Water nexus. Synergies among variations in WEF focus, which tend to emphasize global resource security and development, and FEW nexus research themes such as fundamental understanding and basic research, need to continually be explored, especially with further considerations for how they define ultimate goals (National Science Foundation, 2015; Albrecht et al., 2018; D'Odorico et al., 2018). Despite differences in terminology, we utilize insights from both of these complementary bodies of research.

Sustainability and resilience are also related concepts. Davidson (2010: p. 1136) defines sustainability as a "systemic state of indefinite equilibrium, in which levels of anthropogenic material consumption and waste production remain below threshold productive and absorptive capacities of the ecological system, while at the same time ensuring a quality of life that is considered acceptable by current and future members of that social system." The most common definition of sustainable development comes from the World Commission on Environment Development (1987) report *Our Common Future*, which defines sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

We understand resilience generally to refer to the ability of systems to absorb and adapt to change without the dissolution or transformation of the system (Gunderson, 2000); we expand on this in more detail below. In line with others, we consider resilience in the face of change to be a component of larger sustainability aims (Summers et al., 2017). Yet we recognize resilience is not a synonym for sustainability. Resilience is not always desirable (Fernandez et al., 2016); even when it is desirable it may not be a priority for sustainability, it is not required for or an outcome of sustainable development, and it has limitations when applied to the social realm (Lockie, 2016).

Issues With Incorporating the Social Into FEW Nexus Resilience Research

Social scientists have been critical of work attempting to include social factors in studies of resilience because the concept is often seen as incompatible with social systems (Davidson, 2010; Olsson et al., 2015; Stuart, 2016). Here, we present five areas of complexity when integrating the social into biophysical FEW nexus resilience research. This is useful because understanding the complexity of interdisciplinary integration is necessary in order to move past previous limitations. In highlighting these issues, we provide insights as to how incorporating social considerations can advance understanding of FEW nexus resilience.

Defining Resilience Across Disciplines

A first issue is variation in the concept of resilience across disciplines. "It is evident that the dominant worldview in resource and environmental management of "systems in equilibrium" is incompatible with observations of the complex dynamics of social and ecological systems" (Berkes et al., 2003: p. xi). In engineering and some branches of ecology, resilience is commonly understood as a natural balance, or a steady state to which a system returns after a stress or perturbation. These understandings often reference the ball and cup analogy of returning to a state of equilibrium, or possibly transitioning to a new state with a new equilibrium. Applying a social science lens to the FEW system draws attention to limitations of the engineering definition of resilience and highlights the need to understand ecological and social system realities more explicitly represented in the ecological definition of resilience. While in engineering, resilience may be operationalized as time to return to equilibrium, in ecology, resilience might be measured as the magnitude of change that can be absorbed before transitioning to a new state (Berkes et al., 2003: p. 35; see Davidson et al., 2016 and Quinlan et al., 2016 for reviews of definitions across disciplines). In socio-ecological and other interdisciplinary research, resilience refers to the ability of systems to resist or adapt to changes or shocks and persist, or to move into an alternative, possibly more desirable state (Folke, 2006; Olsson et al., 2015). Addressing conceptual variations in understandings of resilience, and subsequent differences in operationalization and measurement, is a first step in incorporating the social into FEW nexus resilience research (Chuang et al., 2018).

Social Justice Considerations—Resilience for Whom and of What?

A second related consideration when bringing the social into FEW nexus resilience research is the question of whether resilience is normative. Resilience researchers tend to understand resilience as "good" (Olsson et al., 2015). However, social scientists are likely to question this assumption, encouraging resilience researchers to take a more critical approach by asking "resilience for whom?" and "resilience of what?" (Cote and Nightingale, 2012; Olsson et al., 2015)[1].

In terms of "for whom," social scientists, especially sociologists, are likely to highlight the roles of inequality and power in systems (Roberts and Parks, 2006; Jorgenson and Clark, 2009; Jorgenson, 2016; Givens, 2018). Lockie (2015: p. 139)

[1]Resilience researchers occasionally acknowledge that there is not necessarily an implication that resilience is good, because it could get in the way of replacing an undesirable system (Folke, 2006) and sometimes change is desired (Walker et al., 2004). Despite such acknowledgments, much of the writing about resilience assumes it is desirable.

writes, "the pollution that makes some people wealthy makes other people sick, threatens their livelihoods, and increases their risk of injury and displacement." Yet despite knowledge that social problems make societies and systems more vulnerable, resilience research does not tend to prioritize poverty alleviation or address social injustice (Lockie, 2016). Cote and Nightingale (2012: p. 484–485, 479) portray FEW nexus resilience as "a power-laden framework that creates certain windows of visibility on the processes of change while obscuring others." Resilience research has also tended to treat social groups as homogeneous and static (Stuart, 2016). FEW nexus research would be improved by giving attention not only to tradeoffs between sectors (Endo et al., 2017; Larcom and van Gevelt, 2017) but also to conflict, conflicting interests, and power dynamics within sectors and nexus stakeholders (e.g., Huszar et al., 1978; Jarosz and Qazi, 2000; Diver, 2018). Instances of mutually beneficial cooperation and exchange can also be examined and may serve as models.

With respect to "resilience of what," social scientists may question the desirability of FEW system resilience, which presupposes the value of maintaining the system, rather than aiming for system change. In the social sciences, especially sociology, theoretical perspectives emphasize conflict, inequality, and power, see order as determined and maintained by dominant groups, and highlight conflict between groups as a source of change. Therefore, change could be seen as needing to be transformative and involve the redistribution of power. Without a social science perspective, change may be depoliticized (Olsson et al., 2015: p. 5).

Achieving Resilience—What End Goals?

A third related question in research that aims for innovations in FEW nexus resilience is, what are the goals? If the desirability of maintaining the system as a whole is questioned, identifying system functions may be an alternate way to identify what is desirable to sustain and what is meant by adaptation vs. transformation. However, focusing on a system's function tends to ignore inequality and conflict in the system by not attending to who gets to identify what functions are valued and benefit most from valued functions (Hatt, 2013; Olsson et al., 2015: p. 5). Different individuals, groups, and sectors obtain different functions from the FEW nexus. Focusing on system function may also obscure the desirability of system change for some. If adopted unquestioningly, focusing on system functions risks placing the focus on positive functions and obscuring negative and unintended outcomes. For example, increasing the number of salmon in the CRB might come at the expense of irrigation water for farmers, or improving the resilience of per capita economic growth could increase environmental damage. Simply focusing on the function(s) of a system also ignores the possibility of substitutability, that a different system could provide some of the same identified functions in coupled human and natural systems (Chen et al., 2012). Finally, this raises further issues regarding ethical considerations of the "function" of an ecosystem and the consequences for not only humans, but also non-human species and the ecosystem itself. Identifying goals for resilience still represents a productive way forward, as long as an equity dimension is part of conceptualizing FEW nexus resilience.

Conceptualizing and Operationalizing Resilience and Change

Fourth, and especially in order to model FEW nexus resilience, we need to consider how we conceptualize and operationalize adaptation, change, and system change in FEW nexus resilience, especially when it comes to the social. Social relations may not be able to be adequately characterized by the terms either resilience researchers or systems modelers use to describe system interactions. Resilience researchers' differentiation between disturbances vs. deliberate efforts for system change and system modeler's conceptualizations of stocks, flows, and feedback loops may all be inadequate in accounting for variations caused by human agency and in the contexts of norms, cultures, and power inequalities (Olsson et al., 2015). For example, the choice by agricultural workers in one region to strike, the decision by some tribal groups to bring lawsuits that result in the removal of dams, or the election of a president which creates uncertainty about future environmental regulations all represent examples of human agency that vary by context and are difficult to model at the system level. Further, what do we mean by "persist" vs. adapt and change, and how do we give these precise conceptual and operational definitions? Is transformation part of resilience or something different? How do we know when a system has adapted, vs. transformed? In other words, there is ambiguity in resilience research regarding operationalizing and modeling the role of change and transformation in perpetuating the system and making it more resilient vs. shifting to a new system, which is further complicated by the addition of the social (Olsson et al., 2015). Further, a new system may or may not be more sustainable or resilient.

Boundaries and Scale

Fifth, studying the resilience of FEW systems requires delineating boundaries of the system and considering scale. This involves designating factors as exogenous or endogenous to the system, conceptualizing boundaries across space and time, and thinking about multilevel processes across scales. These considerations become even more complex with incorporation of the social, as systems operate at different units or levels. Dietz (2017) offers one useful typology as an illustration, as follows. Ecological systems may be seen as including the biosphere, biotic province, landscape, watershed/airshed, community population, and individual, whereas the social system may be thought of as the world system, nation, culture, political subdivisions, community, household, and individual. Political boundaries, from national to tribal to state to county overlap with natural features. "Human system boundaries and ecological system boundaries are nearly always different" (Dietz, 2017: p. 199).

Social relations also connect actors, institutions, and structures across and beyond the system (Olsson et al., 2015). Adger et al. (2005: p. 1037) find in an increasingly globally connected world, "the resilience (or conversely vulnerability) of coastal societies is more tightly linked to larger-scale processes today than in the past." In a review of research on the WEF nexus, Endo et al. (2017) find stakeholders across boundaries and at various scales, representing research, science-policy interfaces, funders, governments, development organizations, business and industry, civil society (NGOs), and media. Perrone and Hornberger (2014) emphasize the role of boundary crossing trade on FEW nexus security. Peterson (2000) tackles resilience and transformation across scales in interacting natural and social systems in a case study of salmon in the CRB, while Jarosz and Qazi (2000) examine global forces that shape the apple industry in Washington. Such approaches highlight the complexities of boundaries and scale when social system considerations are included; they also demonstrate the necessity of including social considerations for an accurate understanding of FEW system dynamics.

Unequal power dynamics also shape the delineation of boundaries, with important social implications. An emphasis on resilience at local scales may detract from the need for collective responsibility at larger scales to address inequality and risk (Lockie, 2016). Furthermore, what we label as resilient could just be a short-term condition, or a condition enabled by exploitation elsewhere in space or time (Hornborg, 2006; Davidson, 2010). Many studies of sustainability examine one place and do not attend to interactions across boundaries and impacts on sustainability in multiple places; in response Liu et al. (2013) propose an integrated framework based on telecoupling, a concept that draws attention to socioeconomic and environmental interactions over distances.

In sum, social science perspectives help us consider in more depth what we mean by resilience, inequality and power in driving processes and outcomes; goals of the FEW nexus; strategies for adaptation vs. system change; and boundaries of coupled human and natural systems at various scales and across space and time. Consideration of the social helps us reflexively assess "whose environments and livelihoods we seek to protect and why" (Cote and Nightingale, 2012) and who has voice in that process. Such considerations will help advance FEW nexus research by more fully capturing FEW nexus realities and by attending to issues of justice and equity, especially in the context of environmental changes and proposed innovations.

Incorporating social science perspectives into FEW nexus research also highlights data needs: data that capture social inequalities between and within stakeholder groups, data that are compatible to both social and ecological systems at various scales, and data collected over time. We need data that relate to processes, drivers, outcomes, and goals. Next, we turn to some specific strategies for incorporating social considerations and available data into FEW nexus research.

STRATEGIES FOR INCORPORATING THE SOCIAL INTO FEW NEXUS RESILIENCE RESEARCH

There are several theoretical and methodological approaches well-suited to addressing some of the issues highlighted above and enabling incorporating the social into FEW nexus resilience research. Here, we briefly discuss several approaches that we put into categories relating to processes, metrics, or modeling.

Processes

Process-based approaches focus on the participants in the resilience process and assist in developing generalizable frameworks for understanding complex FEW systems. The resilience framework for social-ecological systems analysis is one of the most common process-based approaches for integrating the social into resilience research. This conceptual framework draws on complex systems theory to analyze how human societies interact with ecological change and build capacity to adapt. Resilient social-ecological systems are ones that can adapt to change—both respond to change and shape change—in a way that does not limit future options and actually enhances capacity to adapt (Berkes et al., 2003). Scholars working in this area bring together ecological, social, and economic elements, conceptualize resilience as a dynamic process rather than a state variable, and focus on adaptive capacity, complex adaptive systems, and panarchy, a concept specifically emphasizing systems analysis, multi-scale and temporal interactions, and interdependencies (Gunderson and Holling, 2002; Folke, 2006; Curtin and Parker, 2014; Chaffin et al., 2016; Cosens and Gunderson, 2018; Cosens et al., 2018). Humans are increasingly seen as the cause of system changes and this perspective can provide insights as to why conventional scientific and technological approaches to resource and ecosystem management sometimes make problems worse (Berkes et al., 2003; Folke, 2006).

Much of the research on socio-ecological systems draws from a related and overlapping body of research on governing the commons and managing common pool resources, Ostrom (1990, 2009) also emphasizes process and focuses on self-governance of resources by users to achieve sustainability. Challenging the assumptions that resource users are not able to engage in sustainable self-governance and that market control, i.e., privatization, or state control of resources are the only ways to avoid a "tragedy of the commons," predicted by Garrett Hardin (Hardin, 1968: p. 1243), Ostrom (1990, 2009) documented self-organization as a successful alternative in her empirical research. This research identifies a variety of factors that encourage the likelihood of collective social and institutional organization to sustainably manage social-ecological systems, which makes system collapse less likely. Ostrom (2009) in her article, "A General Framework for Analyzing Sustainability of Socio-Ecological Systems" finds system collapse is more likely in systems that are large, highly valuable, open access, and made up of diverse resource users who do not communicate and fail to develop rules and norms for managing the resource (Ostrom, 2009). Furthermore, examples of locally evolved self-governance, sustained over time but disrupted when outside factors impinge, demonstrate the need to analyze complex systems at different spatial and temporal scales and portray sustainability as an ongoing struggle in the face of increasing resource demands driven by interactions between population, consumption, and advanced technologies that increase resource use (Dietz et al., 2003). In addition to influencing the literature discussed above on socio-ecological system resilience, Ostrom's work has spawned a large body of research on commons governance, some of which engages with FEW issues. For example, Villamayor-Tomas et al. (2015) analyze the role of institutions on environmental outcomes of the FEW nexus. Ostrom's work has also inspired multiple other research areas (see Arrow et al., 2012 for a review). Two relevant examples include work on human drivers of environmental change (Rosa and Dietz, 2012; Dietz, 2017) and work on Coupled Human and Natural Systems (CHANS) (Liu et al., 2007a,b). Within the CHANS framework, Chen et al. (2012) explore systems in which human and natural aspects interact and the production of human, animal, and ecosystem well-being and sustainability.

Metrics

Issues related to equitable access to resources, power, and agency have often been neglected from FEW nexus evaluation (Biggs et al., 2015), but several frameworks of indicators from the social sciences facilitate their incorporation. The Livelihoods Framework (LF) puts people and their needs at the center of the analysis and emphasizes the needs of the poorest and most vulnerable (Tanner et al., 2015). Livelihoods provide a link between the FEW nexus, resilience, and human well-being (Biggs and Watmough, 2012; Biggs et al., 2015). Researchers using the LF often examine local, context-specific livelihoods in rural contexts in less developed countries, and link social outcomes of the FEW nexus to the UN Sustainable Development Goals (Biggs et al., 2015; Rasul, 2016). The multidimensional Livelihoods index includes human, physical, social, financial, and natural metrics and enables measuring and monitoring of outcomes (Donohue and Biggs, 2015).

We are especially concerned with environmental change because of its expected impacts on human well-being (Dietz, 2017). Social science perspectives would likely conceptualize the purpose of the FEW system to be improving human well-being[2]. The theory of structural human ecology draws attention to the use of natural, human, and manufactured resources, and the role of social structure in producing well-being (York et al., 2002; Dietz, 2015). In the past, economic measures of wealth or affluence were used as proxies for well-being, leading to an emphasis on economic growth. There was also an overreliance on "technological fix" approaches to deal with environmental and resource issues. Together, the emphasis on growth and technology, and the assumption that focusing on these would also solve other problems, led to de-prioritization of directly addressing issues of inequality (Dietz, 2015). While the GINI coefficient is one useful and widely used metric of economic inequality, the structural human ecology of well-being perspective addresses relationships between inequality, human well-being, and the environment and employs measures such as life expectancy and subjective well-being. Such approaches and metrics of well-being are particularly well-suited to quantify a variety of system inequalities. Metrics include the environmental efficiency of well-being (Dietz et al., 2009; Knight and Rosa, 2011), environmental or ecological intensity of well-being (Dietz et al., 2012; Jorgenson and Dietz, 2015), energy intensity of well-being (Jorgenson et al., 2014), and carbon intensity of well-being (CIWB) (Jorgenson, 2014; Jorgenson and Givens, 2015; Givens, 2017, 2018). While these metrics are comparable across large geographic areas, there are many efforts to develop well-being focused indicators and indices at various scales. Smith et al. (2013) review ~20 different international well-being indices including the UNDP's Human Development Index, based on the capabilities approach of Sen and Nussbaum (Nussbaum and Sen, 1993). In the US, more nuanced measures may be especially pertinent for evaluating social aspects of FEW nexus resilience. The County Health Rankings and Roadmaps (CHR&R) measures community health at the county level (http://www.countyhealthrankings.org), the Center for Disease Control and Prevention's Social Vulnerability Index (SVI), is measure of community resilience based on US Census Data (https://svi.cdc.gov), and the Environmental Protection Agency's Climate Resilience Screening Index (Summers et al., 2017) incorporates social and environmental variables.

Flora et al. (2004; see also Flora et al., 1997) developed the Community Capitals Framework (CCF) to understand community development. The CCF offers a third way to conceptualize and operationalizing the social in the FEW nexus. The framework consists of seven types of capital: natural, cultural, human, social, political, financial, and built and attends to creating development, wealth, and self-sufficiency, improving leadership, and reducing poverty. In order to experience successful economic development, communities are advised to focus on types of capital and interactions among them (Emery and Flora, 2006). The capitals are seen as building upon each other; investment in some capitals impact other capitals, with the goal being "spiraling up" (Emery and Flora, 2006). The CCF encourages research from a systems perspective, and allows the analysis of stocks and flows, conceptualized as stocks of the various forms of capital and flows as types of capital invested. Capitals are operationalized with some of the same metrics mentioned above, such as census, voting, or survey data, although data availability over time and at various scales remains an issue[3]. While livelihoods and well-being are often conceptualized as outcomes of the FEW nexus, CCF explicitly frames capitals as both drivers and outcomes. For example, Schirmer et al. (2015) operationalize the capitals and interpret the capitals as determinants of human well-being, while Rijkhoff et al. (2017) and Martinkus et al. (2017) utilize the CCF to inform decisions about site selection for bio-fuel development. Donoghue and Sturtevant (2007) describe how various projects have used community capitals indicators to estimate community capacity

[2]Related research calls attention to well-being of nonhuman species and the ecosystem as a whole; for example, the Coupled Human and Natural Systems (CHANS) literature sets forth a research agenda on systems in which human and natural aspects interact (Liu et al., 2007a,b).

[3]There are some issues with the capitals framework. First, Dietz (2015: p. 134) expresses a preference to "reserve the term *capital* for resources that are used with the expectation of a positive return on investment—a profit" and recommends use of the term *resources* unless there is a specific intention to use the resource to generate exchange value. Second, Bourdieu's initial conceptualization in the 1980s of the multiple forms of capital highlighted their role in producing and reproducing inequality (Bourdieu, 1986; Schor et al., 2016).

and resilience in towns and cities of the western United States (for related work see Haynes et al., 1996; Harris et al., 2000).

Modeling

Conceptual maps are useful tools for representing complex system dynamics, including social aspects (Heemskerk et al., 2003). They enable capturing, organizing, and refining understanding of key feedback structures and outcomes within a particular system of interest. Conceptual mapping exercises, by nature, are creative processes in that they seek only to identify those important concepts or structures (whether physical or social) and the relationships that link them. Linkages in these exercises convey basic information, such as directionality or positive/negative impacts, rather than specific mathematical relationships. As such, these general, visual representations of a system are particularly useful for developing and building consensus around how a system is thought to behave (Stave, 2003), and bridging divides in interdisciplinary research (Stuart, 2016). Conceptual maps have been used to bring more explicit attention to social, community, and ecosystem service factors and to highlight composition and competition of communities (Nandalal and Simonovic, 2003), limitations and constraints due to environmental resources (Ghashghaie et al., 2014), co-dependent FEW security needs (Ericksen, 2008), and considerations related to governance, labor, poverty, and population fluctuations (Flora et al., 2004). Conceptual mapping can be a first step toward more precise modeling efforts.

A more rigorous methodology for representing complex system dynamics is system dynamics (SD) modeling. SD modeling is a structured framework for simplifying and simulating the complex feedback dynamics and time delays on the accumulation, movement, transformation, and reduction of key resource stocks (Luna-Reyes and Andersen, 2003). SD models tend to be computationally efficient and relatively flexible, particularly in comparison to the physically-based, mechanistic models often used for biophysical assessments. Models can have any number of feedbacks represented (from several to thousands) that when coupled integrate these myriad interactions into a set of non-linear expressions of accumulation and delayed response-a major strength of SD modeling for systems understanding. While SD modeling efforts span a diversity of disciplines and systems of interest, all center on the assumption that the structure of the system determines the observable behavior (Sterman, 2001). This assumption may be incompatible with social analysis because it minimizes the ability to incorporate human agency.

A second problem is that while some of the feedbacks and processes are quantifiable, many important social components are difficult to quantify adequately. For instance, it is relatively easy to find high-quality, quantitative data on economic or biophysical processes (e.g., yearly accumulated rainfall, annual gross domestic product), but reliable quantitative data for many social processes that are important drivers of system behavior (e.g., social capital, trust) are not widely available at varying geographic and time scales (Castelletti and Soncini-Sessa, 2007; Pahl-Wostl, 2007). Efforts to integrate quantitative and qualitative social data into SD models is ongoing. Many SD models make use of qualitative social data in the conceptual mapping and causal diagramming phases of model construction. In these early stages of model development, such data can be extremely useful for identifying appropriate policies, key structures, and decision-making logic that underlie the structure of the system and its behavior (Coyle, 2000). One promising approach regarding data is offered by current research on interoperable data, data that are compatible at different scales and units of analysis and that can integrate both social and biophysical components. Scholars working in this area highlight the potential for such data collection at scales ranging from the community to networks of environmental observatories, and the need for such data to improve our understanding of complex environmental problems and linked human and natural systems (Alessa et al., 2018; Bourgeron et al., 2018; Griffith et al., 2018).

THE YAKIMA RIVER BASIN (YRB)

In this section, we turn to a case study to flesh out some of the social and FEW nexus dynamics at play in the YRB. We then link examples from the YRB back to the complexities and strategies addressed above for seeing the social as both driver and outcome in FEW systems.

The YRB, located in south central Washington (**Figure 1**), spans four counties, and supports a diverse array of economic activities, wildlife habitat, and cultural heritages. Today, the YRB is perhaps best known for its agriculture, but this area has had a long and complicated history of food, energy, and water development, both from a biophysical and social perspective, that continues to influence FEW management and policy in the basin. Currently, the YRB is one of the most agriculturally-productive regions in the state (Vano et al., 2010). In 2012, crop and livestock production in Yakima County alone generated over $1.6 billion in market sales (USDA, 2012). With approximately one-third of the farmland in the basin currently under irrigation, this area is one of the state's top producers of apples, wine grapes, milk, and hops (USDA, 2012). Estimates in 1978 valued agricultural products to be worth $180 million annually (Huszar et al., 1978); today it is over $3 billion (Yoder et al., 2017). This agricultural success is tied tightly to the development and proliferation of irrigation in the basin, and arguably embodies the heart of FEW nexus issues in the YRB. Given the importance of this basin to the state economy, regional wildlife, and local culture, the YRB has been heavily studied and thus provides a rich body of information and science from which to examine the FEW nexus through time. Here, we identify important technological and social innovations or changes that have shaped FEW nexus development in the basin over the past 150 years to provide a richer understanding of how the FEW nexus developed in interaction with the social context.

The Co-evolution of FEW Systems in the YRB

Before the nineteenth century, this basin was home to the Yakama and other Native American Tribes. These indigenous communities had cultures that entwined tribal traditions and livelihoods with the land, water, and wildlife. Most indigenous people in this area were subsistence-based and relied on root

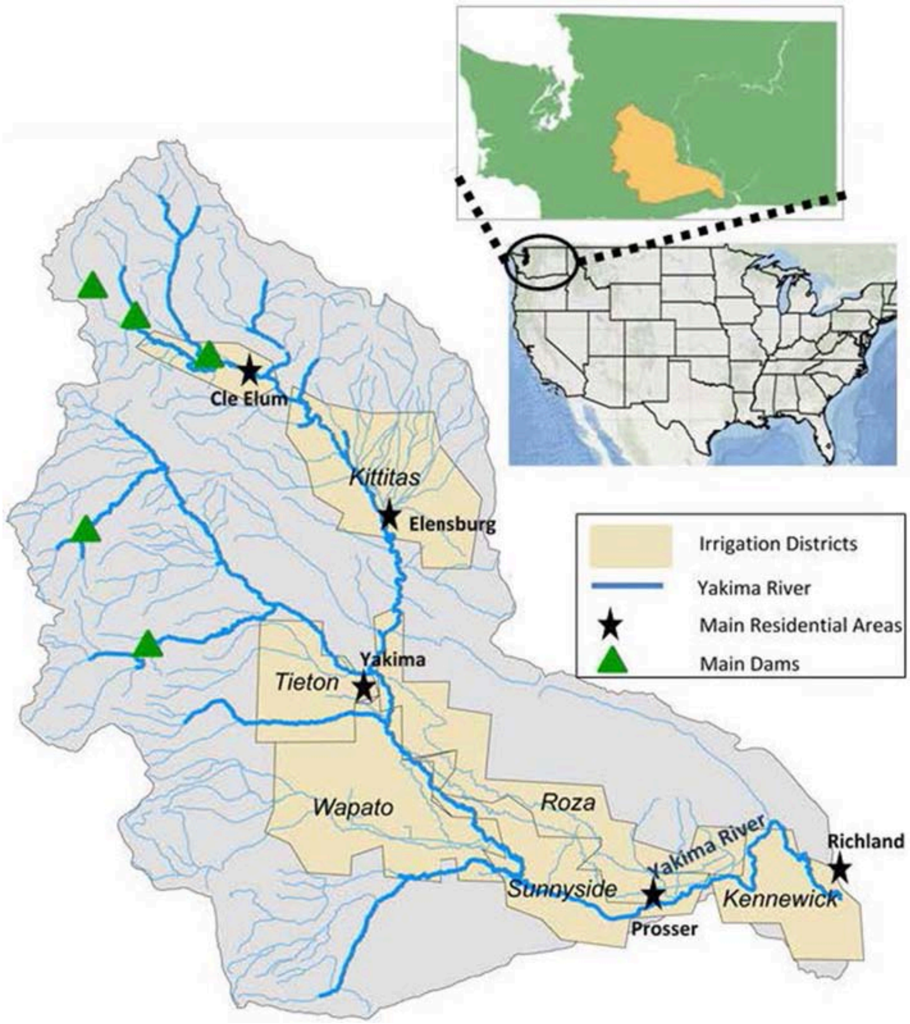

FIGURE 1 | Yakima River Basin in Washington State, USA.

crops and the large populations of anadromous fish, including salmon and steelhead that would enter the Yakima River to spawn (Hunn, 1990). Records from the 1880's suggest runs of up to 790,000 fish per year (McIntosh et al., 1994; USBR and State of Washington Department of Ecology, 2012). The importance of these fish populations to the Yakama people were both tangible, with salmon accounting for upwards of 40% of a tribal person's daily caloric intake, and intangible (Gunnier, 2008). Salmon were honored in ceremonies and places of worship and were deeply integrated into social and cultural heritage (Montag et al., 2014).

In the early nineteenth century, Euro-American explorers arrived, displacing many Native American Tribes and creating the foundations of the agricultural and ranching industry that now dominate the basin (**Figure 2**). Critical to the success of this colonization was the installation of irrigation systems to support production in an otherwise semi-arid environment. The mid-1800's saw a rapid growth of private irrigation systems- series of canals and ditches drawing water from the Yakima River- and railroad development that spurred cattle and sheep ranching as well as irrigated wheat, alfalfa and fruit tree production (Kuhler, 1940). By 1900, more than 700 miles of canals and laterals extended throughout the basin and this number increased by orders of magnitude when Yakima was selected as the first "intervention area" by the Federal Reclamation Act of 1902 to subsidize agriculture through low-cost or free irrigation construction and infrastructure (Sheller, 1997). The culmination of this intervention was the Yakima Irrigation Project, initially constructed between 1905 and 1917, now providing water for nearly 470,000 acres of farmland, and comprising five reservoirs on the Yakima River system, six irrigation divisions, and about 2 million acre-feet of water entitlements (Yoder et al., 2014). By the 1950s, dam construction on the Yakima and Columbia Rivers had blocked a majority of waterways historically used by anadromous fish for passage to upstream breeding grounds, and consequently fish populations declined dramatically. Several species, including the sockeye, summer chinook, coho, steelhead, and bull trout are

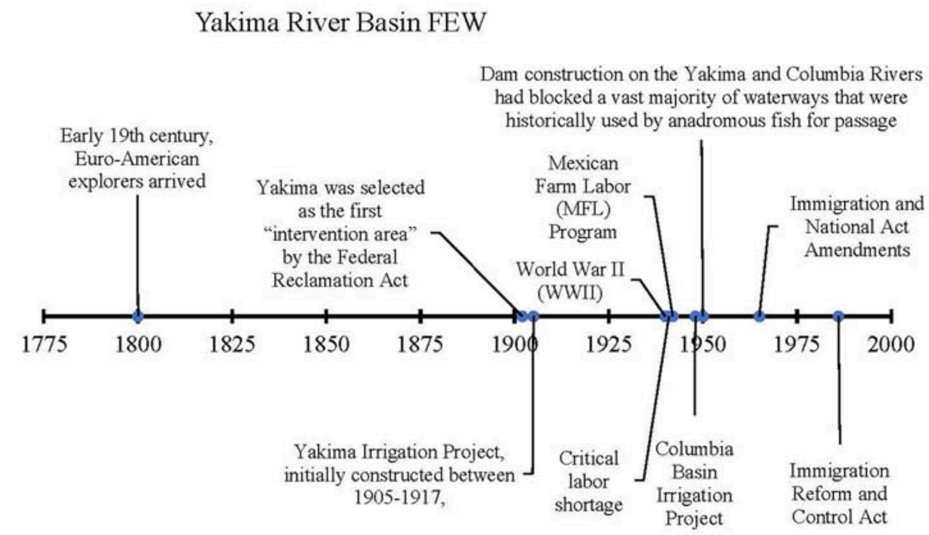

FIGURE 2 | Development of Yakima River Basin FEW Systems.

now listed as threatened under the Federal Endangered Species Act (State of Washington Dept of Ecology, 2012).

Meanwhile, the ability to irrigate large areas of the basin made this location particularly well-suited to food production, but required a large amount of farm labor to plant, tend, harvest, and process goods. This need for labor in the Yakima increased substantially with the onset of World War II (WWII), when many of the farm workers needed to produce food were sent to war. By 1941, there was a critical labor shortage in the YRB and throughout the Pacific Northwest (Gamboa and Leonard, 1990). Women, children, members of Native American Tribes, prisoners were recruited to help bring in harvests, in addition to migrant workers from Mexico under the federally negotiated Mexican Farm Labor (MFL) Program of 1942 (Jarosz and Qazi, 2000; Darian, 2006). While Mexicans had been present in small numbers in the Yakima basin since at least the 1850's, the MFL program brought in nearly 5 million workers to the US, many to the Northwest, in the 22 years the program existed (Darian, 2006). When WWII ended, the labor shortage also subsided, except in Washington. The completion of the Columbia Basin Irrigation Project in 1948 created a continued need for agricultural and food processing labor allowing many migrant workers year-round employment. Between 1950 and 1960, Hispanic populations in the Yakima Valley, and elsewhere in Washington, grew rapidly. Immigration was facilitated by two changes to federal law- the Immigration and National Act Amendments of 1965, which created a preference system for immigrants with relatives in the US, and the Immigration Reform and Control Act of 1986, which granted amnesty to immigrants who could prove they had been living in the US since 1982 (Darian, 2006). Since the 1960's, the Hispanic population in the Pacific states continued to rise, partially driven by the continued need for farm labor, but also because of the well-established Hispanic communities that facilitate integration for new migrants (Darian, 2006).

Hydropower development has also occurred in the YRB. The first power plant was built in Prosser in 1932 in the Kennewick Division and was later incorporated into the larger Chandler Power Plant in 1955. The Roza Power Plant was built in 1958. Today, these plants primarily generate hydropower for the agricultural sector, with an installed generating capacity of 24,900 kW. Surplus is marketed by the Bonneville Power Administration (BPA), which was established as a regional scale entity in 1937 and is now part of the federal Department of Energy. The BPA is responsible for coordinating the sale of hydropower from federal dams in the Pacific Northwest (Cosens et al., 2018). The hydropower economy of the YRB is smaller than the agricultural sector, with two divisions (Kennewick and Roza) using water for irrigation and power. In recent decades, these power plants have been subject to subordination to augment the streamflow and improve the aquatic habitats in the Yakima River as authorized by Title XII of the Act of October 31, 1994 (108 Stat. 4550, Public Law 103-434). There are concerns that further subordination could lead to hydropower deficiency in the agricultural sector.

Current FEW Issues in the YRB

Today, agriculture accounts for nearly 28% of the labor force in Yakima County. Demographics in this county reflect the mixed heritage of the YRB, with 48% of residents claiming Hispanic or Latino descent, 44% registering as White, and 6.2% as American Indian/Alaskan Native (Meseck, 2017). Despite the constant need for field and food processing in the Yakima, many of the jobs in this basin are seasonal, and thus the per capita income in Yakima County ($38,527) is significantly lower than the state average ($51,898), and the poverty rate is higher (19.1%- Yakima, 12.2%- state average) (Meseck, 2017).

Additional FEW issues in the Yakima link to climate change and a long-term trend in increasing water demands that have created tensions between water users in the basin. Inequality is characteristic of water rights in the YRB. The prior appropriation doctrine that guides water rights in this basin favors early water users, or senior water rights holders, over those who acquired water rights later. These later users, or junior water rights holders, may be prorated each season and may only receive water after the senior water allocations have been met. A mechanism for determining water allocations to YRB irrigators in years of shortage was developed with the 1945 Consent Decree [US District Court, 1945] along with a strategy for forecasting drought (and thus how much water junior rights holders could expect to have in a given season). Miscalculations associated with drought forecasting can, and have had, serious economic and societal ramifications for individual farmers in the YRB (e.g., Glantz, 1982; Vano et al., 2010). The issue of the "haves" and "have nots" is amplified as state water permitting agencies (Washington Administrative Code 173 539A-WAC) are forced to recognize and deal with the growing problem of groundwater use impacting surface water user rights, and the need to continue to provide, and in some cases augment, necessary in-stream flows for endangered fish (Gendaszek et al., 2014).

Issues over water rights are reflected not only at the individual scale, but can be seen in sectoral conflicts as well. As streamflow timing and availability shift with climate change, irrigation, hydropower and municipal water users are increasingly coming into conflict as the volume of water available no longer matches when water is needed (and permitted for). This is exacerbated by the subordination of hydropower production in the YRB over the last 20 years in favor of meeting water demands for agricultural production and in-stream flow requirements for endangered fish. Other concerns include agribusiness runoff affecting water quality and lawn watering systems putting heavy demand on available water (Yakama Nation, 2016). Today, the Yakima Basin Integrated Plan (YBIP) aims to balance competing needs for the river (USBR and State of Washington Department of Ecology, 2012). The YBIP contains elements related to improving fish passage and habitat, increasing and enhancing surface and groundwater storage, implementing market-based water reallocation programs, and promoting water conservation (State of Washington Department of Ecology, 2013; S. 714 amendment to Public Law 103–434). The plan while contentious due in part to concerns by tribes about the impacts and benefits of additional infrastructural development on fish survivability and cultural heritage sites, has progressed into the first of three phases for the $3.8 billion, 30-year Plan (State of Washington Department of Ecology., 2018). Some of the YBIP's main aims are to assure water reliability for the Yakama Nation and to create a consensus-based management approach that provides an alternative to litigation (S. 714 amendment to Public Law 103–434).

INTEGRATING THE SOCIAL INTO THE FEW NEXUS AND MODELING

The YRB case demonstrates the value of considering how the social is integrated into FEW nexus research. Rather than thinking of the resilience of this system as characterized by a return to equilibrium, the social component represents ongoing change over time. Furthermore, inequalities shape the system and inequality is an outcome. In terms of social justice and "resilience for whom," system change had negative ramifications for tribal groups and non-human species such as the salmon, while others prospered, albeit unevenly, from agricultural revenues. The question "resilience of what," or questions of system function, highlights inequalities in power to shape the prioritization of valued functions. For example, we can see the role that powerful agricultural played in policy development and passage of laws regarding multiple aspects of the FEW system- migration to meet labor needs, the building of dams for irrigation and energy, or in the designation of water rights.

In addition to encouraging a deeper consideration of how resilience is defined, an incorporation of the social allows researchers to explore questions such as: Do these unequal outcomes mean the FEW nexus is less resilient in certain aspects? Would the system as a whole be more resilient if there was less inequality in process and/or outcome? Further, are these changes over time accurately characterized as innovations to increase resilience? Also, when should they be considered adaptations vs. system changes? For example, some affected parties might characterize YRB FEW nexus changes as adaptation, while others, such as the tribal groups who experienced drastic alterations in their lives and cultures, might perceive this as system change. External forces, including colonization, war, and market pressures, also highlight the complexity of delineating system boundaries and forces across scales.

The YRB case study also demonstrates the social is both driver and outcome of the FEW nexus, shaping how we conceptualize and model FEW nexus resilience and sustainability. A social science lens allows researchers to ask, how do these inequalities shape our assessment of FEW nexus resilience? The CCF literature highlights how livelihoods, well-being, and the various capitals are not only outcomes, but also drivers that shape future options (Emery and Flora, 2006). Clearly, social forces were key in driving the development of the FEW nexus in this region and they continue to shape the region today. The presence or absence of adaptive governance practices, emphasized in the socio-ecological resilience literature (Folke et al., 2005), or common pool resource governance practices, described by Ostrom (1990), draw attention to inequality in process and how it affects uneven outcomes in terms of resource access. Examples include access to fish species and water resources (Cosens et al., 2018). Additionally, these processes link to uneven outcomes in terms of livelihoods and well-being for some groups in the region. Negative social ramifications are especially important to consider when designing innovations for improving FEW nexus resilience or modeling innovation outcomes, in order to make interventions more just and accurate and to help avoid unintended consequences of proposed changes.

This case study provides a structure from which we can start parsing the social and biophysical together into a unified modeling effort. While the modeling effort is on-going, below we highlight how such social frameworks and indicators may be integrated to model the FEW nexus.

Conceptual Mapping the Evolution of the FEW Nexus Over Time

Building on the information presented in the Yakima case study, we use a type of conceptual map (causal loop diagrams) to show how YRB socio-ecological systems have developed over time and what factors dominate. A timeline (**Figure 2**) highlights the introduction of innovations, especially government policies, in which affected groups had unequal access to shape processes and changes had lasting societal impacts. **Figure 3** shows the development of linkages and feedbacks in the Yakima River Basin. In this figure, a series of successive conceptual maps depict simplified linkages and feedbacks related to these trends which demonstrate a (A) pre-1900s era, (B) 1900-1950s era, and (C) 1950s-2000s era management of the water available. The initial social-ecological system in **Figure 3A** revolves around the boundaries and scale of the Yakama Nations in the YRB. The local FEW system was defined by the water availability that contributed to habitats for large populations of anadromous fish, including salmon and steelhead, which produced local food security and social and cultural heritage (Montag et al., 2014). Resilience of this food resource benefited the tribes' and bands' well-being in 4.6 million ha of the Lower CRB. This food system's resilience and change is illustrated in the subsequent eras (**Figures 3B,C**).

After ceding 90% of this land to the U.S. government and with the increase in Euro-American settlers into the region (**Figure 3B**), a new FEW system began intensely affecting the previous one with the rising dominance of irrigated agriculture. Washington apple production in particular begin to cause rising tensions related to social justice and conflicting goals for food systems. Federal policies and actions privileged the production of apples for shipment to Hong Kong, Honolulu, and Europe by 1900 (Jarosz and Qazi, 2000) effectively exporting water to global consumers and in contrast to the previous food system developed for local consumption. Similarly, many other regional agricultural products were produced for national and international markets. This caused regional social shifts, such as decreasing the presence and power of the Yakama nations and increasing Euro-American settlers' influence, and demographic shifts, such as increasing the Mexican migrant labor population. Salmon populations significantly decreased and global shocks begin to have more direct impact via war-time policies and international agricultural market competition.

The 1950s to 2000s era (**Figure 3C**) saw further interaction between the local FEW system and the export-driven FEW system. Hydropower and diversion rules that decreased the supply and quality of instream flows were established, however legal measures also became available to require the water needed for endangered anadromous fish.

Figure 3 demonstrates that throughout these three periods, the questions of "resilience for whom?" and "of what?" shifted from a focus on local residents' sustenance to export-driven economic development and finally to more emphasis on market forces, management of resources, and an attention to the

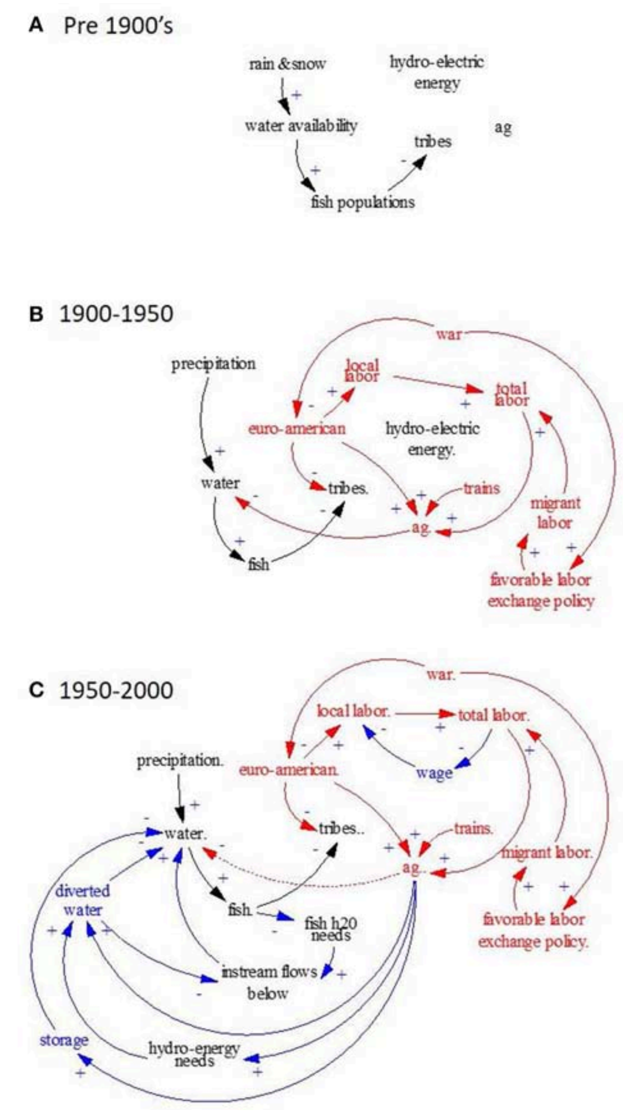

FIGURE 3 | Development of linkages and feedbacks in the Yakima River Basin. **(A)** Pre 1990, **(B)** 1900-1950, and **(C)** 1950-2000.

incorporation of multiple stakeholders enabled through legal mechanisms[4]. We do not mean to suggest that this is either a desirable or undesirable change, nor that it necessarily results in a decline in overall local resilience. We simply aim to suggest that

[4]Key features of governance in the region are dominated by legislation and acts of Congress that enable feasibility studies for enhancement projects (93 Stat. 1241, Public Law 96-162) and later funding to implement mitigation (phase 1; 98 Stat. 1333, Public Law 98-381; 98 Stat. 1379, Public Law 98-396) and conservation (phase 2; Title XII 108 Stat. 4550, Public Law 103-434) (USBR, 2018). While legal recognition and facilitation is enabling the space for reconciliation of highly developed river systems with ecosystem functions (Cosens et al., 2018), significant effort is needed to continue to promote adaptive governance that includes effects on stakeholders' well-being (Montag et al., 2014). With phase 3 of the Yakima River Basin Enhancement Project being authorized in 2017 (S. 714 amendment to Public Law 103–434), $3.8 billion has been allotted toward collaboration that enhances long-term resiliency.

modeling resilience in this way can incorporate social factors, and that the best conceptualizations of resilience take into account the uneven impacts, impacts at various scales and across boundaries, and multiple definitions of and desired pathways to resilient situations for different groups.

Conceptual Maps of the FEW System That Further Incorporate the Social

The timeline conceptual maps in **Figure 3** show how conflicting goals for multiscale FEW systems can shape which groups dominate both processes and outcomes, and how these have lasting impacts by shaping future opportunities. Next, we incorporate more components, both biophysical and social, into a map of the current YRB FEW system (**Figure 4**). **Figure 4** is a conceptual map of FEW system demands and allocations based on distribution between users that prioritize water for development (D) and users that prioritize water for fish and ecosystem function (EF). To create this we build on several modeling efforts that address various components. For example, Ericksen (2008) models aspects of food systems that contribute to food security; this can be adapted to include energy and water security and considerations of livelihoods, well-being, and elements of the CCF. Nandalal and Simonovic (2003) create a conceptualization where the power with which a group of stakeholders is able to employ to pursue their interests results in a decreased allocation for the neighboring stakeholder. Loops are negative when the variable dynamics balance each other or positive when they are reinforcing and leading to positive feedbacks. This model assumes an ultimate equilibrium dependent on the aspirations and the weight of the fight in each group (in what can be seen as the balancing loops of B2 and B3, for ecosystem function and development priorities, respectively). While built upon clearly limiting assumptions, this serves to highlight the fundamental social interactions that are at the basis of the FEW nexus. Other modeling efforts show that while increased water utilization could encourage the development and growth of a community (Loops R1, R2, R3), this is limited by resource availability (Ghashghaie et al., 2014) which in this case is demonstrated through the reservoir water balancing loop (B1). **Figure 4** represents our attempt to build on these previous models and incorporate attention to the social as both input and output of FEW system mapping. For example, in **Figure 4** one section of the conceptual map indicates how governance plays a role in introducing policies that ultimately negotiate and prioritize FEW security of various stakeholders as well as how their satisfaction and aspirations (e.g., livelihood, well-being) create feedbacks. Starting with archetypes of resource allocation (Loops B1, R1,R2,R3) and combining with resource conflict (Loops B2, B3) demonstrates a adjustable, specific, and reproducible methodology that has been called for in nexus assessment (Ghashghaie et al., 2014; Albrecht et al., 2018).

Our next conceptual map shown in **Figure 5** then incorporates the CCF, including financial, built, political, social, human, cultural, and natural capital (Flora et al., 2004,

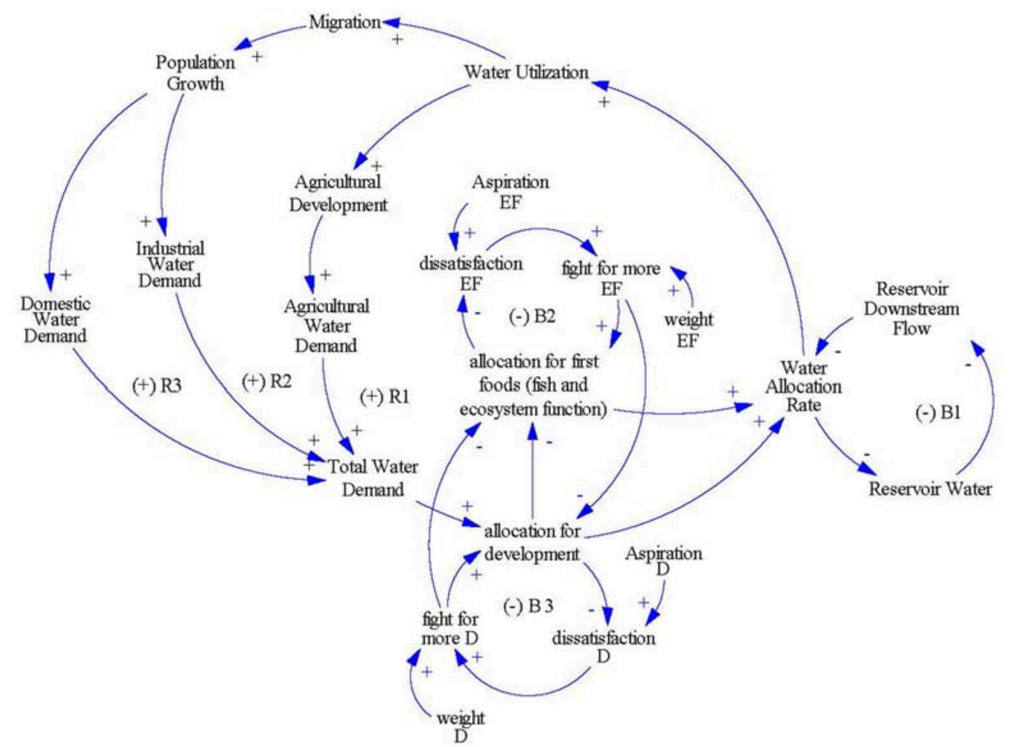

FIGURE 4 | Conceptual map of FEW system demands and allocations based on distribution between users that prioritize water for development (D) and users that prioritize water for fish and ecosystem function (EF). R and B represent positive and negative feedback loops.

2005). In this conceptual map that incorporates the capitals framework into FEW system mapping, green text highlights ecosystem functions and blue text indicates development aspects within the Yakima River Basin. Pink text demonstrates where community capitals influence interactions in the FEW nexus, and red text shows areas that can influence intensification or alleviation of frictions. In conceptualizing the structure of the system, this map can assist researchers in evaluating what shapes the resilience of components of the system. This set of feedbacks and loops is an initial visualization of where certain policies have potential to increase or decrease frictions between diverse stakeholder groups within the FEW nexus. It also helps inform what dynamics are behind incentives to compete or cooperate. Modeling social-ecological system complexities in a way that allows us to form multiple testable hypotheses is vital to evaluating resilience (Gunderson, 2003). **Figure 5** demonstrates how the CCF can be integrated into a model that allows for testing of multiple hypotheses, especially related to proposed system innovations. For instance, if aquifer storage and recovery is developed within the Yakama Nation (S. 714 amendment to Public Law 103–434), this might allow natural capital to be amassed, leading to a decreased need to fight for more water. If this innovation combines with a shift in norms in the YRB away from landscaping requiring watering this could further alleviate water demand and conflict.

Integrated Modeling for Improved Management of the YRB FEW Nexus

After expanding our understanding of social aspects of the FEW nexus through conceptual mapping, we incorporate these insights into an existing object-oriented river basin modeling system. **Figure 6** shows a conceptual map of interaction among FEW systems and society in the YRB. This conceptualization lays the groundwork and provides a roadmap toward developing a simulation tool that can answer more profound questions related to FEW-society interactions. The YAK-RW (left panel) has been developed and used to simulate the river system processes (FEW systems) over the YRB (Carron et al., 2000; Zagona et al., 2001); in the right panel, examples of the community capital frameworks that have been presented in past studies (e.g., Emery and Flora, 2006) are included to build upon work discussing the characteristics of connections between FEW and society

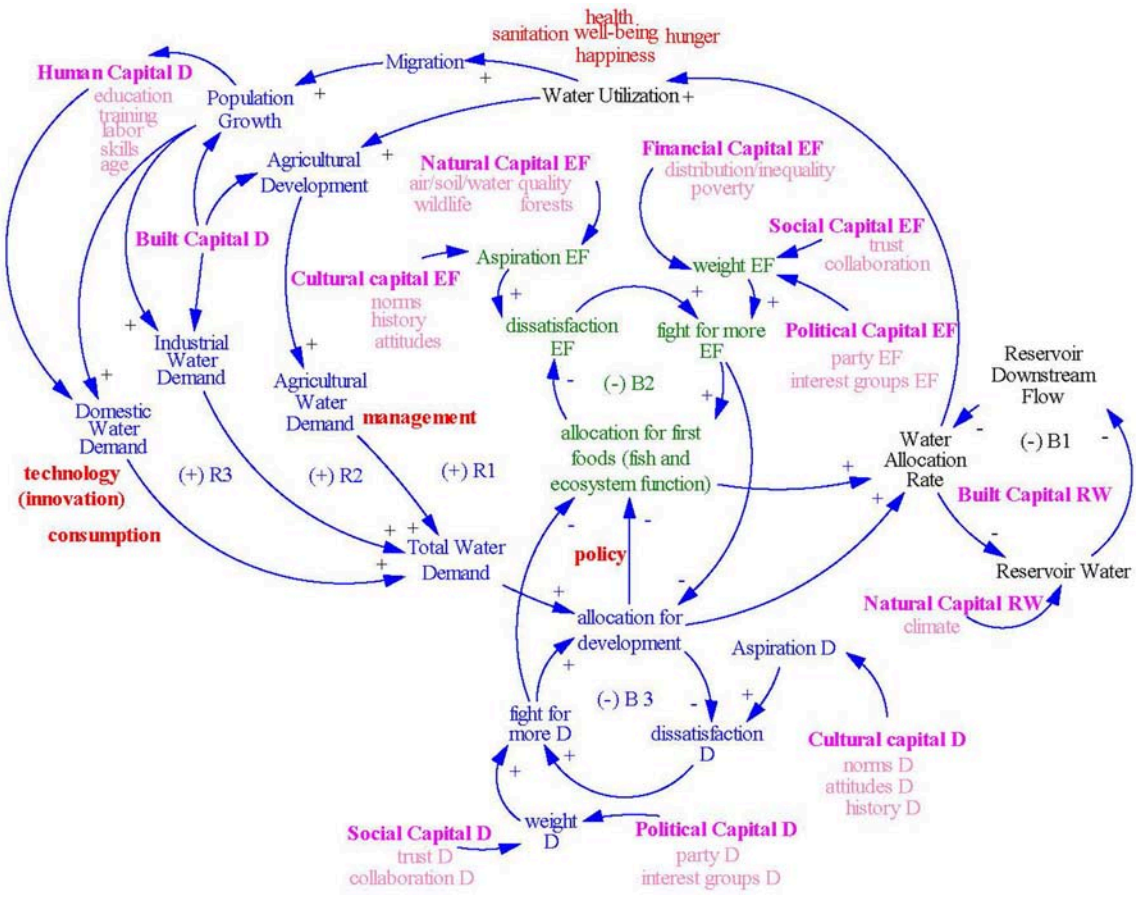

FIGURE 5 | Conceptual map of incorporated capitals into FEW systems with green text highlighting ecosystem functions and blue text indicating development aspects within the Yakima River Basin. Pink text demonstrates where community capitals influence interactions in the FEW nexus and red text shows areas that can influence intensification or alleviation of frictions.

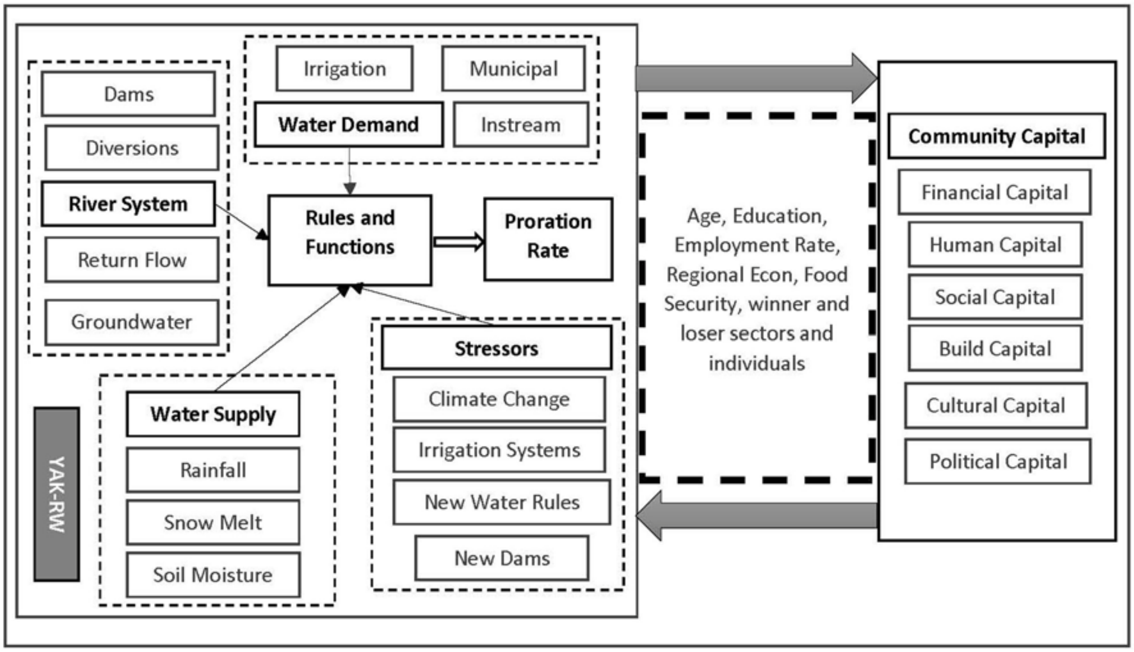

FIGURE 6 | Conceptual map of Yakima River Ware with social components.

(D'Odorico et al., 2018). YAK-RW (Yakima RiverWare) is a case-specific implementation built on the RiverWare generic platform (Zagona et al., 2001), a platform system that, similar to System Dynamics, simulates river system processes through stocks and flows such as streamflow movement, dam operations, irrigation and municipal diversions, and surface-ground water interaction (**Figure 6**, left side). YAK-RW has been widely used to explore how stressors such as climate change and farmers' adaptation decisions such as farm-level water conservation (Malek et al., 2016) modify the FEW nexus. The model has also been used to assess how infrastructural developments such as building a new dam [USBR (US Bureau of Reclamation), 2008; USBR, 2012, 2018; Yoder et al., 2017] can affect the economy of FEW sectors including agriculture, hydropower, and fisheries. Below, we draw upon YAK-RW's recent application in the YRB to highlight salient social impacts and feedbacks related to water-saving technologies. Other research could incorporate social considerations into similarly developed SD models.

The YRB has been historically sensitive to droughts and is projected to experience more frequent and severe droughts in the future (Elsner et al., 2010; Vano et al., 2010; Malek et al., 2018). Malek et al. (Forthcoming) explore how future droughts provide financial incentives for farmers to switch to more-efficient irrigation systems. The authors used YAK-RW to model the compound impacts of climate change and farm-level irrigation decisions in the YRB. Results indicate the economy of the agricultural sector improves under more-efficient irrigation scenarios and the agricultural sector as a whole will be more resilient to droughts. Moreover, streamflow increases in some of vulnerable areas of the YRB. The increase in streamflow facilitates salmonid outmigration. However, while the economy of the energy sector is smaller than other sectors, it declines when irrigation systems are more efficient. This suggests that irrigation technology innovations have conflicting impacts across FEW sectors and may create cross sector conflicts.

Ongoing research (e.g., Malek et al., Forthcoming) also addresses the impacts of FEW-related changes in the YRB such as farm-level investment in greater irrigation efficiency, by identifying the "winners and losers" within the agricultural sector and rural communities. Results indicate that growers of high-value crops (e.g., grapes, cherries, apples) and multiple-cutting crops (e.g., alfalfa) benefit the most from the way their yields respond to the compound effects of climate change and improvements in water use efficiency. However, investment is not viable for growers of annual crops (e.g., corn, potatoes, and wheat) which currently make up about 23% of total farmed areas in the YRB (Malek et al., Forthcoming). Furthermore, farmers' decisions depend on several factors, such as age, education, risk appetite, gender, and familiarity with new systems (Gardebroek and Lansink, 2004; Crane et al., 2011; Viscusi et al., 2011; Taylor and Zilberman, 2017). For example, older farmers might be more reluctant to invest because it could be more challenging for them to adopt new techniques, or the investment horizon might be longer than their perception of their own lifespans (Wang and Hanna, 1998). Moreover, efficient irrigation systems that are installed usually degrade the quality of return flow, which is a key component of water supply for downstream users (Bliesner et al., 1977; Causapé et al., 2004). Therefore, efficient irrigation systems might lead to additional socio-economic complications through lower quality of return flow.

This research on irrigation efficiency and the broader social implications demonstrates that although efficient irrigation systems cause an overall improvement in the agricultural economy of the YRB and make the economy of the basin more resilient to water stress (i.e., droughts) other interests are affected and need to be considered. This includes asking the questions: resilience for whom and of what? For example, a social science approach allows us to ask how labor demand is affected, since research shows that reduction in labor demand can lead to adverse outcomes for rural economy (Jobbins et al., 2015). We also see that a single economic indicator (e.g., improvement in overall or sectoral economy of FEW systems) oversimplifies the conflicting dynamics, such as those between instream stakeholders (e.g., tribes) and out-of-stream stakeholders (e.g., farmers) or even between farmers of different types of crops. Furthermore, local socioeconomic and biophysical interactions are complex and generalizations across time and space must be completed carefully. No single best management practice (e.g. farm-level water conservation) that benefits all parties may exist, but an inclusive and transparent policy-making process can lead to a mutually understandable plan that minimizes conflicts and eventually creates a lasting self-organized and self-governed system (Ostrom, 2009).

Our conceptual maps and integrated modeling efforts are useful in the planning phases of large decision-making processes. The YAK-RW YRB example (**Figure 6**, left side) shows how the components of the FEW system are represented in the YAK-RW. Despite its strength simulating FEW system components, though, YAK-RW cannot capture the ways that society interacts with FEW systems. The middle panel of **Figure 6** shows several socioeconomic factors that could be used to characterize the feedback process between FEW systems and society. The right panel shows components of the CCF that could be integrated. The implementation of these factors, however, is still cumbersome and hindered by data issues. Our model presented in **Figure 6** represents progress to date in capturing how shifts in FEW systems affect society and vice versa, this can inform YAK-RW and other modeling moving forward.

CONCLUSIONS

FEW nexus research is a complex and highly interdisciplinary endeavor. This paper demonstrates the complexity, but also the importance, of considering social factors when examining FEW nexus resilience. We find, via historical case analysis and conceptual modeling over time, that FEW management decisions in the YRB led to starkly unequal outcomes. This demonstrates that a resilience focus that does not incorporate insights from the social sciences may unintentionally privilege a status quo created by those in power. This structures unequal opportunities, limits diverse understandings of resilience, and may have real impacts on FEW nexus sustainability. Considerations of the social enable us to ask questions about inequality, power, and multiple indicators of resilience, and may productively shift how we conceptualize FEW nexus sustainability. To encourage the incorporation of social factors, we highlight complexities to address. We then provide examples of multiple approaches to incorporating the social, including ones that focus on participatory processes and others that focus on indicators for incorporation, as both drivers and outcomes, in conceptualizations and modeling of systems at multiple scales. We then use these in conceptual and system dynamics modeling. While our research focuses on the YRB within the CRB, it is applicable to other FEW systems around the world. Including considerations of social drivers and social outcomes improves research by making it more accurate in that it is (1) a more holistic conceptualization of reality, (2) more likely to produce desired advances, such as innovation adoption, and avoid unintended negative consequences, and (3) more just, by taking into account inequalities in the FEW system.

While some research methodologies such as the case study approach facilitate considering the social, conceptual mapping and attempts at bringing the social into a modeling system such as RiverWare highlight complexities and data needs. We need data that enable us to explore questions such as how do inequalities in power to shape process and outcomes matter to various conceptualizations of resilience and FEW system outcomes? And, how do system inequalities affect different groups and various aspect of resilience and sustainability? Modeling allows us to explore these relationships. While conceptual mapping does not require data, it, along with suggested framework and indicators, draws attention to important concepts to consider and thus it points to data needs. We need data at multiple scales and time points and data that are compatible across biophysical and social systems. For example, in the YRB better data at multiple scales, collected over time, on water rights allocations, prorationing, litigation, and cultural damages would allow us to explore how inequalities (e.g., cultural or between senior and junior water users) develop and evolve, and how different innovations may directly or indirectly impact these relationships. This dearth of data is a challenge to accurately modeling socio-ecological systems. Despite these difficulties, we maintain that the social science frameworks presented, including those that capture livelihoods, well-being, and community capitals, offer productive ways forward to incorporate important social components into FEW nexus research.

AUTHOR CONTRIBUTIONS

JG, JP, CG, and KM contributed to the conception and design of the study. JG wrote the first draft of the manuscript, and took the lead in overall organization, on all subsequent drafts and revisions, and on writing the sections that pertain to the social science aspects of the research. JP and CG took the lead on the YRB case study section and JP, CG, and KM took the lead on the modeling sections. All authors contributed to manuscript revision and read and approved the submitted version.

ACKNOWLEDGMENTS

We would like to thank the Columbia River FEW team composed of researchers from Washington State University, University of Idaho, Utah State University, and Pacific Northwest National Laboratories for their collaboration, research support, and helpful discussions in formulating conceptualizations of FEW systems and resilience. Funding for this work was provided by: NSF EAR #1639458 and USDA #2017-670 04-26131.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Environmental Science

SYSTEMATIC REVIEW
published: 30 October 2018
doi: 10.3389/fenvs.2018.00128

What Is Driving the Water-Energy-Food Nexus? Discourses, Knowledge, and Politics of an Emerging Resource Governance Concept

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OPEN ACCESS

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Specialty section:
This article was submitted to Freshwater Science, a section of the journal Frontiers in Environmental Science

Received: *13 July 2018*
Accepted: *10 October 2018*
Published: *30 October 2018*

Citation:
Wiegleb V and Bruns A (2018) What Is Driving the Water-Energy-Food Nexus? Discourses, Knowledge, and Politics of an Emerging Resource Governance Concept. Front. Environ. Sci. 6:128. doi: 10.3389/fenvs.2018.00128

In the context of accelerated global socio-environmental change, the Water-Energy-Food Nexus has received increasing attention within science and international politics by promoting integrated resource governance. This study explores the scientific nexus debates from a discourse analytical perspective to reveal knowledge and power relations as well as geographical settings of nexus research. We also investigate approaches to socio-nature relations that influence nexus research and subsequent political implications. Our findings suggest that the leading nexus discourse is dominated by natural scientific perspectives and a neo-Malthusian framing of environmental challenges. Accordingly, the promoted cross-sectoral nexus approach to resource governance emphasizes efficiency, security, future sustainability, and poverty reduction. Water, energy, and food are conceived as global trade goods that require close monitoring, management and control, to be achieved via quantitative assessments and technological interventions. Within the less visible discourse, social scientific perspectives engage with the social, political, and normative elements of the Water-Energy-Food Nexus. These perspectives criticize the dominant nexus representation for its managerial, neoliberal, and utilitarian approach to resource governance. The managerial framing is critiqued for masking power relations and social inequalities, while alternative framings acknowledge the political nature of resource governance and socio-nature relations. The spatial dimensions of the nexus debate are also discussed. Notably, the nexus is largely shaped by western knowledge, yet applied mainly in specific regions of the Global South. In order for the nexus to achieve integrative solutions for sustainability, the debate needs to overcome its current discursive and spatial separations. To this end, we need to engage more closely with alternative nexus discourses, embrace epistemic pluralism and encourage multi-perspective debates about the socio-nature relations we actually intend to promote.

Keywords: discourse analysis, geography of knowledge, resource governance, socio-nature relations, sustainability

INTRODUCTION

In recent years, the Water-Energy-Food Nexus approach has attracted growing attention within international politics, academia and other areas of society. Originally, the concept emerged within the realms of international politics under the influence of the World Economic Forum and related policy makers. Cairns and Krzywoszynska (2016), for instance, trace the nexus back to the year 2008, where business leaders of the World Economic Forum issued a call to engage with nexus issues between economic growth and water, energy, food resource systems. The Bonn2011 Nexus conference marks an additional milestone, which gained prominence through its influential background paper: "Understanding the Nexus: Background paper for the Bonn2011 Nexus Conference" (Hoff, 2011). The World Economic Forum, simultaneously, published another leading report on "Water-Security: The Water-Food-Energy -Climate Nexus" (World Economic Forum). By arguing that an integrative approach to water, energy and food may enhance resource security, efficiency, poverty reduction and better resource governance across sectors, these documents set the tone for future debates.

The overarching nexus debate is shaped by many different societal domains and the significant influence of development actors. Hence, a large part of the nexus literature consists of policy reports, position papers, working papers or strategy documents compiled by international agencies, national ministries, NGOs, consultancies, transdisciplinary networks, or financial institutions like the World Bank. As the Water-Energy-Food Nexus debate gains traction, it progressively influences international development and resource governance approaches. The United Nations (UN) and EU Commission, for instance, seek to adopt a nexus perspective to implement the UN Sustainable Development Goals (SDGs; The Nexus Dialogue Programme, 2015). The nexus also acts as international development agenda, which diffuses into regional policy programs across multiple scales, mainly from north to south (Middleton et al., 2015). International non-governmental organizations such as IUCN and WWF highlight the need for a nexus approach to achieve resource security (IUCN, 2013; WWF and SAB Miller, 2014). Although research organizations like the Stockholm Environment Institute were involved in organizing the Bonn2011 Nexus conference, the concept only later became the focus of scientific investigation. Consequently, various academic nexus platforms emerged, as the nexus frames research agendas and provides growing funding opportunities for scientists.

Despite this growing prominence, the nexus in its nascent form is still ambiguous and serves multiple purposes. First, it is employed as analytical perspective to describe and better understand the interlinkages between water, energy, and food resource systems (e.g., El Gafy et al., 2017; Martinez-Hernandez et al., 2017). Second, it serves as *boundary concept* to facilitate discussion between the academia and politics concerning resource governance and sustainable development (e.g., Bazilian et al., 2011; Hernandez et al., 2014; Abdullaev and Rakhmatullaev, 2016; Brouwer et al., 2018). Third, the nexus acts as governance concept, aiming to integrate resource sectors across policies and infrastructures to promote sustainability and better resource allocation (e.g., Rasul, 2014; Laurentiis et al., 2016; Karan et al., 2018). To achieve these goals, the nexus approach highlights the need for technological innovations, recycling, and the reduction of waste. Moreover, the concept advertises knowledge integration via inter- and transdisciplinary research approaches and collaborative decision-making (e.g., Ringler et al., 2013; Hernandez et al., 2014; Allouche et al., 2015; Conway et al., 2015; Laurentiis et al., 2016).

Though international guiding concepts, like the Water-Energy-Food Nexus, may become very influential in shaping policy programs, and scientific funding schemes, critical engagement with these concepts is often limited or neglected. Within the leading political and (natural) scientific debates, the nexus is rarely questioned but described as neutral and apolitical concept. This represents an important misconception, as "[i]nfluential concepts in policy making are not merely neutral or scientific; they do not emerge by chance but, rather, are the emanation of complex webs of interests, ideologies, and power" (Molle, 2008: p. 132). Hence, we deem it necessary to critically investigate the nexus approach before further endorsing it as analytical or resource governance framework. Timely reflexivity is important, as opening up such concepts to critical investigation can be very difficult, once they are established as social, political or scientific facts. The ambiguity of concepts like the nexus make them susceptible to processes of appropriation by powerful actors to suit particular agendas (Cairns and Krzywoszynska, 2016).

While critical investigation of the Water-Energy-Food Nexus concept is limited, several studies exist that review the nexus from a social scientific perspective. These contributions mainly challenge the nexus concept for neglecting socio-political aspects of resource use and allocation. They argue that the prevailing technical-managerial nexus framing is inadequate for addressing social aspects like poverty reduction, distributional justice, or power asymmetries in resource governance (e.g., Allouche et al., 2015; Benson et al., 2015; Foran, 2015; Leese and Meisch, 2015; Middleton et al., 2015; Mdee, 2017). Although this critical research provides important insights into actor interests and power relations, most of these papers are conceptual or theoretical in nature. Empirical studies exist but often focus on particular aspects of the nexus or specific geographical locations, which hinders an overarching generalization of research results. Mdee (2017), for instance, analyzes two case studies in Tanzania and concludes that, here, the nexus does not sufficiently disaggregate the political nature of water allocation. Cairns and Krzywoszynska (2016) identify the nexus as contested "buzzword" (ibid. p. 164) but solely focus on UK natural resource debates, which may differ from international ones.

In order to address these shortcomings, we investigate the academic nexus debate from a meta-level perspective. To overcome the methodological restrictions of most social scientific nexus research, we also aim to provide a strong empirical foundation for our argument. To reveal overarching knowledge and power relations, we take a discourse analytical approach to study the international scientific nexus debates. First, we explore various discursive formations of the WEF-Nexus. Can we identify dominant or marginalized discourses and, if so, what knowledge and power relations are at work? This relates to the questions of who produces nexus knowledge and what knowledge is seen as more legitimate or authoritarian. We also focus on the geographical context of these knowledge and power relations by analyzing the stem of nexus knowledge and its destination. Second, we examine central discursive elements of the scientific WEF-Nexus by referring to the way environmental problems are framed and what solutions are legitimized to solve these problems. Are there different socio-nature relations shaping nexus discourses and what (political) implications emerge from this?

Addressing these questions is important, as certain understandings of environmental issues gain dominance and emerge as truths through specific knowledge and power effects (Hajer, 1995; see section Analytical Framework). The way environmental problems are defined is important for how these problems are dealt with politically. Particular understanding of environmental challenges may also reflect in physical or material effects (Feindt and Oels, 2005). In this sense, academia plays an important part, as science currently holds the "monopoly on knowledge claims" (Hajer, 1995: p. 281) in western societies. Science is actively engaged in shaping ideas, concepts and categorizations that have significant political implications. While the nexus debate is influenced by many different sectors, science plays a prominent role in defining and legitimizing the nexus as a resource governance concept to be implemented by policy makers. We focus on analyzing the scientific nexus discourse, as scientists are also increasingly called upon as experts in environmental governance processes, where they play an important (political) part (Castree, 2015). During the Bonn2011 Nexus conference, for instance, international scientists and research organizations like the Stockholm Environment Institute took very active roles. In this sense, the nexus represents a *hybrid* concept, which renders the distinction between scientific and non-scientific contributions difficult.

This hybridization becomes particularly obvious in global environmental politics, where the boundaries between science and non-science are increasingly blurred (e.g., Demeritt, 2001; Grundmann, 2007).When regarding the nexus as a hybrid, the conventional view of science as independent of the political or ideological realm becomes untenable. Science does not provide neutral or objective evidence for rational decision-making. Instead, we need to recognize the dynamic interactions or intrinsic connections between knowledge production and decision-making (Grundmann, 2007; Wesselink et al., 2013; Benessia and Funtowicz, 2016). Amidst this difficult distinction, we demarcate the scientific contributions to the nexus debate by focusing our analysis exclusively on peer reviewed journal articles (see section Research Methodology). A discourse analysis of the academic literature allows us to identify the underlying socio-political and geographical contexts of nexus research, different discursive formations, competing interpretations of environmental issues and promoted solutions to these problems. By exposing these discursive formations and elements, discourse analysis is able to shift marginalized positions closer to the center of attention in order to promote alternative interpretations or policy options (Feindt and Oels, 2005; Glasze and Mattissek, 2015).

In this article, we first outline our analytical framework and discourse theoretical approach. In the following sections, we present our research methodology and results. We then discuss our findings in terms of discursive formations, elements, and context of nexus research. The article concludes with some wider implications and reflections on our findings.

ANALYTICAL FRAMEWORK

Discourse analysis presents a well-established interpretative research approach within social sciences and human geography. The primary aim of social scientific discourse analysis is to identify ideas, concepts and categorizations through which we understand and give meaning to the world (Waitt, 2010). For the purpose of this paper, we define these ideas, concepts and categorizations as discourses that arise from a particular social context (Hajer, 1995). Discourse analysis in geography questions how spatially or environmentally relevant concepts are established through language and social practices. Through discourse analysis, geographical notions like "the Orient" (Said, 1978) or "national borders" (Newman, 2000) are identified as discursive entities that shape our social realities (beliefs, values, norms, practices) and vice versa. Who is involved in the constitution of these ideas, concepts and categorizations? What meaning is associated with them for what purpose? What social and spatial effects result from these particular discourses and who is to be addressed?

Discourse theory is based on the assumption that discourses manifest in talk, texts, social practices and institutional settings. A discourse theoretical perspective emphasizes that social and natural phenomena can only be observed, perceived, and interpreted through language, texts, and within discourses (Dingler, 2005). Language and texts are not seen as a neutral medium through which information, events or reality are communicated in a transparent way. Instead, language, and texts are argued to form social meaning and establish social facts (Tonkiss, 2004). From a discourse theoretical standpoint, it is impossible to access reality directly in an objective and neutral way, as the perception of reality always takes place within a discursive framework (Dingler, 2005). However, discourse theory does not minimize the existence of physical processes. Instead, environmental issues like climate change or the WEF-Nexus are established as social facts through expert language, specific concepts and research practices. Environmental issues are interpreted as social and discursive entities despite referring to apparently natural phenomena (Feindt and Oels, 2005).

According to Foucauldian discourse theory, the establishment of discursive entities as social facts is deeply embedded in socio-temporal contexts. Ideas that become dominant common-sense knowledge are (re)produced, maintained and circulated within social and institutional settings, while alternative interpretations of the world are marginalized (Waitt, 2010). Discourse analysis situates and interprets environmental accounts within their historical, cultural, and political settings instead of treating them as universally true knowledge claims (Dingler, 2005; Hajer and Versteeg, 2005). From a discourse theoretical perspective, environmental issues are not seen as naturally given problems but, rather, as being shaped by multiple competing interpretations (Feindt and Oels, 2005). By establishing the WEF-Nexus as environmental governance concept various actors are likely to hold different perceptions of what the problem *really* is and what solutions are to be legitimized (Hajer, 1995). These struggles about the correct interpretation of environmental issues are intrinsic to environmental discourses or political conflict and can be revealed through discourse analysis (Feindt and Oels, 2005).

Discourse analysis in the realms of environmental politics pursues several objectives. First, discourse analysis aims to identify why a particular understanding of environmental issues gains dominance, while other understandings are discredited. Hence, environmental discourse analysis helps to reveal multiple competing interpretations of environmental issues and their manifestation within leading or marginalized discourses. Discourse analysis may reveal the intrinsically political nature of what is presented as apolitical and objectively true knowledge claims (Hajer, 1995; Feindt and Oels, 2005). For instance, although the WEF-Nexus is often presented as "unarguably true" (Cairns and Krzywoszynska, 2016: p. 166), a discourse analytical approach to the nexus may expose political dynamics and several competing interpretations. Second, discourse analysis closely engages with knowledge production and power effects within discourses. Competing interpretations of environmental issues are often based on different forms of knowledge. When a particular understanding of environmental issues gains dominance, its associated form of knowledge production is legitimized as more authoritative, while other ways of knowing are sidelined (Hajer, 1995; Waitt, 2010). According to discourse theory, particular environmental accounts and forms of knowledge are established as dominant and more legitimate by exercising power within discourses (Dingler, 2005). For instance, a discourse perspective can illustrate how dominant interpretations of the nexus emerge from particular knowledge and power relations that operate within the nexus discourse.

The way environmental issues are constituted through discourses, knowledge and power relations shapes if and how a problem is dealt with politically. The interpretation of environmental issues that gains dominance enables or constrains particular policy options. It also defines the range of actors that are legitimized for the resolution of these issues. Hence, by revealing marginalized discourse, discourse analysis may offer alternative policy options and solutions. Apart from shaping political action, environmental discourses also manifest in material and physical effects, as they are closely linked with social practices, institutional capacities and technologies (Feindt and Oels, 2005).

Our analytical approach is based on the Sociology of Knowledge Approach to Discourse (Keller, 2005, 2011, 2013), which combines Foucauldian discourse theory with the Peter Berger and Thomas Luckmann sociology of knowledge tradition.

RESEARCH METHODOLOGY

Data Selection and Corpus Compilation

Discourse analysis is based on social scientific approaches, as textual data are studied via qualitative research methods within their social, historical and geographical context (Tonkiss, 2004). During discourse analysis, linguistic and textual data gather in large text corpora that are compiled in accordance to selection criteria reflecting the research goal (Waitt, 2010; Keller, 2013). As we aim to analyze the scientific nexus discourse, we assorted our text corpus in line with criteria allowing us to detect discursive structures within the academic nexus literature (**Table 1**). Our final text corpus comprises 352 academic documents which were subjected to further analysis (see **Table S1**).

Scientific publications for our corpus were selected from the Web of Science online database (last accessed 17.04.2018). International scientific discourses manifest in English and various text formats including peer-reviewed articles, conference materials, scientific books, dissertations or working papers, which can all be studies as data (Keller, 2013). However, to ensure data coherence, comparability and quality we only included peer-reviewed articles, proceeding papers and special issue editorial contributions into our text corpus.

The Web of Science online database was searched with a combination of the keywords *water, energy, food* and *nexus*. These keywords were selected, as the *Water-Energy-Food Nexus* designation is dominant within current scientific debates, although multiple other names exist. These include for example: the *Water, Energy and Food Security Nexus* (Hoff, 2011), the *water-energy nexus* (Siddiqi and Anadon, 2011) or the *water-food-energy-climate nexus* (Beck and Walker, 2013). By focusing explicitly on these content-related keywords, we sought to guarantee the data's immediate relevance for our research topic. Furthermore, comparative searches including the additional keywords *climate* or *security* did not result in a significantly different selection of documents.

The selection of texts was conducted with the Web of Science database, as it identifies scientific peer-reviewed material, while also allowing a systematic literature review and data analysis. Comparative searches with Google Scholar led to a similar selection of scientific publications but contained additional text formats such as book chapters, working papers, technical reports and student thesis that did not meet our selection criteria.

Although we compiled our text corpus in a controlled and transparent way, several limitations are associated with this approach. First, the Web of Science database is not free of bias and cannot represent a complete citation search or the entire range of scientific discourses within alternative text formats. Social sciences and humanities are also less likely to publish in peer-reviewed journals, which could result in an unintentional bias toward natural sciences. Older journals and scientific contributions are potentially underrepresented within the Web of Science database. By focusing solely on contributions in English, we are also unable to display discourses taking place in other languages. Despite these limitations, we argue that the controlled compilation of our extensive text corpus allows us to reconstruct discursive

TABLE 1 | Criteria guiding the selection of documents for the overall text corpus.

Selection criteria		Justification
Database	Web of Science Core Collection (Indexes = SCI-EXPANDED, SSCI, A&HCI, ESCI)	WoS mainly comprises scientific text formats Allows systematic literature review and analysis of results Guarantees comparability of text formats within the final corpus Comparative Google Scholar searches did not result in a significantly different selection of scientific texts
Timeframe	All years	No time limitation imposed on the literature search, in order to map the emergence and historical development of the WEF-Nexus discourse
Language	English	Research focus on the international scientific nexus discourses, which is held in English. Restriction to one language to ensure data comparability and coherence during qualitative analysis
Keywords searched	Water; energy; food; nexus	Content-related selection of keywords based on our research goal to identify scientific discourses around the WEF-Nexus. Comparative searches with the additional keywords *security* or *climate* did not result in a significantly different selection of documents
Document types included (total 352)	Peer-reviewed articles; proceedings papers; special issue editorial material	Selection of documents according to scientific standards to ensure data comparability and coherence

formations and draw overarching conclusions on nexus discourses.

Discourse analysis presents an interpretative research approach during which a justified selection of texts or text extracts is analyzed in more detail. The selection of data for this in-depth analysis is an open and criteria-driven process, which consolidates the corpus material to represent the range of discourses and their structures. The selected texts need to traverse and record the breadth of the entire corpus material in a controlled way (Keller, 2013). Following these guidelines, we initially selected 22 documents from our corpus for an in depth analysis. These documents were chosen to outline the development of the scientific WEF-Nexus discourse(s) over time, illustrate the discursive structures and comprise major thematic priorities. Hence, we selected the 10 most cited articles and 12 additional texts, aiming to proportionally represent the distribution of publication years and most common article keywords within our corpus (see **Table S1**). However, by focusing on the most cited documents, a bias emerges, as older publications are cited more often. Focusing on most common article keywords will most likely result in a selection of texts that represent the dominant discourses. To overcome this bias and to also portray alternative or marginalizes nexus discourses, 5 additional texts were subjected to an in-depth analysis. These 5 texts were selected from the Water Alternatives journal, which presents one of the very few journals in our text corpus diverging from the mainstream nexus approach by taking a very critical perspective.

Data Analysis

As mentioned above, discourse analysis is concerned with what is being said as well as the social, historical and geographical context in which things are being said (Hajer, 1995). Hence, our data analysis occurred in two main steps as shown in **Figure 1.**

To gain a more detailed understanding of the social, historical and geographical context of WEF-Nexus discourses, the overall text corpus (352 publications) was subjected to several analytical procedures. First, we identified the number of publications over time to trace the emergence and historical development of nexus discourses. Second, the most frequent article keywords and journals were extracted to investigate scientific communities, research approaches and thematic priorities around the nexus. Third, the location of nexus case-studies was derived from article keywords and texts themselves. This geographical focus of nexus research was then opposed to the location of knowledge production in terms of authors' countries of work (affiliation).

For the in-depth analysis of our 27 selected papers, we employed the methodological suggestions provided by Keller (2013) and his Sociology of Knowledge Approach to Discourse. As per Keller (2013), our analysis occurred along two lines, namely the material or context dimension and a content-based interpretative analysis. The analysis of both dimensions was conducted via coding, commentaries and memos within the qualitative software ATLAS.Ti.

The interpretative analysis of our 27 selected papers was conducted in an open and iterative process that was closely linked to our data but also informed by our research goal (Keller, 2013). Several questions guided our initial evaluation including: What key ideas, concepts, categories and classifications mobilized in the documents (Waitt, 2010)? What re-occurring themes, images and metaphors cluster around the nexus (Tonkiss, 2004)? Following this initial evaluation, we followed the three stages suggested by Keller (2013) for an interpretative dissection of text passages. These three stages comprise an in-depth analysis of (i) interpretative schemes, (ii) phenomenal structure, and (iii) narrative structures:

i. *Interpretative schemes*

Interpretative frames are considered socially and historically embedded devices for interpreting events and deriving possible actions. According to Keller (2013), for instance, the notion of risk presents an overarching modern frame which structures the perception and action toward certain phenomena like climate change.

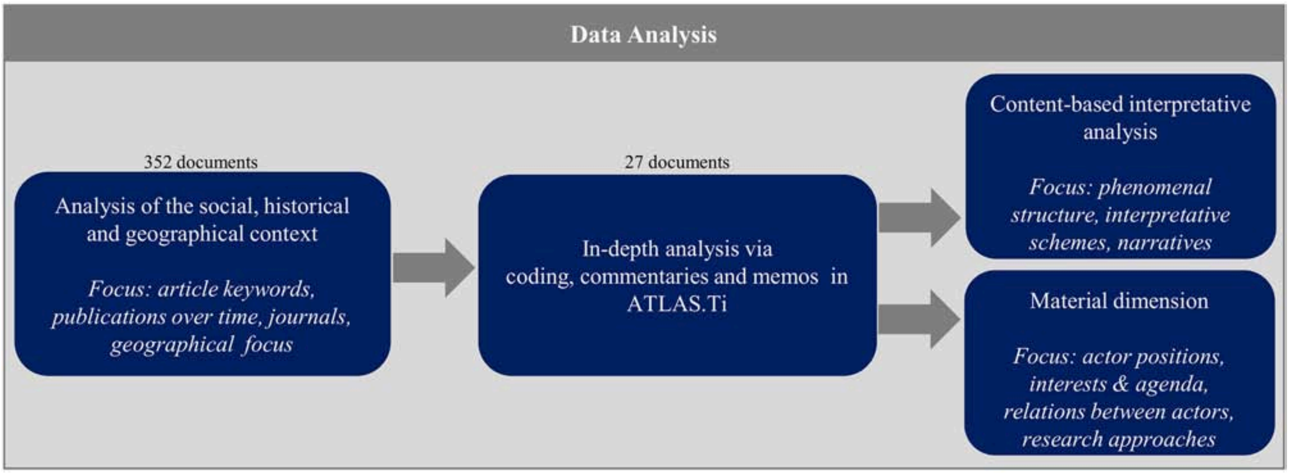

FIGURE 1 | Different steps of data analysis based on Keller (2013).

ii. *Phenomenal structure*

The phenomenal structure refers to the way phenomena like the WEF-nexus are constituted within discourses in terms of key themes, problem structure, legitimization of certain actions and practices to deal with particular phenomena (Keller, 2013). Concretely, our analysis revolved around interpretations, metaphors, and normative claims concerning the nexus concept, problem and solution structures as well as conceptualizations of socio-environmental relations.

iii. *Narratives*

Narratives are story-lines that tie together various discursive elements into a coherent structure to explain who is doing what and why. According to Hajer (1995), narratives combine elements from different domains to provide actors with a set of symbolic reference that suggest a common understanding. These may be stories of progress, apocalypse, causalities, responsibilities, or dangers (Keller, 2013).

The material and context dimension was investigated with a focus on the role of particular actors within discourses, relations between actors, intended audiences and research approaches (e.g., natural or social sciences). By analyzing this material and context dimension of discourses, we can identify the social dynamics carried into the production of knowledge and texts (Waitt, 2010).

Finally, results from our interpretative analysis and material dimension were aggregated into general statements about the discourses present in the overall corpus (Keller, 2013).

RESULTS

Social, Historical, and Geographical Context of Nexus Discourses

Since 2009, research interest in the Water-Energy-Food Nexus has increased almost exponentially (**Figure 2**) with the sharpest rise in the number of publications occurring between 2014 and 2015. We relate this increase to the adoption of the SDGs in 2015, in which the nexus is to play an important role (The Nexus Dialogue Programme, 2015). Naturally, water, energy and food present the most frequent article keywords within our text corpus. Additional thematic priorities around the nexus include sustainability, sustainable development, food security, agriculture, bioenergy, climate change, IWRM, and water resources (**Figure 2**).

The most prevalent journals in our text corpus are presented in **Table 2**. Regarding the scope and topics of these journals, dominant research approaches and topics clustering around the nexus become apparent. Most commonly, journals focus explicitly on resource management, environmental science topics, technology and sustainable development. Although some journals like *Environmental Science & Policy*, *Water International*, the *International Journal of Water Resources Development* or *Sustainability* present themselves as interdisciplinary platforms that purposefully include social and political aspects, we argue that Water Alternatives portrays one of the very few critical social scientific journal in **Table 2** and our overall text corpus. Unlike other journals, Water Alternative explicitly challenges the narrow framing of and technical approach to water. The journal aims to focus more on the political dimensions of water resources development through constructive critiques and alternative approaches (Water Alternatives Journal, 2018).

The map presented in **Figure 3** illustrates the geographical context of nexus research by comparing the places of nexus knowledge production to the location of nexus case-studies. Regarding individual countries and their frequency of occurrence, we detect that nexus knowledge is mainly produced in *developed* industrial countries of the Global North. Contrary to this, the nexus is mainly applied and researched in *developing* countries of the Global South with a strong focus on South-East Asia.

Interpretative Analysis

Based on our in-depth analysis, we identified two major discursive formations around the Water-Energy-Food Nexus which are characterized by different interpretative schemes,

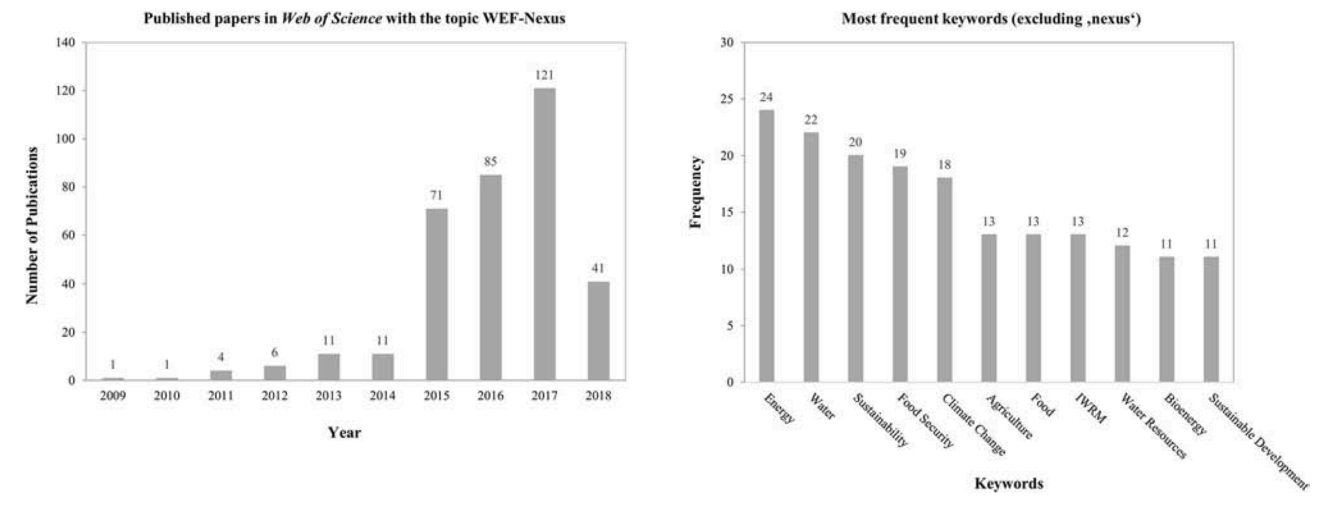

FIGURE 2 | Number of publications over time and article keywords with a count higher than or equal to 10 (last accessed 17.04.2018).

phenomenal structures, narratives and material context. Although it may prove difficult to clearly assign individual documents to specific discourses, we associate 21 papers with the leading nexus discourse, while only 6 constitute an alternative formation. The main features of each discourse are presented below.

Most Influential Nexus Discourse

Based on our in-depth analysis of 21 papers, we derived overarching conclusions about the leading nexus discourse.

i. *Interpretative schemes*

Within the leading nexus discourse, we identified interwoven interpretative schemes. These include *risk and security*, an *economic rationale* and an overarching *ecological modernization frame* shaped by *techno-scientific approaches*. The security and risk frame is shaped by the notion of resource scarcity posing a risk to the global economy or humanity as a whole. Consequently, resources like water, energy and food need to be securitized. For example, Bazilian et al. (2011) state that water, energy and food "all have deep security issues as they are fundamental to the functioning of society" (ibid. p. 2). The techno-scientific rationale and ecological modernization frame aim to solve sustainability issues by increasing resource use efficiency via technological and scientific innovations. The economic rationale conceptualizes and frames the nexus in terms of resource demand, supply, consumption, input, output, trade-offs, volatility spill-overs, value chains, and economic efficiency.

ii. *Phenomenal structure*

Problem descriptions and promoted solutions within the leading discourse are strongly related to the interpretative schemes mentioned above. Problems are framed prominently in terms of global resource scarcity, constrains and over-exploitation. Global water, energy, and food resources are argued to become increasingly scarce in response to economic and population growth, increasing standard of living, urbanization and environmental degradation. Climate change is interpreted as aggravating this situation also in terms of poverty and lack of access to resources. In the context of this worsening global resource crisis, the isolated development of water, energy, and food nurtures inefficient resource use and allocation. The sectoral approach to management practices, policies and institutional settings concerning water, energy and food is seen as major issue. Economic aspects are presented as additional challenge. Inefficient water use in agriculture, for example, is related to "[l]ow subsidized tariffs" (Abdullaev and Rakhmatullaev, 2016: p. 6) and the pricing of water below market value. Missing expert knowledge and data on the interconnections between water, energy and food systems is also seen as major disadvantage.

Related to these issues, the primary goals is to achieve global resource security through an integrative nexus approach to water, energy and food. Resource demand needs to be regulated, resource use optimized and consumption rendered more efficient. Water, energy and food policies, programs, and institutions are to be managed in a cooperative cross-sectoral way to advance sustainable development. As part of a nexus framework, resource use efficiency and optimization are achieved mainly via technological innovations and market instruments. Market mechanisms, in this case, often relate to water and energy pricing signals. For example, misguided water and energy subsidies are to be eliminated, in order to "introduce better pricing signals" (Bazilian et al., 2011: p. 4) and to encourage farmers to "invest in a more efficient irrigation technology" (Berardy and Chester, 2017: p. 8). Problems of access and distribution of resources are solved primarily via policy integration, management and planning. To solve resource challenges in an integrative nexus approach, inter- and transdisciplinary research is promoted.

The leading discourse is characterized by specific themes and ideas clustering around the nexus. First, the WEF-Nexus is employed as analytical concept to describe the interactions

TABLE 2 | Journals within the overall text corpus with a count higher than or equal to 10.

Journals	Nr. of publications in overall text corpus	Journal scope and topics
Water ISSN 2073-4441	21	Water science and technology; ecology; water resources management; water governance; hydrology; hydraulics; water scarcity; flood risk; water quality
Applied Energy ISSN 0306-2619	17	Energy conversion and conservation; optimization of energy processes; mitigation energy pollutants; sustainable energy; innovative technologies; modeling and forecasting; energy conservation strategies
Environmental Science & Policy ISSN: 14629011	15	Interdisciplinary research of policy relevance on environmental issues; climate change; biodiversity; environmental pollution and wastes; production; transport; consumption; growth; demographic changes; well-being; health
Water International ISSN: 0250-8060	15	Journal of the International Water Resources Association (IWRA), founded for the sustainable management of water resources around the world
International Journal of Water Resources Development ISSN: 0790-0627	13	Interdisciplinary policy and practice-oriented journal that covers all aspects of water resources; water resources and their economic, financial, social and environmental-related impacts; interdependences and inter-linkages between the water and the agricultural, energy, industrial and health sectors in both developed and developing countries
Journal of Cleaner Production ISSN: 0959-6526	13	Focusing on cleaner production, environmental, and sustainability research and practice; cleaner production and technical processes; sustainable development; sustainable consumption; environmental sustainability assessment; sustainable products and services
Environmental Science and Technology (Letters) ISSN: 0013-936X	11	Aim is to provide authoritative source of information for professionals in a wide range of environmental disciplines; advances, trends and challenges in environmental science, technology and policy
Sustainability ISSN 2071-1050	11	Forum for studies related to sustainability, experimental and theoretical research relating to natural sciences, social sciences and humanities; scientific predictions and impact assessments of global change and development; air pollution and climate change; water pollution and sanitation; misuse of land; desertification and drought; industrial development and energy crisis
Advances in Water Resources ISSN: 0309-1708	10	Theoretical, computational, or experimental approaches used to advance fundamental understanding of surface or subsurface water resources systems or the interaction between these systems; surface and subsurface hydrology; hydrodynamics and hydrometerology; multiphase transport phenomena; modeling fluids
Environmental Progress & Sustainable Energy ISSN: 1944-7450	10	American Institute of Chemical Engineers reporting on critical issues of the environment, including remediation and treatment of solid or aqueous wastes, air pollution, sustainability, and sustainable energy; alternate energy technologies; biofuels; biorefineries
Water Alternatives ISSN 1965-0175	10	Aim is to challenge narrow framing of water problems and technical and engineering approach to water; focus more on political dimension of water resources development and management at all scales; journal is to provide space for creative and free thinking on water, fostering debate, eliciting innovative alternatives, promoting original analyses and constructive critiques

between water, energy and food. Interlinkages between water, energy, and food are conceptualized within a coupled systems approach characterized by feedbacks and interdependencies. The dominant perspective argues that a nexus approach will enable us to better understand or assess the complex dynamics between water, energy and food resource systems. Second, the WEF-Nexus is supposed to act as "boundary concept" (Abdullaev and Rakhmatullaev, 2016: p. 1) between science and policy. Indeed, authors often state that nexus research should support decision-making to allocate increasingly limited resources more effectively. Third, the WEF-Nexus is directly promoted as emerging resource governance concept to achieve and monitor sustainable development. From this leading perspective, the nexus is to reduce competition over resources, eliminate trade-offs, and maximize synergies between sectors. As the nexus concept allows to implement more efficient infrastructure and environmental policies, increasing global demand for water, energy, and food resource can be managed more effectively. The WEF-Nexus concept itself is rarely questioned and critical points are only touched upon within the dominant discourse.

As shown in our Analytical Framework, discourses (re)produce particular nature-society relations. Within the leading nexus discourse, for instance, the environment is addressed in a *command and control* approach that follows a utilitarian logic and sees nature as economic resource. Environmental aspects need to be monitored and controlled for human use and benefit. Karan et al. (2018), for instance, state that "since dollars are the only measure common to food, energy, and water components, the changes in the sustainability are formulated in terms of dollars" (ibid. p.20). Ringler et al. (2013) argue that "natural resources are beginning to limit, to a substantial degree, economic growth and human well-being goals" (ibid. p. 617). Nature and society are predominantly conceptualized as two distinctly separate spheres; an approach which is often referred to as *Cartesian dualism* (Dingler, 2005). This *Cartesian dualism* manifests in the coupled-systems perspective which is typical for the dominant nexus approach.

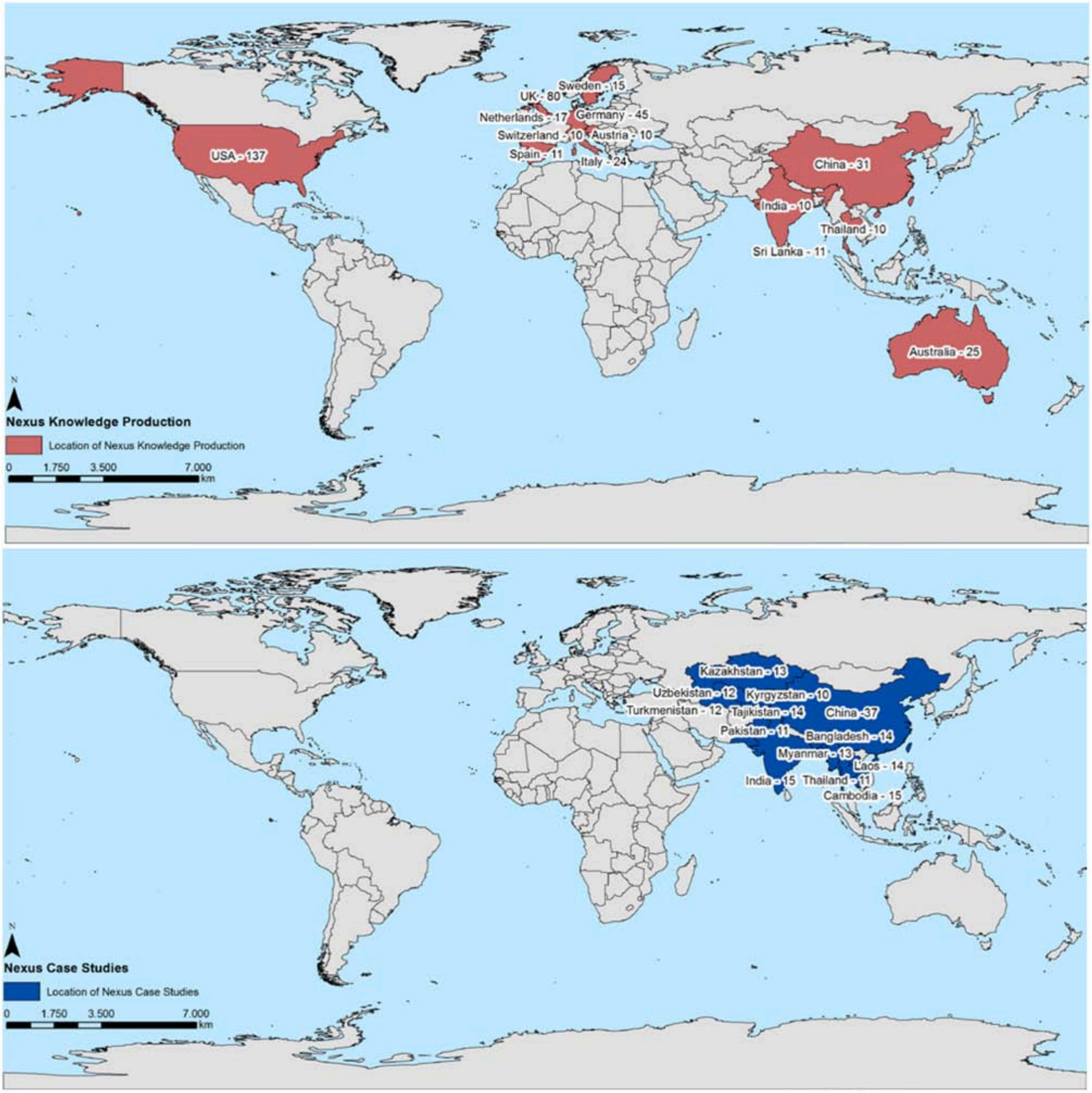

FIGURE 3 | Geographical focus of nexus research and spaces of nexus knowledge production. Map based on places with equal or more than 10 counts.

iii. *Narratives*

These various discursive elements consolidate into a dominant nexus narrative based on apocalyptic story-lines. According to this narrative, multiple global crises cumulate in resource scarcity that poses an ultimate threat to human existence. Researchers and decision-makers are called upon to urgently adopt an integrative approach to water, energy and food systems. Only a nexus approach, so the story goes, will help us prevent a global catastrophe. A nexus approach promises to maximize synergies between resource systems, reduce trade-offs, optimize resource use, help us allocate limiting resources more effectively and promote sustainable development.

Alternative and Marginalized Nexus Discourse

Based on our in-depth analysis of 6 papers, we derived overarching conclusions about the alternative or marginalized nexus discourse.

i. *Interpretative schemes*

Contrary to the leading discourse, the alternative nexus discourse is characterized by a social constructivist interpretative scheme. For example, authors employ a "constructivist reading of security" (Leese and Meisch, 2015: p. 700). Others highlight the "constructed and political nature of global resource scarcity" (Allouche et al., 2015: p. 616). This indicates that nexus aspects like "global resource scarcity" are not seen as objectively true facts. Instead, it is argued that these notions are embedded in wider socio-political contexts, political dynamics, and that they are shaped by various actors and interests. As part of this social constructivist perspective, authors focus on nexus language, aim to "disaggregate narratives of water scarcity" (Mdee, 2017: p. 100) or analyze different interpretations of the nexus amongst international actors. These social constructivist approaches emphasize the "particular policy settings, [...] arenas of power and contestation" (Allouche et al., 2015: p. 616) surrounding the nexus approach.

ii. *Phenomenal structure*

Within this alternative discourse, the dominant techno-scientific nexus framing is defined as overarching problem. A primary critique focuses on the exclusion of socio-political dimensions within the leading discourse. It is argued that decisions concerning resources like water, energy, and food are not neutral but highly political. The allocation and distribution of resources take place within areas of unequal power and often lack transparency or public participation. For instance, Allouche et al. (2015) argue that the framing of the nexus as technical issue actively "hides its politics" (ibid. p. 610). By neglecting socio-political aspects, the current nexus framing may further powerful interests, and dominant worldviews. Powerful actors may easily adopt and appropriate the nexus to safeguard their interests, consolidate pre-established positions and marginalize subordinate actors. For example, framing the nexus in terms of security creates a sense of alarm or urgency and allows water, energy and food to be treated as economic goods in order to address an apparent economic emergency. By neglecting the politics of resource distribution or scarcity, the dominant nexus risks "marginalizing those who are least likely to be able to articulate their needs" (Mdee, 2017: p. 103). Furthermore, the current nexus is challenged for not being sufficiently pro-poor, as its techno-managerial approach overlooks the complex dynamics between "financial investment, the developmental states, different classes of people, and distributional outcomes on the ground" (Foran, 2015: p. 656).

The dominant nexus is also described as contested, controversial, immature and diffuse political project that is "far from unified" (Benson et al., 2015: p. 759). Essentially, the nexus itself is seen as socially constructed and normative concept. The alternative nexus discourse challenges the "normative primacy" (Leese and Meisch, 2015: p. 696) of the dominant nexus approach. It is argued that the nexus is not shaped by objective scientific evidence. Instead, statements concerning resource scarcity or ineffective resource allocation are embedded within their historical context and prevalent political discourses. This context, however, is often neglected. For example, the dominant natural scientific nexus approach inadequately addresses the "social, productive and cultural values" (Mdee, 2017: p. 103) associated with resources like water. The reason for this disregard is argued to result from a lack of critical social sciences conceptualizations. By ignoring the social dimensions, "resource linkages remain thinly described and under-theorized" (Foran, 2015: p. 656). Finally, the integration of water, energy, and food sectors itself is seen as problematic. It is suggested to compare the nexus to existing governance frameworks before endorsing it as new paradigm. From this alternative perspective, it remains questionable, whether the nexus presents anything new, or may provide added value for resource governance.

To overcome these challenges, an alternative nexus framing is suggested that highlights the socio-political dimension of resource governance. This extended nexus approach recognizes the political nature of decisions concerning resource use and allocation. A more in-depth political analysis may be required to understand different assumptions already embedded in policy. This political analysis may also reveal the political nature of different narratives surrounding the nexus (e.g., scarcity). A more explicit focus on the socio-political dimensions will illuminate powerful interest and power asymmetries concerning the re-allocation of resources. Researchers need to pay closer attention to the politicized relationship between water, energy, and food governance systems in addition to the socio-political and historical context of nexus narratives. For instance, the alternative nexus also "recognizes that global priorities may not reflect local concerns" (Allouche et al., 2015: p. 618). A political perspective allows to assess whether the nexus centralizes or de-centralizes control and decision-making, reduce or increase inequality.

To this end, the alternative perspective suggests to engage more strongly with issues of social justice. To achieve poverty reduction, the nexus needs to focus more on the question of: Whose water, energy and food use is to be secured? Whose water, energy, and food use is termed inefficient? How are the needs of the marginalized prioritized? To promote sustainable development, the nexus needs to "address poverty and redress inequality and social justice" (Allouche et al., 2015: p. 619). Open and transparent decision-making are required to overcome the dispossession of the poor. Resource governance needs to be rendered more inclusive and collaborative. Additionally, the alternative nexus perspective highlights the need for interdisciplinary inquiry to foster a more holistic understanding of the resource nexus. The dominant approach is to be extended by social scientific perspectives to value plural approaches toward the nexus challenge. A social scientific perspective would focus more explicitly on power relations and asymmetries, implications for people and socio-spatial patterns of inequalities. Extending the current nexus by social scientific approaches would highlight the importance of local contexts, diverse ways of knowing and acknowledge the value of plural interpretations of resource issues. An extended nexus "may help us think through multiple scales and interfaces of competing claims for water use" (Mdee, 2017: p. 104).

Within the marginalized nexus discourses, a non-dualistic view on nature and society is prevalent, as the relations between society and nature are conceptualized as co-constituted. Therefore, socio-nature need to be analyzed within their socio-political, institutional, and historical context.

iii. *Narrative*

These various discursive elements aggregate into a narrative opposing the dominant nexus story-line. The dominant techno-scientific nexus approach claims normative primacy but neglects to address the highly political nature of resource governance, use and allocation. The dominant nexus framework is unable to adequately address poverty or social justice, as power relation and asymmetries are neglected. To promote sustainable development and poverty eradication, the nexus needs to include social scientific political analysis and more collaborative decision-making.

Material Dimension

Two distinct research communities characterize the major discursive formations surrounding the Water-Energy-Food Nexus. The leading nexus discourse is shaped by natural scientific, engineering and economic perspectives, which is mirrored in the scope and topics of the most common journals (**Table 2**). Leading nexus research focuses on assessing the interlinkages, trade-offs, and synergies between water, energy and food systems via quantitative measurements and computer modeling. Papers associated with the leading nexus discourse are cited more often and prevail in terms of quantity. Many more researchers and authors contribute to the dominant nexus discourse.

The alternative and marginalized nexus discourse is characterized by a critical social sciences community. The alternative perspective takes a social constructivist and political approach to resource management. Papers are often conceptual and theoretical in nature. The marginalized discourse cumulates in the Water Alternatives journal, one of the very few critical journals found within our text corpus. Fewer authors shape the alternative discourse and papers associated with this alternative discourse are cited less frequently. They are, therefore, less influential in conceptualizing the nexus framework.

Interestingly, both discourses refer to similar actors, events and institutions, which are often part of the international political sphere. Important points of reference include for example the United Nations (e.g., FAO), the Rio+20 summit, the MDGs and SDGs and the IPCC platform. The World Economic Forum is identified as one of the major nexus promoters and the Bonn2011 Nexus conference is often named as major milestone in developing the nexus. The Bonn conference is referred to mostly in terms of its background paper provided by Hoff (2011). Indeed, the publications by Hoff (2011) and the World Economic Forum (2011) present very influential texts that are often mentioned and cited within our text corpus. The nexus is also sometimes compared to and associated with the Planetary Boundary Concept (Rockström et al., 2009) and the Club of Rome's Limits to Growth report (Meadows et al., 1972).

The two discourses have two distinctly separate intended audiences. Authors associated with the leading discourse aim to address and inform policy makers directly with their research results, in order to promote better and more sustainable decision-making. Contrary to this, the marginalized discourse addresses authors involved in the dominant nexus framing, in order to re-conceptualize the current nexus.

DISCUSSION

By taking a discourse analytical approach, our findings reveal a splintered WEF-Nexus, with one leading and one counter-discourse. This finding highlights that the nexus is not uniform but, rather, presents a contested concept that is shaped by competing interpretations. According to Hajer (1995), discursive structures and formations are not given but emerge from a continuous struggle over discursive dominance, which indicates that the leading nexus discourse is not closer to an objective truth. Instead, it establishes and maintains its leading position by exercising power in various ways (Dingler, 2005). For instance, compared to the alternative approach, many more authors are involved in (re)producing the prevalent nexus narrative. The leading nexus discourse is also more prominent in terms of number of publications, citations and range of scientific journals. Within the leading approach, the nexus itself is not questioned but handled as proven fact, while researchers focus on targeting policy makers with their research findings. By directly addressing policy makers, scientists contribute to establishing, and promoting the nexus concept further within the political realm. We assume that this strategy is often successful, as researchers and research organizations are called upon as advisors when designing meetings like the Bonn2011 Nexus conference.

Important consequences ensue from the leading nexus discourse continuously establishing and maintaining its dominant position and supremacy over its counterpart. As shown in our Analytical Framework, particular forms of knowledge production are legitimized and seen as more authoritarian, depending on what understanding of environmental issues gains dominance (Hajer, 1995). Based on our analysis, we showed that the leading nexus discourse is based on techno-scientific research approaches. In other words, natural scientific, economic, and engineering knowledge is seen as more legitimate and authoritarian when dealing with solutions surrounding the nexus than social scientific knowledge. This observation correlates with the powerful and persisting ideals of modernity: science and technology should merge to foster societal progress, unlimited wealth, economic prosperity, and control over nature (Benessia and Funtowicz, 2016).

Additional knowledge and power effects reflect in the geographical context of nexus research. As shown in **Figure 3**, the nexus is shaped by western knowledge, which is then diffused or exported across the Global South with a strong focus on South-East Asia. This observation is in line with the history of the concept as traveling idea for development interventions. This is also supported by Middleton et al. (2015), who demonstrate that international organizations and high-income donor countries work with governments and politicians in South-East Asia to translate the nexus concept into national or regional policies. In mainland South-East Asia, aid funding shifts toward the nexus, as international organizations establish global nexus programs (e.g., UN agencies). The projection of the nexus onto South-East Asia exemplifies the regionalization of a global policy discourse and development agenda promoted through and beyond the Rio+20 conference or the World Economic Forum (Middleton et al., 2015).

This explicit regional focus of nexus research may have several reasons. First, the dominant discourse frames the need for a nexus approach in terms of global resource scarcity supposedly caused by rapid urbanization, changing lifestyles and economic growth. Currently, these three trends coalesce in South-East Asia. The geographical focus of nexus case studies largely corresponds with the region of the world exhibiting the highest density of fastest growing cities. Second, countries like India and China are experiencing population increases, economic growth and rising standards of living. Resource governance debates in China or India also highlight the need for resource securitization and the coordination of competing uses (e.g., Chen, 2007; Xue and Xiao, 2013). Additionally, major river basins transcend countries like China, India, Myanmar, or Cambodia. The Mekong River, for instance, is extensively managed, researched, and appears several times within our text corpus. Its long lasting development history, institutional context and management settings to coordinate water, energy, and food supplies for rapidly growing cities may provide a favorable platform for nexus research. We presume that the specific combination of these factors contribute to South-East Asia's particular popularity for nexus research.

By embedding our geographical observations in the geography of knowledge debate, we argue that the western idea of a single scientific rationality producing universally true knowledge is highly questionable, as science is spatially situated. As Livingstone (2003) illustrates: "What has been promoted as scientific objectivity, as the 'view from nowhere,' turns out to have always been a 'view from somewhere'" (ibid. p.184). The universal claim of western nexus knowledge has to be challenged with regard to Middleton et al. (2015) observing that many rural farmers, fishers or community groups in South-East Asia do not perceive water, energy, and food as separate entities in the first place. This local approach to water, energy, and food stands in contrast to the disciplinary fragmentation of knowledge occurring in the (western) world of scholars.

Apart from these overarching knowledge and power effects, our results also showthat the two discursive formations are shaped by distinct actor groups that conceive socio-nature relations in very different ways. These differences are based on and reflected in the different forms of knowledge, interpretative schemes, competing problem definitions, and opposing solutions suggested to solve these problems. Within the leading nexus discourse, nature and society are interpreted as two separate but coupled systems, interlinked through dynamic feedback processes. This coupled-system approach to nature emerges from the natural scientific, economic and engineering knowledge base aiming to control, monitor and manage nature. Nature is perceived as economic resource to be used and regulated for human benefit. Schmidt and Matthews (2018) even argue that the nexus concept serves to financialize nature, as it was deliberately developed by global financial networks to effect the transition from state-oriented to financialized approaches of water development and sustainability. This conceptualization of society-nature relations also underpins the security and risk frame, ecological modernization approach, and economic rationale. As mentioned above, the leading nexus narrative contends that population and economic growth, changing lifestyles, urbanization and climate change inevitably cumulate in a global resource scarcity that poses a threat to human existence. Suggested solutions for addressing these global risks are based on scientific or technological innovations and market incentives aiming at allocating limited resources more effectively.

In this sense, the leading nexus discourse (re)produces a neo-Malthusian narrative: Giampietro (2018) even speaks of "the return of the Neo-Malthusians" (ibid. p. 2). This neo-Malthusian narrative locates the causes for resource scarcity in places that experience population and economic growth, changing lifestyles and urbanization. To date, these places are mainly located in countries of the Global South, which are implicitly made responsible for unsustainable development and environmental degradation. Hence, neo-Malthusian approaches are not neutral or objective but highly political. As Harvey (1974) argues, neo-Malthusian approaches may have important political implications by directing policies toward neo-imperialism abroad. Although this statement cannot be confirmed by our analysis and goes beyond the scope of this study, we illustrate that nexus implementation and application strongly focuses on the Global South. In particular, the nexus is projected onto South-East Asia, which currently experiences population and economic growth, changing lifestyles, and urbanization. By interpreting environmental problems through a security and risk frame, ecological modernization approach and an economic rationale, resource intensive (western) lifestyles, capitalist economies or utilitarian approaches to nature are not addressed as underlying problems. Hence, we argue that the leading nexus discourse presents a typical techno-scientific approach to sustainability that gears policies toward addressing environmental problems without dealing with deeper causes responsible for these problems (Harvey, 1974; Beck, 1992; Castree, 2001). The security and risk frame creates an additional sense of urgency for action, which may legitimize far reaching interventions to control an apparent emergency. Inclusive decision-making and alternative policy options may easily become suspended (Beck, 1992).

To the contrary, the alternative nexus discourse actively engages with the political nature of resource governance, allocation and scarcity. Nature-society relations are acknowledged to have political dimensions that must be investigate within their socio-political, institutional and historical contexts. The alternative nexus discourse suggests expanding the current nexus to focus more explicitly on power asymmetries, social justice and the socio-political or historical context of resource allocation, in order to overcome poverty and social inequalities. More social scientific and political analysis are promoted in addition to more collaborative decision-making. However, this alternative nexus approach is less visible and influential within the overarching nexus discourse.

Our analysis demonstrates that the nexus discourse as a whole is shaped by distinctly separate discursive formations, knowledge bases, and limited geographical foci. Despite highlighting the need for integrative approaches, the leading nexus discourse takes place in a rather confined intellectual and geographical space. Instead of conceptualizing the nexus in a truly interdisciplinary way, social scientific knowledge seems to be less legitimate or authoritarian and plays a negligible role in shaping the overarching nexus idea. Additionally, the nexus is mainly informed by western knowledge, which is then exported to the Global South.

These distinctions then contrast with the definition of the term *nexus*, which refers to the "connection or series of connections linking two or more things" and "a connected group or series" (Oxford Dictionary, 2018). Both nexus discourses advertise integrative solutions via inter- and transdisciplinary research approaches and collaborative decision-making (Ringler et al., 2013; Hernandez et al., 2014; Allouche et al., 2015; Conway et al., 2015; Laurentiis et al., 2016). We attribute this divide between rhetoric and real collaboration to a misconception of *integration*. As shown by Hofer and Meisch (2018), narrowly framed and solution-oriented research often promotes a limited understanding of disciplinary *integration*. Instead of endorsing truly inter- and transdisciplinary exchange, genuine cooperation between scientific disciplines is actually limited. Research projects aiming to *integrate* different types of knowledge often reflect wider power imbalances between natural and social sciences. While such research projects are largely dominated by techno-scientific approaches, social scientists taking marginal positions are often required to subscribe to natural scientific analytical frames and are employed as "afterthoughts" (Strang, 2009: p. 6). However, genuine collaboration, multiple types of expertise, and truly integrative approaches are required to explain the complexities of environmental challenges (e.g., Strang, 2009; Gerlak and Mukhtarov, 2015).

In this sense, we do not oppose or refute the WEF-Nexus concept *per se*. Instead, we argue that the overarching nexus discourse needs to bridge the current gap between rhetoric and real collaboration by developing into a more holistic, inter-, and transdisciplinary concept that also moves beyond its current spatial constrains and scientific reductionism. The current nexus debate needs to overcome its limitations by endorsing epistemic pluralism and knowledge claims from various sources and places. For this purpose, the techno-managerial approach, on the one hand, needs to recognize and acknowledge the deeply political nature of resource use and governance. Indeed, any debate about the nexus "necessarily entails a political or ideological dimension that must be explicitly acknowledged" (Giampietro, 2018: p. 4). Social scientists, on the other hand, are called upon to become more future and action-oriented, by engaging in environmental debates early on and by moving beyond purely theoretical and conceptual approaches. Otherwise, it remains questionable whether the nexus will be able to promote sustainable resource governance. Instead of creating emblematic issues shaped by techno-scientific approaches, we wish to see a wider debate around which nature and society relations actually intend to promote (Hajer, 1995).

Within the alternative nexus discourse, critical scholars argue along the same lines (e.g., Allouche et al., 2015). In this sense, we position this paper in the realms of what we termed the alternative nexus discourse. Discourse analysis cannot produce objectively true knowledge, as the researcher is an integral part of the analysis and may reproduce or contribute to particular discourses. Despite this intrinsic limitation, discourse analysis presents a valuable analytical perspective for environmental research. First, we illustrate the distinct discursive formations and the wider context of the nexus concept. Second, most social scientific contributions are conceptual or theoretical in nature and discourse analysis provides a strong empirical foundation for our argument. By exposing different discursive formations, various interpretations of environmental issues or possible solutions, we hope to emphasize and strengthen alternative nexus positions. This may also help to promote alternative interpretations or policy options (Feindt and Oels, 2005; Glasze and Mattissek, 2015).

CONCLUSION

In this paper, we closely engaged with the Water-Energy-Food Nexus and showed that the concept in its current form is shaped by several fractures and lines of conflict. By employing a discourse analytical approach, we identified two distinct formations of the scientific nexus discourse. The leading discourse is based on natural scientific, economic, and engineering research approaches, frames problems in terms of resource scarcity or global crises and aims to solve these problems via technological innovations or market incentives. The leading discourse occupies much more space by establishing and maintaining its authoritative position in various ways. We argue that the leading techno-scientific nexus reproduces a neo-Malthusian narrative which directs policies toward addressing environmental issues without dealing with the root causes for these problems. Its counter-discourse is based on social scientific approaches, identifies the current techno-scientific nexus framing as major problem, and actively engages with the socio-political aspects of resource governance. We illustrate that this alternative nexus discourse is less influential and seen as less legitimate. A second line of separation runs between places of nexus knowledge production, located in Global North, and nexus application focusing mainly on South-East Asia. By referring to the geography of knowledge debate, we claim that the nexus as western concept cannot have universal aspiration.

We conclude that the current Water-Energy-Food Nexus represents a splintered concept that is shaped by separation rather than integrative approaches to resource governance. In order for the nexus to critically investigate solutions for future sustainability, it needs to overcome its discursive and spatial separations. By embracing epistemic pluralism and different forms of knowledge from different sources or places, the nexus can develop into a more holistic concept. We also suggest to engage more closely with the geographies of nexus knowledge: What are local nexus approaches and conceptualizations of socio-nature relations in countries where western nexus knowledge is currently applied? To support more integrative and diverse discussions, we also encourage social scientists to engage sooner and more actively in ongoing environmental debates. As shown, environmental politics are often shaped by natural scientific and techno-scientific approaches to sustainability. Social scientists are called upon to engage and contribute to environmental discourses by becoming more future and action-oriented. To the contrary, natural scientists are encouraged to acknowledge and recognize the political nature of resource use and governance. Timely involvement of multiple perspectives could result in more fundamental debates about the nature and society we intend to promote instead of endorsing emblematic issues and concepts.

AUTHOR CONTRIBUTIONS

VW contributed to the conception and design of the study, conducted the study, organized the database, and wrote the first draft of the manuscript. AB supervised and contributed to the conception and design of the study. All authors contributed to manuscript revision, read and approved the submitted version.

ACKNOWLEDGMENTS

We would like to thank all members of the Governance and Sustainability Lab, who commented on earlier versions of this article and Jonathan Hassel for helping to produce the map for this paper. This research has been partially funded by the German Federal Ministry of Education and Research (BMBF) under the project funding number 01 LN 1316 A. The publication was also funded by the Open Access Fund of Universität Trier and the German Research Foundation (DFG) within the Open Access Publishing funding programme.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2018.00128/full#supplementary-material

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Environmental Science

ORIGINAL RESEARCH
published: 12 November 2018
doi: 10.3389/fenvs.2018.00112

Toward an Understanding of Synergies and Trade-Offs Between Water, Energy, and Food SDG Targets

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Achieving the targets set out in the UN Sustainable Development Goals (SDG) will require committed efforts by nations and organizations over the coming decade. To determine which actions work most harmoniously within funding, infrastructure development, and implementation of three closely aligned goals, we conducted an assessment to identify where the greatest synergies may occur and where conflicting resource needs create trade-offs that may threaten SDG success. The SDGs each have several targets that need to be realized for the goal to be reached. In the present study, we developed a methodology where each target of the SDG 2 (food), 6 (water), and 7 (energy) was analyzed for its input requirements, infrastructure needs, and the risks and benefits for the provision of ecosystem services. Then the targets were compared pairwise and a total score of interaction was calculated to determine different levels of synergies and trade-offs for every pair. In some cases targets were mutually supportive, in other cases there were no interactions among the targets, and for some areas the targets were in conflict with each other. For example, targets 2.5 (maintain genetic diversity), 6.5 (implement integrated water resources management) and 7.a (enhance international cooperation to facilitate access to clean energy) have no conflicts with other targets and have different levels of synergies with most of the other targets. On the contrary, various targets of SDG 2, and especially the target 2.b (correct and prevent trade restrictions), are in slight conflict with other targets by potentially overusing resources needed by other targets or threatening ecosystem services. Our approach confirms the general belief that SDG 6 (water) has the highest number of potential synergies (a total of 124). Thus, achieving the water targets will make it continuously easier to achieve other targets. While the results may need to be adapted for a specific locality or country, overall they provide an improved understanding of the interactions between the targets. The value of the study lies in the quantitative methodology as it can be used as a replicable analysis for any level of work on SDG implementation.

Keywords: water-food-energy nexus, SDGs 2, 6, 7, trade-offs among SDG targets, synergies between SDG tagets, sustainable development goals - SDGs

OPEN ACCESS

Edited by:
Anik Bhaduri,
Griffith University, Australia

Reviewed by:
Nidhi Nagabhatla,
United Nations University Institute for Water Environment and Health, Canada
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Specialty section:
This article was submitted to Freshwater Science, a section of the journal Frontiers in Environmental Science

Received: *26 June 2018*
Accepted: *13 September 2018*
Published: *12 November 2018*

Citation:
Fader M, Cranmer C, Lawford R and Engel-Cox J (2018) Toward an Understanding of Synergies and Trade-Offs Between Water, Energy, and Food SDG Targets. Front. Environ. Sci. 6:112. doi: 10.3389/fenvs.2018.00112

INTRODUCTION

With the aim of reaching economic, social and environmental sustainability, improving life quality for all and unfolding human potentials, countries of the world agreed in September 2015 to 17 Sustainable Development Goals (SDGs) to be achieved by 2030. A total of 169 targets have been established to provide a basis for major advances toward achieving the overall goals through concrete objectives, such as increasing renewable energy, doubling agricultural productivity, or improving water quality. Indicators have been defined for each target to provide a measure of the progress that is being made toward them; some of those indicators continue to be developed and approved. Three of the SDGs refer specifically to food (SDG 2), water (SDG 6) and energy (SDG 7). These three goals are intrinsically linked, as are the resource management, infrastructure development and political measures needed to reach them. The interconnectedness between these sectors implies the potential for synergies but also the risk of trade-offs. Synergies are understood in this study as positive effects of a target achievement on ecosystem services that would, in turn, allow reaching other targets, or mutually beneficial development of infrastructure and policies, which can facilitate SDG implementation. Trade-offs are created where one target intensively uses resources necessary for the achievement of another target, or when environmental degradation caused by the achievement of one target limits the chances to achievement of another target. For example, the path(s) taken by individual nations to achieve the targets for energy could affect their ability to achieve the water and food targets in either a positive or negative way. To achieve the goals while minimalizing trade-offs, there will need to be a reliance on policies that take into consideration the interdependence between water, energy and food.

Fortunately these developments have come at a time when policy makers (Pardoe et al., 2017; Scott, 2017), as well as the science community (Pittock et al., 2015; Endo et al., 2017) are becoming increasingly aware of the interlinkages between water, energy, and food through Water-Energy-Food (WEF) Nexus studies. However, while WEF Nexus studies have become common, there are very few assessments analyzing synergies and risks between SDG targets. A report prepared in 2016 by the UN-Water Task Force provides a first evaluation of the interlinkages of SDG 6 (focused on water) with the other SDGs. Focusing on the three dimensions of sustainable development, namely social, economic and environmental, the brief captures the complex nature of the SDGs, giving a qualitative snapshot of the many considerations that go into the success of a single SDG (6); an inclusive assessment across all SDGs will help governments establish the mechanisms and procedures needed to address trade-offs (UN-Water, 2016). A 2017 study on wastewater highlights that target 6.3, improve water quality by reducing pollution and eliminating dumping and minimizing the release of hazardous chemicals and materials, will challenge SDG 7 targets as collection and treatment of wastewater requires a significant amount of energy; achieving this target, while acknowledging SDG 7, will be financially burdensome on low-income countries that may not have access to the technological upgrades needed (Connor et al., 2017). Nilsson et al. (2016) developed a systematic way for policy makers to map out target interactions so that they can identify which stakeholders will need to be involved to create synergies amongst the SDGs. They designed a seven-point scale that indicates if a target is inextricably linked to the achievement of another goal (indivisible) or if the target clashes with another goal (counteracting). Coopman et al. (2016) use a similar methodology to assess SDG 12 ("Sustainable consumption and production") against the other 16 SDGs. They developed a methodology to analyse the implications of the policy measures needed for achieving the SDGs by focusing on the linkages between the targets in SDG 12 and the other SDG targets relevant to it. Four analysts evaluated and assigned a rating to the linkages separately and categorized target interactions into three categories, supporting, enabling/disenabling, and relying. Pradhan et al. (2017) quantified SDG target synergies and trade-offs by applying a statistical correlation analysis to the country and country-disaggregated data from the United Nations Statistics Division. The interactions for each SDG pair are analyzed and ranked at country and global scales, so it provides a broad analysis of SDG interactions, showing the varied compatibilities between all 17 SDGs. The approach used in this paper is more focused, analyzing interactions of the three SDGs that typically have the strongest nexus (Bhaduri et al., 2015; Biggs et al., 2015).

Our analysis works to build on Nilsson et al. (2016) by expanding their scale and establishing a systematic approach to define where each pair of WEF targets are on that scale. Similar to Pradhan et al. (2017), we aim to quantify synergies and trade-offs but our assessment focuses on target interactions and does not use indicator data. The aim here is to be able to improve society's understanding of how actions can be taken in one sector to benefit that sector and one or both of the other sectors. At the same time, we aim to warn nations about the risks and lost benefits from a lack of communication and coordination between sectoral strategies. This approach is based on resources and infrastructure needs to reach every WEF target, as well as potential benefits and risks for ecosystem services arising from measures taken to reach such targets. The nature of our methodology allows for replication across varying temporal and spatial scales within the WEF Nexus.

METHODS

This section summarizes the methodology; full details and explanations can be found in the **Supplementary Material**. **Figure 1** shows the steps developed in this study to quantify synergies and trade-offs between two SDG targets.

Evaluation of Target Needs and Impacts

Based on the expert knowledge of the authors, every target is first evaluated regarding inputs needs in three domains (1) water, (2) land and soil, and (3) electricity and fuel. If any component of that resource group is needed to reach the target a -1 is assigned, otherwise, a zero is assigned.

After that the infrastructure requirements are assessed in three domains (1) health care and hospitals, (2) education, technology,

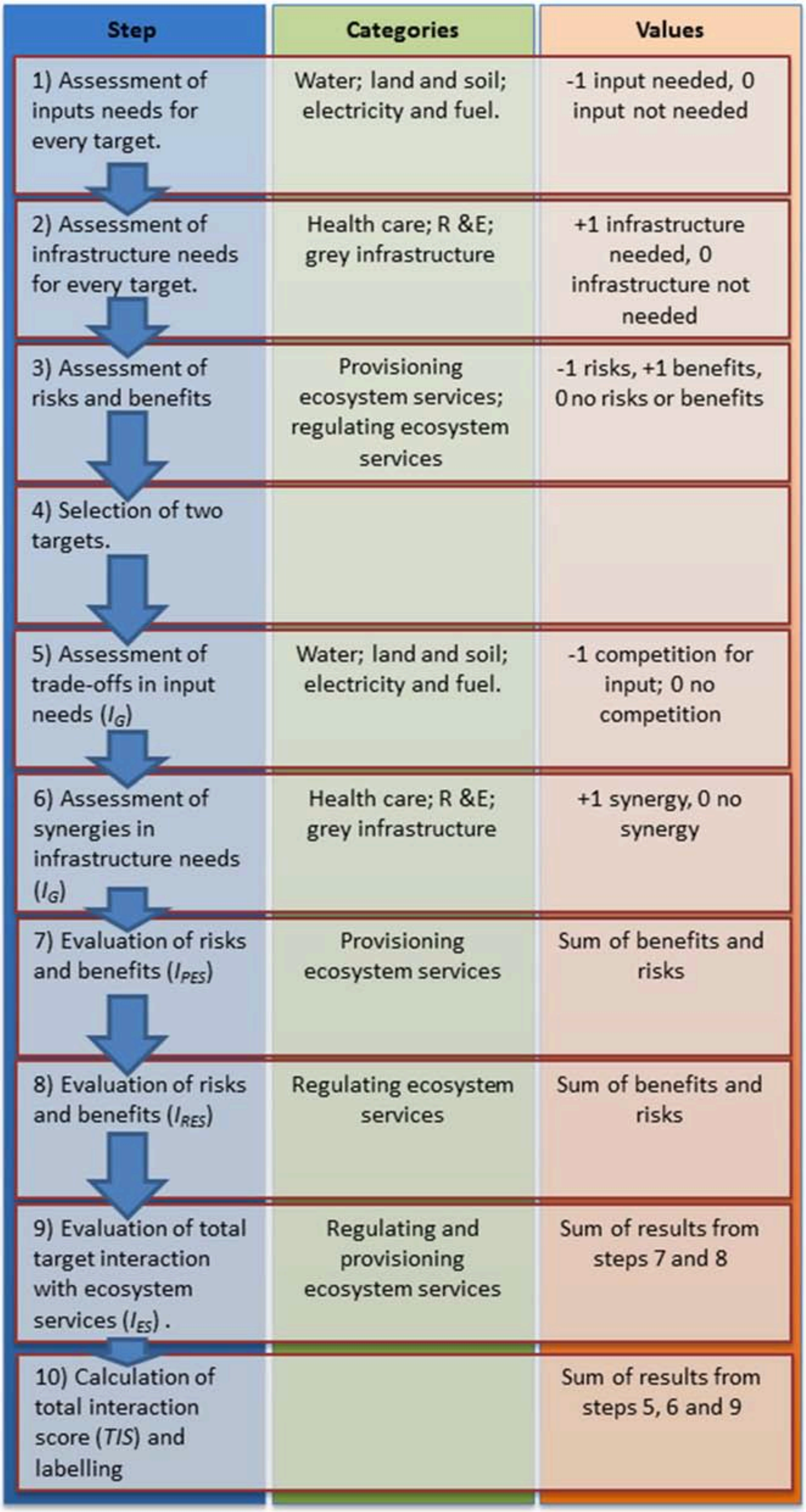

FIGURE 1 | Steps for assessment of synergies and trade-offs between two SDG targets.

and research ("R&E"), (3) streets, pipes, rails, airports, seaports, channels, dams, energy production, sewage, and water treatment ("gray infrastructure" for simplification). If any component of that infrastructure group is required a +1 is assigned, otherwise, a zero is assigned.

Following, for every SDG target it was investigated if its achievement would imply a risk or produce benefits for provisioning and regulating ecosystem services. Supporting ecosystem services were included in the evaluation of regulating services. While it is recognized that cultural ecosystem services are an important consideration, it was not possible to include them in this study due to the multicultural diversity of nearly all nations and the complexity of their evaluation. If there are risks for regulating or provisioning ecosystem services, the value −1 is assigned, if there are benefits, the value +1 is assigned. Otherwise zero is assigned.

Assessing Trade-Offs and Benefits Between Two Targets

First, an arbitrary pair of SDG targets is selected. If the achievement of both targets requires the same group of inputs (e.g., water), it is considered that a competition for this resource will occur and the value −1 will be assigned for the interaction, otherwise it will be zero. The process is repeated for the three resource domains (water; land, and soil; electricity and fuel).

Second, if both targets require the presence or the development of the same group of infrastructure in order to be achieved, it is considered that the infrastructure developed for the achievement of one of the targets can be also used to achieve the second target. In that case it is considered that there would be infrastructural synergies when intending to achieve both targets and the value 1 will be assigned for the interaction; otherwise it will be assigned a zero. The process is repeated for the three infrastructure domains (health care and hospitals; R & E; gray infrastructure).

Third, risks and benefits are evaluated against each other, respectively for provisioning and regulating ecosystem services as well as for the total interaction of the targets with ecosystem services.

Finally, the total interaction score (*TIS*) between two targets was calculated as the sum of competition for input requirements, synergies in infrastructure development and the total effects (risks and benefits) on ecosystem services. The labeling of the results for *TIS* is based on an extension of the categories presented in Nilsson et al. (2016) to allow a more detailed description fitting the theoretical rage of results. These categories are defined in **Table 1**, showing that positive *TIS* represent different levels of synergies between the targets. The same way, negative *TIS* represent trade-offs between the targets. **Table 2** shows an example of the calculation of a two target interactions and total interaction score *TIS*.

RESULTS

The results of this study include three aspects: the interactions between every pair of targets, the number of positive, neutral, and negative interactions as well as the average of interaction for every SDG target, and the same parameters aggregated by SDG.

TABLE 1 | Categories for defining interaction values between targets.

Interaction	Name	Explanation
−4	Canceling	Makes it impossible to reach another goal
−3	Restricting	Obstructs the achievement of another goal
−2	Counteracting	Clashes with another goal
−1	Constraining	Limits options on another goal
0	Consistent	No net significant positive or negative interactions
1	Enabling	Creates conditions that further another goal
2	Reinforcing	Aids the achievement of another goal
3	Supporting	Strongly facilitates the achievement of another goal
4	Indivisible	Inextricably linked to the achievement of another goal

Table 3 shows the *TIS* for all targets of SDG 2, 6 and 7. The matrix is color-coded to match the values given to each interaction. Each target interaction is mirrored in the matrix, a pair of targets whether leading from the x axis or y-axis will give the same result. The most noticeable result is that there are no restricting, counteracting and canceling interactions. This could mean that the SDGs are well-designed or that the analysis was too lenient on the implications associated with ecosystem services. Another reason for the lack of very strong negative interactions is that the risk and benefits, and the input competition and infrastructure synergies compensate each other.

Figure 2 shows statistics for every target of the three SDG separately and aggregated for the three SDG. There are a total of 166 positive interactions vs. a total of 26 negative interactions. The positive interactions (synergies) have higher values than the negative ones, with 59 positive interactions labeled as "supporting" (+3), and all negative interactions are in the level of "constraining" (−1). The average of total interactions is 1.5 and the median is 2.0, establishing the overall interactions between these three SDGs between enabling and reinforcing. Considering every SDG separately, the average of the interactions for every SDG has values of > 1 (1.8 for SDG 7, 1.1 for SDG 2, 1.8 for SDG 6) (**Figure 2**). Our approach confirms the general belief that SDG 6 (water) has the highest number of potential synergies; this goal has a total of 124 positive interactions with an average of positive interactions of +2.1 ("reinforcing"). Thus, achieving the water goals will make it continuously easier to achieve more goals and targets, including those outside of the WEF nexus.

Negative Interactions

The SDG with the highest negative interaction count is SDG 2 (End hunger, achieve food security, and improved nutrition and promote sustainable agriculture) with 26 negative interactions (**Figure 2**). All negative interactions in the matrix are connected to a target of SDG 2. Food related targets are highly dependent on the use of other resources and reaching them with unsustainable techniques (as it has been done in conventional agriculture) has the potential of damaging ecosystems. Therefore, these results indicate that the implementation of SDG 2, while fundamental for food security, must be done with care. Despite this, SDG 2

TABLE 2 | Example of two targets interaction assessment.

Targets	Inputs needs −1 means input needed, 0 input not needed			Infrastructure needs 1 means infrastructure needed, 0 means not needed			Provisioning ecosystem services		Regulating ecosystem services		
	water	Land and Soil	Electricity and fuel	Health Care and hospitals	Education, technology and research	Streets, pipes, rails, airports, channels, dams, sewage, ports, water treatment	Risks	Benefits	Risks	Benefits	
6.3	0	0	−1	0	1	1	0	1	0	1	
2.1	−1	−1	−1	1	1	1	−1	1	−1	0	
Trade–off/synergy	0	0	−1	0	1	1	1		0		*TIS* = +2
							+1				

Colored in green and orange the N1/2$_G$ values, in red the R1/2$_{RES/PES}$ and B1/2$_{RES/PES}$ values, in light blue the I_G and $I_{RES/PES}$ values, in yellow the I_{ES} value, and in dark blue the TIS value. See equations 1 to 4 in the ***Suplementary Material****.*

TABLE 3 | Total interaction score (*TIS*) between targets of SDG 2, 6 and 7.

	6.1	6.2	6.3	6.4	6.5	6.6	6.a	6.b	2.1	2.2	2.3	2.4	2.5	2.a	2.b	2.c	7.1	7.2	7.3	7.a	7.b
6.1		1	2	2	3	1	1	2	0	0	0	1	3	3	−1	1	2	2	2	3	2
6.2	1		2	2	3	1	1	3	1	1	1	1	3	3	−1	1	2	2	2	3	2
6.3	2	2		2	3	2	1	3	2	2	2	2	3	3	0	1	2	3	2	3	2
6.4	2	2	2		3	2	1	3	2	2	2	2	3	3	0	1	2	3	2	3	2
6.5	3	3	3	3		2	2	3	3	3	3	3	3	3	0	1	3	3	2	3	3
6.6	1	1	2	2	2		2	1	−1	−1	−1	0	2	2	−1	1	2	1	2	2	1
6.a	1	1	1	1	2	2		2	0	0	0	1	2	2	−1	1	1	2	2	2	1
6.b	2	3	3	3	3	1	2		2	2	2	2	3	−1	3	1	3	2	2	3	3
2.1	0	1	2	2	3	−1	0	2		−1	−1	0	3	1	−1	−1	1	1	1	3	−1
2.2	0	1	2	2	3	−1	0	2	−1		−1	0	3	1	−1	−1	1	1	1	3	−1
2.3	0	1	2	2	3	−1	0	2	−1	−1		0	3	1	−1	−1	1	1	1	3	−1
2.4	1	1	2	2	3	0	1	2	0	0	0		3	3	0	1	2	2	2	3	1
2.5	3	3	3	3	3	2	2	3	3	3	3	3		3	0	1	3	3	2	3	3
2.a	3	3	3	3	3	2	2	−1	1	1	1	3	3		−1	0	3	3	2	3	2
2.b	−1	−1	0	0	0	−1	−1	3	−1	−1	−1	0	0	−1		−1	−1	−1	−1	0	−1
2.c	1	1	1	1	1	1	1	1	−1	−1	−1	1	1	0	−1		1	1	1	1	0
7.1	2	2	2	2	3	2	1	3	1	1	1	2	3	3	−1	1		3	2	3	2
7.2	2	2	3	3	3	1	2	2	1	1	1	2	3	3	−1	1	3		2	3	3
7.3	2	2	2	2	2	2	2	2	1	1	1	2	2	2	−1	1	2	2		2	2
7.a	3	3	3	3	3	2	2	3	3	3	3	3	3	3	0	1	3	3	2		3
7.b	2	2	2	2	3	1	1	3	−1	−1	−1	1	3	2	−1	0	2	3	2	3	

4 = indivisible	(-4) = cancelling
3 = supporting	(-3) = restricting
2 = reinforcing	(-2) = counteracting
1 = enabling	(-1) = constraining
0 = consistent	

has a total of 106 positive interactions, reaching those targets will generally help in reaching the water and energy targets.

The target with the most negative interactions (13 in total) is 2.b (Correct and prevent trade restrictions and distortions in world agricultural markets), all of them are labeled as "constraining" (**Figure 2** and **Table 3**). This target is also the only one with a negative average of interactions (−0.4). This reflects mainly the potential risks for ecosystem services arising from a likely reorganization of food production patterns following market liberalization. For example, if the European Union would stop subsidizing their agricultural sector, production in other regions (e.g., South America) would become more profitable for exports and the consequent expansion and intensification of agriculture could lead to soil degradation, deforestation, and other environmental problems, if the change is not combined with strong environmental protection laws. It is worthwhile noticing that in this hypothetical case, agriculture in Europe may become less profitable, leading to abandonment of agricultural

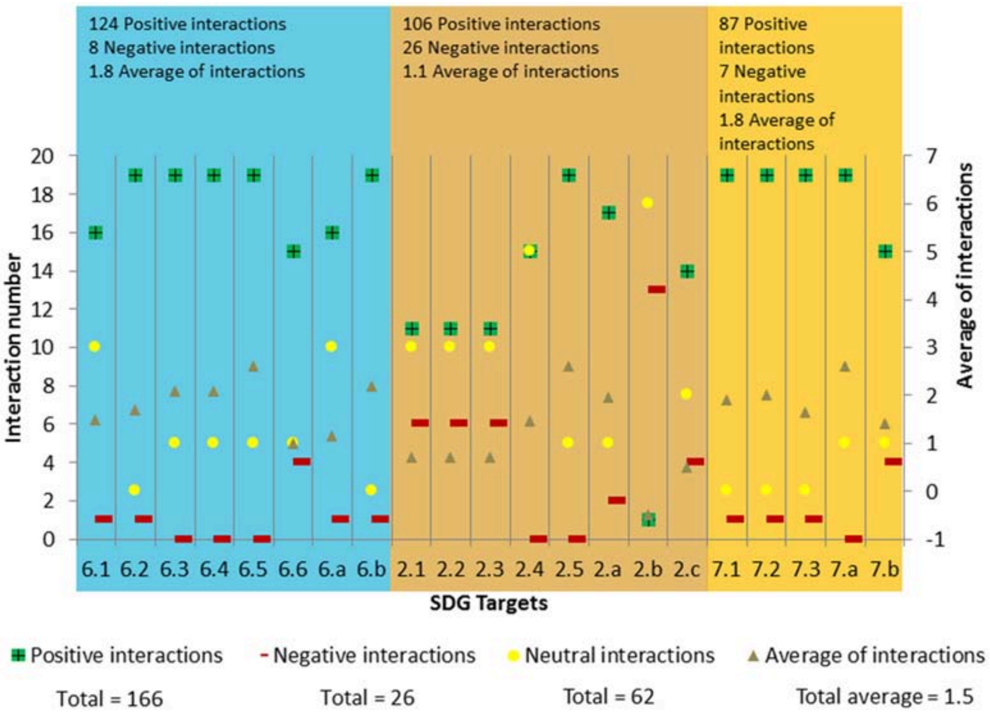

FIGURE 2 | Interaction number (positive, neutral and negative) (left y-axis) and average of total interaction value (*TIS*) (right x-axis) for SDG targets of the water (blue), food (orange) and energy (yellow) goals (x-axis). The values written on the upper part of the graph correspond to total positive, negative and average of interactions per SDG. The values below the legend represent the total number of positive, negative, neutral interactions, and average of interactions, for all SDG targets taken together.

land, possible succession of natural ecosystems and reduction of provisioning ecosystem services. Potential socio-economic changes in both regions would also be very likely.

Table 3 shows that target 2.1 (End hunger) in particular may have a constraining effect on targets 2.2 (end malnutrition) and 2.3 (double the agricultural productivity in terms of income and labor) because of the potential negative consequences for regulating ecosystem services if food security would be achieved by intensification or deforestation. While there is clear potential for synergies in terms of infrastructure use and development that are captured in our estimation, there are also similar input needs that can cause competition for resources. This is the case since water, land and soil, and electricity and fuel are all needed in mass amounts to produce the food necessary to address hunger, malnutrition and to double agricultural productivity. This result is based on the assumption that the fight against rural poverty, malnutrition, and hunger in the framework of the current economic system is likely to be addressed by increases in cheap food production and not by redistribution of resources, means, or food. Achievement of these targets produces benefits for provisioning ecosystem services in the form of food production while at the same time has a negative, draining effect on resources and implies a risk to regulating ecosystem services such as issues of water quality and over-extraction. The water and land needs required from targets 2.1, 2.2, and 2.3 have a constraining (−1) effect on target 6.6, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers, and lakes. The goal to protect ecosystems yet establish high yield agriculture that satisfies global hunger issues is challenging, especially if high yields are achieved by conventional (agro-chemical intensive) agriculture. However, extensive technology advancements and policy implementation can help to achieve all these targets in a sustainable manner (Gupta et al., 2014). The above findings have implications for the WEF Nexus because it emphasizes the critical role economics and trade policies play in production of food. If the demands for food diminish in any one country the demands for water and energy resources will also decrease. Both the WEF Nexus and the SDGs would benefit from a better understanding of the interactions of economic policy with the biophysical aspects of the WEF Nexus.

Positive Interactions

There is no indivisible interaction (+4 value) in the matrix, indicating that in every target pair there is at least one area with possible risks for ecosystem services or competition for resources (**Table 3**). However, many targets have numerous positive interactions and all targets except 2.b have averages of interactions >0 (**Figure 2**).

Certain targets are notably positive across all their target interactions; what the target is looking to achieve will ultimately aid the other targets in their success. The targets with the highest averages of interactions are 7.a (enhance international cooperation for clean energy), 2.5 (maintain genetic diversity) and 6.5 (implement integrated water resource management) (**Figure 2**). An additional pattern emerges amongst the highly positive targets: they are mostly advocating cooperation and are policy focused. For example 7.a, is assessed as having only positive interactions, with the exception of one consistent (0) interaction with 2.b (correct and prevent trade restrictions and distortions in world agricultural markets). Targets 7.a, 6.5 and 2.5 have also the highest average of interactions (2.6).

Target 7.a. takes a cooperative approach; achieving international cooperation in energy technology will increase knowledge transfer and quicken the pace at which these technologies are created, shared, and implemented. Shared infrastructure needs additionally create a positive value between targets due to cost sharing opportunities. Thus, achieving 7.a will be beneficial for all energy, water and food targets, with the exception of 2.b (which has a consistent interaction equal to 0). Achieving 7.a will also produce benefits for both provisioning and regulating ecosystem services; energy infrastructure aids in the provisioning of food and water resources, and advances in energy efficient buildings such as green roofs will help to regulate climate extremes. The success of 7.a will have a cascading influence on other targets. The use of fresh water within the energy industry impacts water quality and quantity, such as the large amounts of water used in the process of converting coal or uranium into electricity (Yillia, 2016). Efficient and clean energy use technologies will typically result in a lower burden on water input needs (Cooley and Donnelly, 2013). The water-efficiency established from these practices can lend themselves to agricultural needs, furthering SDG 2 targets.

Target 6.5, the implementation of integrated water resource management, is supportive amongst most interactions. It is another example of a cooperative, policy-focused target that does not require significant input needs, and creates benefits for provisioning and regulating ecosystems. The overall supporting effect it has on the WEF targets could be attributed to the similarities between nexus thinking and an integrated water resources management approach. Both champion sustainable resource development within society by taking on a holistic environmental, economic and social view (Benson et al., 2015).

While it is gratifying to see these synergies among the SDGs, the possibilities would be much easier to realize at the national level if each country had a strong WEF Nexus implementation framework in place to ensure all three sectors and SDGs were supported by a coherent policy that was based on a broad understanding of all the factors that could affect each sector.

DISCUSSION

This study presents a quantitative approach to estimate the strength of potential trade-offs and synergies between the water, food and energy SDG targets. In addition to elucidating the relationships between the targets at the macroscale, the methodology can be adapted to a particular region where it could provide useful insights for decision makers and local implementation plans. Some interactions among targets are discussed in the following paragraphs to show the complexity and nesting of relationships between SDGs in the WEF Nexus framework.

The links between food targets are complex. Target 2.3 (double the agricultural productivity and incomes of small-scale food producers) must be achieved at the same time as Target 2.1 (end hunger) and Target 2.2 (end malnutrition). Higher food production (at least in the short term) may be achieved by expanding the use of agro-chemical and increasing agricultural outputs through larger farms with more mechanization, and the wider use of Genetically Modified Organisms (GMO) (Adenle and Ammann, 2015). However, Target 2.3 constrains this approach by requiring more small-scale producer development which may also reduce environmental degradation and health risks (e.g., Sheahan et al., 2016). This insight derived from the results of this analysis, would favor satisfying the requirements of all three targets by promoting sustainable (organic), small-scale agriculture which can enhance agricultural productivity while reducing environmental impacts and protecting small-scale food producers (Rockström et al., 2017). GMOs carry the added risk that they could threaten the long-term sustainability of plant and animal biodiversity (Azadi et al., 2015), affecting the achievement of target 2.5. The approach outlined here provides a quantitative basis for initiating discussions about different pathways for reaching targets while minimizing trade-offs, especially needed in developing countries with food insecure situations.

Target 2b which is neutral or in some conflict with most of the other targets seeks to minimize trade restrictions. However, some of the food targets as well as the energy and water targets may require protection from uncontrolled globalization to be achieved. Interactions with target 2.b are especially difficult to analyse since a reorganization of trade patterns would most likely lead to changes in land use and income, and to diverse, spatially heterogeneous consequences for ecosystem services and food production (e.g., Dean, 2002; Fader et al., 2011). The famous debate on "land sparing" vs. "land sharing" reflects also the complexity of this issue (e.g., Tscharntke et al., 2012). Here again, a detailed application of our approach needs to be undertaken in future studies, accounting for scenarios on which countries would minimize trade restrictions (and how), and what that would mean for the analyzed country and its trade partners in terms of land use, water, energy, and food security.

Target 6.3 deals with water quality which is affected by the by-products of many energy and agricultural activities. This target is shown to have synergies with almost all other targets, due to low competition for water, land and energy, and benefits for ecosystem services. Water quality is often diminished by using water to dilute and dispose thermal and chemical by-products from thermal power plants. As a result, water treatment is needed to bring water back to a safe and usable state. This requires substantial capital investments and continuous energy inputs. In farming, fertilizers, and pesticides from farm operations find their way into water courses and eventually to lakes or coastal areas where their accumulated effects result in phytoplankton blooms and even eutrophication. Overall, reduced use of thermal power stations to produce electrical energy as a result of increasing share of non-thermal renewables as well as the growth of organic agriculture and the development of environmental laws should improve the general trend in water quality. However, as noted in ICSU/ISSC, 2015, both emerging and developed countries will likely have to use different approaches to achieve target 6.3. Thus, testing our approach in future studies by contrasting different implementation pathways with stakeholder participation would be desirable and useful.

Water quantity and accessibility are as important as the water quality issues. Agricultural needs plus an easily accessible supply of energy may create a situation where water resources are overused. Areas with food insecurity are often those with the greatest water loss and therefore smart approaches to water use in agriculture are needed (Ringler et al., 2013). Providing low-cost energy for irrigation is a case where a silo approach is used. In particular, there has been a large growth in groundwater extraction in India and South Asia due to irrigation strategies built from flat rate tariffs and subsidies on power to boost the agricultural sector (Lele, 2013). If similar approaches are taken when attempting to achieve SDG 2, many of SDG 6's targets will not be met. Coherent water-energy policies are essential (Yillia, 2016) if food production is going to increase in a sustainable manner. The WEF Nexus approach is intended to address this problem specifically by encouraging more communication and joint planning between the three sectors to avoid these resource use conflicts.

When considering clean energy (SDG 7) in the context of water and food, attention must be given to the method of production of the clean energy. Target 7.a defines clean energy as "renewable energy, energy efficiency and advanced, and cleaner fossil-fuel technology." Renewable energy alone includes solar photovoltaics, solar thermal, wind, hydropower, geothermal, and biomass, which all can be implemented either through large centralized facilities or through distributed systems via large electrical energy distribution grids, microgrids, and offgrid applications. When considering the relationship of renewable energy to water and food, the effects become highly dependent on the type of energy, the location, and the method of deployment. Water will be conserved by the use of solar photovoltaics and wind energy which have few demands for water apart from construction and cleaning. For example, wind turbines use very little to no water, have a small footprint, and allow for growing crops in conjunction with the wind farms, often supporting farmers through small payments for land access (Fthenakis and Kim, 2009; Spang et al., 2014). Solar photovoltaics have very low water usage and distributed systems are often on tops of buildings with little to no land impact; centralized solar facilities do occupy land areas comparable to conventional energy. However, new research shows that crops can be grown in the shade under the solar panels depending on their installation (Fthenakis and Kim, 2009; Spang et al., 2014; Jossi, 2018).

Hydropower production involves withdrawing or restraining water, using it for a short period of time and returning it to the river water body without any significant reduction in quality or volume. Hydropower dams can also provide co-benefits to farmers in terms of more consistent access to water and control of flooding. However, large dams flood significant land areas and often displace many people, remove prime agricultural lands from production, and affect natural ecosystems and their services. Depending on their location, large reservoirs can also be inefficient due to large evaporative loses. On the other hand, small run-of-the-river or conduit-based hydropower systems may be an effective way to generate power and irrigate crops with little to no land conversion (Fthenakis and Kim, 2009).

In the evaluation of the technologies relevant to targets of SDG 7 with other targets, biofuels created the most uncertainty. Increased access to electricity produced by renewable energy can reduce dependence on wood and other biomass used for heating and cooking that causes deforestation—threatening regulating ecosystem services—and exposure to indoor air pollution (Pereira et al., 2011). However, biofuels generated from food crops or grown on land that could be used for food were seen to have the largest potential conflict with water and food with the largest land and water use per unit of energy generated (Spang et al., 2014; Trainor et al., 2016). It was recognized that the development of new cellulosic-based biofuels from agricultural wastes could provide an important secondary income stream for farmers.

Overall, our analysis indicates that renewable and other clean energy will result in a general net positive effect for the Energy SDG (SDG 7) and also for the water and food SDGs. However, as access to clean and affordable energy increases to meet this goal, careful attention to synergies with water, and food goals will need to be pursued to increase the potential for positive synergies and improvements over traditional energy sources. The exposed arguments mean also that depending on the mix of renewables used for achieving target 7.2, the consequences and trade-offs for and with other targets will strongly differ. Coupling our approach with models providing scenarios of the outputs of different possible energy mix may help to better evaluate the trade-offs between targets.

LIMITATIONS OF THE APPROACH

There are many considerations not analyzed in this methodology that can be further assessed. For example, mineral inputs are needed for achieving certain targets (e.g., for photovoltaic devises, agro-chemical production, water purification, etc.). However, the variety of minerals used in the different sectors as well as their heterogeneous availability would need a much more detailed analysis in order to integrate them in this approach. Similarly, infrastructure costs and labor that are needed have not been considered. There are many targets that require these investments and would ultimately share the investment. For example, targets 6.2 (sanitation) and 6.3 (water quality) would likely share water treatment infrastructure. Yet, some infrastructural developments may be too expensive for some developing countries. To reduce the complexity of these issues they are best considered with a more geographically focused area in mind.

Furthermore, the approach developed here does not account for cultural ecosystem services due to their complexity and difficulty to quantify and evaluate. However, for local applications where the cultural, management, and recreational contexts are well-known, it would be easy to expand the methodology in order to include the risks and benefits for such services.

We do not consider air, wind, temperature, solar radiation, or precipitation as inputs or the impacts that the WEF targets may have on climate targets. A further analysis of how SDG 13's (Take urgent action to combat climate change and its impacts) targets could impact the success of the WEF targets, and vice versa, would be beneficial. In the longer term, climate change and its extremes may have significant impacts on the interactions among the water, energy, and food sectors. The trend to replace carbon-based energy with renewables may, however, slow that trend and reduce these concerns. Also, in future studies, synergies and conflicts between the WEF targets and the targets of SDG 14 (life below water), 15 (life on land), and 11 (sustainable cities and communities) should be evaluated. This is especially important since the provision of ecosystem services will very much depend on the implementation of SDG 14 and 15. Moreover, the decoupling of food production and consumption areas due to urbanization may significantly change fuel and energy consumption through changes in (international) trade volumes and patterns.

Our analysis assumes that if two targets need a resource (e.g., water), they will compete for it. However, resource constraints may be partially addressed by developing their supply side. For example, water could be made available from desalinization plants or pumping (more) groundwater where these reserves exist. Groundwater that is heated underground can also play an important role in the energy supply for both power and heating (e.g., Lund and Boyd, 2015). The application of the approach developed in this study during periods of surface water scarcity in regions where groundwater use is intense (e.g., Mediterranean, Middle East, western North America) could elucidate important regional WEF Nexus issues that may affect the achievement of the SDGs at the national level.

The quantification approach developed in this study was made for a general case, based on expert knowledge and assuming mainly business as usual implementation and development plans (conventional agriculture, gray infrastructure, inequality, etc.) Accordingly, coarse assumptions on input and infrastructure needs as well as on the benefits and risks for ecosystem services were made for quantifying target interactions. The use of this approach requires defining the way a country or region aims at reaching the SDG targets, since SDGs establish what to achieve and when, but not how, so that countries and regions can develop different plans for doing so. This all means that the matrix can have very different results when the approach is used in a specific context or with a specific implementation pathway.

Although the interaction matrix evaluates only the interconnection between two sectors at a time, all three sectors, water, energy, and food, are intrinsically linked in many situations around the globe. With a specific area in mind, and concrete development pathways from policy making, this approach can be further developed to account for cascading effects, i.e., the consequences of a synergic or conflicting interaction between two targets on a third target.

Overall, the approach developed in this study offers a replicable, quantitative and criteria-oriented methodology for evaluating synergies and conflicts between SDG targets of the WEF domain.

COMPARISON WITH SIMILAR STUDIES

Fuso Nerini et al. (2018) and McCollum et al. (2018) analyzed based on literature review the interactions between the SDG 7 targets and the rest of the targets. Our results agree with the findings of both papers by indicating that the positive interactions between the SDGs substantially outweigh the negative ones. McCollum et al. (2018) also assessed the strength of interactions based on Nilsson et al. (2016) for SDG 7 as a whole and some group of targets from other SDGs. Unfortunately, they do not report the relationships for each target separately, so that a quantitative comparison is not possible, though both studies agree on various interactions and on the general positive magnitude of interactions.

Pradhan et al. (2017) analyzed synergies and trade-offs based on correlations of indicator values for all SDGs in 227 countries. They found that synergies outweigh trade-offs in general—in agreement with our results—and that there are more synergies than trade-offs within SDG 6 (100% synergies in our study, 75% in their study). Some major differences can be observed, for example they found mostly synergies within SDG 2 (our study finds 40% of trade-offs), many non-classified relationships within SDG 7 (our study finds only synergies), and trade-offs between access to energy services (target 7.1) and increase the share of renewables (target 7.2), while we assessed the both targets to be mutually reinforcing. Furthermore, they found high percentage (∼50%) of trade-offs between SDG 7 and SDG 6, while we found only synergies. Since Pradhan et al. (2017) uses indicator data of the past, he accounts for resource competition and infrastructural needs, as we do. However, their pairwise correlations do not account for degradation of ecosystem services through the achievement of targets which indicators are not directly linked to those services. Also, and as opposed to our approach, their methodology is not able to capture alternative (future) pathways for which there would be a lack of indicator data. Thus, both studies and methodologies are complementary, with the one applied in Pradhan et al. (2017) more able to monitor progress, and the one developed here more able to project success or conflicts, and support decision makers in the design of implementation plans.

Mainali et al. (2018) qualitatively and quantitatively assessed target interactions of the SDGs 1, 2, 6, and 7 in the period of time 1990–2012 for some South-Eastern and Sub-Saharan African countries by means of network analysis techniques, correlation of indicators values, and advanced sustainability analysis. They found synergies between targets 2.1 and 7.1 and between 7.1 and 6.1, in agreement with our results. However, their results diverge regarding the interactions between the targets 2.3 and 6.4 (their Figure 9 indicates trade-offs but the text and the correlation of indicator values suggest synergies), while we found a reinforcing influence. Most importantly, Mainali et al. (2018) and Pradhan et al. (2017) show that the same approach when applied in different countries may yield very different results.

CONCLUSIONS

The SDGs provide us with an opportunity to improve each of the water, food, and energy sectors now to make them less vulnerable under future change and to optimize their relationships so the benefits in one sector are spread among the other two and in fact among all of the SDGs. Our analysis reveals that SDG 6 has the highest number of potential synergies, 124 positive interactions, and SDG 2 has the most negative interactions (26). The achievement of SDG 6, including sustainable management of water resources and improved quality and access of water will facilitate the achievement of SDG 2 and 7 targets. The negative interactions of SDG 2 targets are due to the high dependency of food production on water, energy, and land resources and to potential degradation of regulating ecosystems services through unsustainable farming practices. Thus, for food security to be achieved sustainably, careful and holistic policy implementation in the Water-Energy-Food Nexus framework is paramount.

Our results show that the targets receiving the most positive interaction scores are those that advocate cooperation and are policy focused. Target 6.5, implement integrated water resource management, provides a framework for all levels of government in many aspects of planning and management processes. Target 7.a, enhance international cooperation to facilitate clean energy research and technology, if achieved, will increase and improve clean energy sources that will reduce the burden on water resources and the degradation of ecosystems caused by energy production based on fossil fuels. Thus, our findings indicate that cooperation across all levels of government and civil society may be a key tool for the success of the SDGs.

The approach used in this paper shows how each of the WEF targets are interconnected with one another and what opportunities exist for mutually beneficial solutions in terms of investments and programmes, as well as the possibilities of one target impairing another. The analysis of SDG targets interactions can also aid in policy development for target achievement by providing a broader scope of the connections between the SDGs. Policy makers can use this methodology to take into account a more holistic view of possible outcomes from certain action or inaction. This analysis has been done on a broad global scale, attempting to factor in considerations of time, space, economics and feasibility. However, by using a quantitative analysis the process can be reproduced within other contexts, being suitable to be scaled down to suit a specific a country or an ecosystem, and even be applied for analyses of targets from other SDGs. The study also supports an assessment of the ways in which the WEF Nexus approach can contribute to the achievement of the SDGs and to identify co-benefits that could be developed between the SDGs and the WEF Nexus implementation.

In summary, it should be recognized that, apart from infrastructure investments, much of the economic rationale for achieving water SDGs will come from the choices we make in developing the resource sectors of water, energy, and food. While this discussion deals with the macroscale effects, the connections themselves occur over many different scales, and innovation and scale interactions can move from the local level to trigger changes and disruptions that can influence the entire global balance. Given the important insights this study has provided regarding the relationships among the targets for energy, water, and food, the SDG stakeholder and research communities for each of these sectors should reach out to the WEF Nexus community to see how they can benefit from collaboration.

AUTHOR CONTRIBUTIONS

RL and CC conceived the research idea. MF designed and developed the research methodology and programmed the equations. JE-C provided input to energy analysis, MF analyzed synergies and trade-offs in the food and water domain, CC and RL assessed the risks and benefits for ecosystem services. MF and CC performed the calculations. All authors provided critical feedback and helped shape the research and manuscript.

ACKNOWLEDGMENTS

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2018.00112/full#supplementary-material

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Environmental Science

ORIGINAL RESEARCH
published: 22 November 2018
doi: 10.3389/fenvs.2018.00141

Spatial Assessment of Water Use Efficiency (SDG Indicator 6.4.1) for Regional Policy Support

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Countries are facing the challenge of identifying the most effective implementation strategies and measures for achieving Sustainable Development Goals (SDG) and their specific targets. The standard procedure proposed by international organizations consists of a set of indicators (one or more per target) assessed at country level. However, such country scale assessments have only limited potential for regional or national policymaking, because of aggregation and averaging effects, which limit the identification of phenomena, their causal relationships, and their spatial-temporal dynamics. The need thus emerges for defining assessment procedures that go beyond national level aggregation and zoom into local phenomena, while maintaining a link with the approach adopted at the global level for monitoring and reporting the progress toward the meeting of the SDGs. SDG 6 focuses on water resources and aims at achieving safe water and sanitation for all, which are essential to human health, environmental sustainability, and economic prosperity. SDG 6 is evidently interconnected with several other SDGs, and in particular with those focused on food production (SDG2) and other socio-economic activities using water as a production factor. This paper proposes an approach to assess SDG 6, based upon freely available global data sets. The methodology is suitable for both reporting at international level in accordance with approved guidelines proposed by custodian agencies and –more importantly–analyzing the spatial features of the phenomena related to the SDGs and their targets, producing information useful to support effective sustainability oriented policies. The proposed approach is demonstrated for the assessment of the indicator 6.4.1 (Change in water use efficiency) in South and South-East Asia, with the ambition to provide operational solutions timely applicable at the global level by exploiting the ever-increasing availability of spatial information deriving from ongoing exercises in the field of global change. This will allow identifying current and emerging water management issues, such as the areas where strategies are required to increase the availability of water resources, or those necessitating transboundary strategies. Scenario analysis driven by the IPCC Shared Socioeconomic Pathways is developed to explore policy and technological solutions across the nexus between water management and agriculture.

Keywords: sustainable development goals, water use efficiency, spatial assessment, ISODATA, policy support

OPEN ACCESS

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Specialty section:
This article was submitted to Freshwater Science, a section of the journal Frontiers in Environmental Science

Received: 25 June 2018
Accepted: 05 November 2018
Published: 22 November 2018

Citation:
Giupponi C, Gain AK and Farinosi F (2018) Spatial Assessment of Water Use Efficiency (SDG Indicator 6.4.1) for Regional Policy Support. Front. Environ. Sci. 6:141. doi: 10.3389/fenvs.2018.00141

INTRODUCTION

The United Nations (UN) adopted an ambitious global sustainability agenda for the period up to 2030 (UN, 2015). In September 2015, heads of state and government from 193 member states of UN agreed to adopt the 2030 Agenda for Sustainable Development consisting of 17 goals and 169 targets (UN, 2017; UN-Water, 2018). Achieving the Sustainable Development Goals (SDGs) will require major efforts on how the monitoring of the progresses toward the goals can be tracked (UN, 2017; UN-Water, 2017b), and how consequent implementation actions can be identified and targeted to different situations (Gain et al., 2016). The multiplicity of essentially non-comparable measures of sustainable development necessitates the generation of "relevant" SDG indicators so that "clear, unambiguous messages be conveyed to users" (Hák et al., 2016). In this respect, there were attempts by their drafters, the UN Inter-Agency and Expert Group on SDG Indicators (IAEG-SDG), to ensure relevance. Although there are criticisms that many suggested indicators lack comprehensive, cross-country data and some even lack agreed statistical definitions (Schmidt-Traub et al., 2017), the United Nations Statistical Commission (UNSC) adopted a set of 230 indicators proposed by the IAEG-SDG on March 2016 as a practical starting point to monitor progress on the 17 goals and 169 targets of the SDGs (Allen et al., 2017).

Developing countries are usually those with the higher needs, bigger gaps between current capabilities and the targets and the more limited resources for accurate monitoring, due to limitations in the availability of information and in the statistical institutions to manage them (UN-Water, 2017a).

In order to move from agreeing on the goals to implementing and ultimately achieving them, Yonehara et al. (2017) suggested to divide the SDGs' 15-years time frame into three 5-years phases: a planning phase driven by proactive evaluation and evaluability assessment, an improvement phase characterized by formative evaluation and monitoring, and a completion phase involving outcome and impact evaluations (see **Table 1**). Reyers et al. (2017) and UN-Water (2016) stated that there must be greater attention on interlinkages across sectors (e.g., finance, agriculture, energy, and transport), across societal actors (local authorities, government agencies, private sector, and civil society), and across scales (Liu et al., 2017, 2018). In order to improve these interlinkages, Reyers et al. (2017) also provided seven recommendations pertaining to the following areas: finance, technology, capacity building, trade, policy coherence, partnerships, and, finally, data, monitoring and accountability. Among these seven recommendations, data collection, monitoring and accountability at different levels are highly important for the implementation of SDGs. Vanham et al. (2018) and FAO (2017), for example, suggested that SDGs implementation should be monitored at least three levels: national (e.g., country level), sub-national (e.g., basin level), and local level (see **Table 2**).

The main challenge for monitoring the implementation of the SDGs at national, sub-national and local levels remains in the availability of comparable global raw data collected with adequate spatial detail and quality at regular time intervals (Giupponi and Gain, 2017; Farinosi et al., 2018; UN-Water, 2018). Usually, country-level data are available globally from international organizations, such as the global water information system, AQUASTAT of the Food and Agriculture Organization (FAO). However, country-level averaging and aggregation hide the variability of physical and socio-economic phenomena (Gain et al., 2016). Therefore, the spatial detail is crucial to identify hot spot areas of greatest interest for planning the interventions toward the achievement of the SDGs (Giupponi and Gain, 2017; Farinosi et al., 2018). In addition, there is an urgent need for the research community to develop scientifically robust tools to help operationalize the SDGs at the global, regional, national and sub-national levels, with an aim to support the tracking of cross scale, local and aggregate, regional and global trends (Reyers et al., 2017). Specifically, quantitative assessments based on robust models and scenarios are required to foresight sustainable futures to back cast potential development pathways (Reyers et al., 2017).

In order to support implementation of SDGs, several recent studies (Gain et al., 2016; Obersteiner et al., 2016; Allen et al., 2017; Giupponi and Gain, 2017; Schmidt-Traub et al., 2017; Unver et al., 2017; Vanham et al., 2018) proposed approaches for quantitative assessments. Most of these studies have been conducted at national or transboundary river basin scale. Schmidt-Traub et al. (2017) and Gain et al. (2016), for example, developed an SDG index based on selected indicators at global level, while Allen et al. (2017) focused on Arab regions. However, most of those studies focus on a single SDG or sector and they do not consider interactions across sectors and hence the possible

TABLE 1 | Three 5-years phases for SDG implementation and evaluation, according to Yonehara et al. (2017).

Phases	Activities	Evaluation concern
Phase 1 (2016–2020)	Planning and initiation of major programs	Proactive evaluation Evaluability assessment
Phase 2 (2021–2025)	Project continuation, modification, improvement, addition	Monitoring Formative evaluation
Phase 3 (2026–2030)	Project completion	Follow-up Outcome evaluation Impact evaluation

TABLE 2 | Monitoring of SDG implementations at different levels, according to FAO (2017).

National level	Sub-national level	Local level
The indicators can be populated with estimations based on national data aggregated to the country level.	The indicator can be populated with nationally produced data, which increasingly can be disaggregated to the sub-national basin unit level.	For more advanced levels, the nationally produced data have high spatial and temporal resolution (e.g., geo-referenced and based on metered volumes) and can be fully disaggregated by source (surface water/groundwater) and use (economic activity).

synergies and trade-offs among SDGs are neglected (Liu et al., 2018), while they are extremely important for policy support toward successful implementation of SDGs. Using network analysis approach, Le Blanc (2015) showed that some goals (SDG 12 and SDG 10) are strongly connected to many other goals through multiple targets, while other goals are weakly connected to the rest of the system. Obersteiner et al. (2016) found that coherent cross-sectoral policy combinations can manage trade-offs among environmental conservation initiatives and food prices. Recently, Neely et al. (2017) documented several cases (e.g., Bangladesh, the Gambia, Nepal, Guatemala, India) on cross sectoral coordination for food and agriculture and its benefit to national policies of these countries. A recent study by Giupponi and Gain (2017) provided an integrated assessment of SDG 2 (food), 6 (water), and 7 (energy), highlighting synergies and conflicts amongst and within the three sectors (water, energy, and food), in the Ganges–Brahmaputra–Meghna (GBM) River Basin in Asia and in the Po River Basin in Europe. However, they did not analyze current situations in view of possible future scenarios, which is essential for moving from monitoring of SDGs to the implementation of targeted policies. Recently, Vanham et al. (2018) assessed the indicator SDG 6.4.2 "Level of water stress" for monitoring progress toward SDG, considering future scenarios across different spatial scales (e.g., national, basin, and catchment scales), but they did not consider interactions with other targets and goals.

In summary, an analysis of the most recent literature shows the following gaps: (i) consideration of synergies and trade-offs, or cross-sectoral interactions while assessing SDGs; (ii) assessment procedures that go beyond national level aggregation and zoom into local phenomena, and (iii) analysis of links between past trends and current situations and possible future developments to support the identification of effective and robust policy options.

In order to help fill the above mentioned gaps, this study presents an approach for the spatial assessment of Water Use Efficiency (WUE; SDG indicator 6.4.1), to explore how the economic value generated by water varies within countries. Maps of WUE (US$ per cubic meter of water) are first produced at country level and then at the level of small administrative units. The most recent spatial estimations of related variables for current times and for the time at the end of the Agenda 2030 planning period are used to characterize future scenarios and guide the identification of water management policies with consideration of expected developments of the economy as a whole and of the agricultural sector in particular, in order to explore the nexus, in terms of potential trade-offs and synergies between water use for food production and other uses of water.

The main aim of the proposed approach is to show how it is possible to provide policy support for the achievement of SDGs (in this case water use efficiency, i.e., indicator 6.4.1 for Target 6.4), by making use of freely available global information with the highest possible spatial detail. It is expected that the possibility would be of particular interest for those countries that may face challenges in the acquisition of data needed for the assessment. The countries of South and South-East Asia are facing many data acquisition challenges. In addition, these countries face similar challenges, such as overexploitation of freshwater for irrigation, poor governance, and social conflicts for water allocation. In these areas, specifically in South Asia, the authors have significant first-hand experiences, e.g., Giupponi et al. (2013), Gain et al. (2015), Giupponi and Gain (2017), Roy et al. (2017), Gain et al. (2017a), and Gain et al. (2017b). Therefore, South and South-East Asia has been selected as the demonstration area for the proposed approach.

METHODS

Assessment of Water Use Efficiency

Target 6.4 of SDGs aims to "by 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity, and substantially reduce the number of people suffering from water scarcity" (UN, 2015). To monitor progress toward this target, two indicators are used: Indicator 6.4.1 measuring water use efficiency (WUE) to address the economic component and 6.4.2 measuring the level of water stress to address the physical component. Recently, Vanham et al. (2018) provided a detailed assessment of the indicator 6.4.2 (i.e., Level of water stress). In this study, we assess the indicator 6.4.1 (change in WUE over time) taking into account interactions across sectors and scales.

As suggested by FAO (2017), the WUE is defined as the value added per unit of water withdrawn over time (showing the trend in water use efficiency over time) and is calculated in US$ per cubic meter of abstracted water as the sum of the three main sectors (agriculture, industry and services), weighted according to the proportion of water withdrawn by each sector over the total withdrawals (see Equation 1).

$$WUE = A_{we} \times P_A + I_{we} \times P_I + S_{we} \times P_S \tag{1}$$

where:

WUE = Water use efficiency [US$/m^3]
A_{we} = Irrigated agriculture water use efficiency [US$/m^3]; see below
P_A = Proportion of water withdrawn by the agricultural sector over the total withdrawals
I_{we} = Industrial water use efficiency [US$/m^3]
P_I = Proportion of water withdrawn by the industry sector over the total withdrawals
S_{we} = Services water use efficiency [US$/m^3]
P_S = Proportion of water withdrawn by the service sector over the total withdrawals

To calculate water use efficiency for irrigated agriculture, the Equation (2) is used:

$$A_{we} = \frac{GVA_a \times (1 - C_r)}{V_a} \tag{2}$$

where:

A_{we} = Irrigated agriculture water use efficiency [US$/m^3]
GVA_a = Gross value added by agriculture (excluding river and marine fisheries and forestry) [US$]

C_r = Proportion of agricultural GVA produced by rainfed agriculture [–]; see below
V_a = Volume of water withdrawn by the agricultural sector (including irrigation, livestock and aquaculture) [m^3]

C_r can be calculated from the proportion of irrigated land on the total arable land, as shown in Equation (3):

$$C_r = \frac{1}{1 + \frac{A_i}{(1-A_i)^{*}0.375}} \tag{3}$$

where:

A_i = proportion of irrigated land on the total arable land
0.375 = Generic Default Ratio Between Rainfed and Irrigated Yields

To calculate water use efficiency for industry, the following Equation (4) is used.

$$I_{we} = \frac{GVA_i}{V_i} \tag{4}$$

where:

I_{we} = Industrial water use efficiency [US\$/m^3]
GVA_i = Gross value added by industry [US\$]
V_i = Volume of water withdrawn by the industry [m^3]

For calculating WUE for service sector, the Equation (5) will be used.

$$S_{we} = \frac{GVA_s}{V_s} \tag{5}$$

where:

S_{we} = Service sector water use efficiency [US\$/m^3]
GVA_s = Gross value added by service sector [US\$]
V_s = Volume of water withdrawn by the industry [m^3]

Using above equations (Equations 1–5) and collecting the most recent data from variety of selected sources (see **Table 3**), we have calculated WUE at country level. The data sources for the input variable is summarized in **Table 3**. All the map layers were referenced on the same coordinate system and eventually converted in raster layers to allow for spatial analysis at the highest possible resolution (see **Table 4**). The gaps in input data were filled by alternative sources providing values comparable with those recommended by the custodian agencies. For example, gaps in A_i values per country in the AQUASTAT databases were filled by data derived from AQUASTAT publications and country reports, while gaps in the socio-economic variables of the World Bank data bases were filled with the corresponding values of the International Monetary Fund.

Initially, we have calculated country-level WUE for the year 2016, as required by FAO, for comparative purposes. Even if almost all data layers were downloaded at global level, as stated above, we have focused our assessment on South and South-East Asia, by framing maps according to a window with North-East corner longitude 73° latitude 34°N and South-West corner longitude 110° latitude 5°N.

The entire data processing has been conducted in the TerrSet GIS environment, by Clark University (version 18.31) and coded in a single macro file, to allow for easy revisions and updates. **Figure 1** presents a flow-chart of the procedure.

TABLE 4 | Metadata information of developed GIS layers.

Variables	Metadata
Reference System	EPSG:4326–WGS84–Geographic Coordinate System
Bounding Box	−180, −90, 180, 90
Rows	2,160
Column	4,320
Resolution	0.083333333
Units of Measure	Decimal degree
Approximate area of one cell	ca. 80 sq. km, depending on the latitude

TABLE 3 | Data sources for country level calculation of WUE.

Variables	Indicators	Temporal resolution	Data sources
V_a	Volume of agricultural water withdrawal	Yearly	FAO AQUASTAT http://www.fao.org/nr/water/aquastat/data/query/index.html http://www.fao.org/nr/water/aquastat/data/popups/itemDefn.html?id=4250
GVA_a	Agriculture, value added	Yearly	World Bank https://data.worldbank.org/indicator/NV.AGR.TOTL.CD
A_i	proportion of irrigated land on the total arable land	Yearly	World Bank https://data.worldbank.org/indicator/AG.LND.IRIG.AG.ZS
V_i	Volume of industrial water withdrawal	Yearly	FAO AQUASTAT http://www.fao.org/nr/water/aquastat/data/popups/itemDefn.html?id=4252 http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en
GVA_i	Industry, value added	Yearly	https://data.worldbank.org/indicator/NV.IND.TOTL.CD
V_S	Volume of services water withdrawal	Yearly	FAO AQUASTAT http://www.fao.org/nr/water/aquastat/data/popups/itemDefn.html?id=4251 http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en
GVA_S	Services, value added	Yearly	https://data.worldbank.org/indicator/NV.SRV.TETC.CD

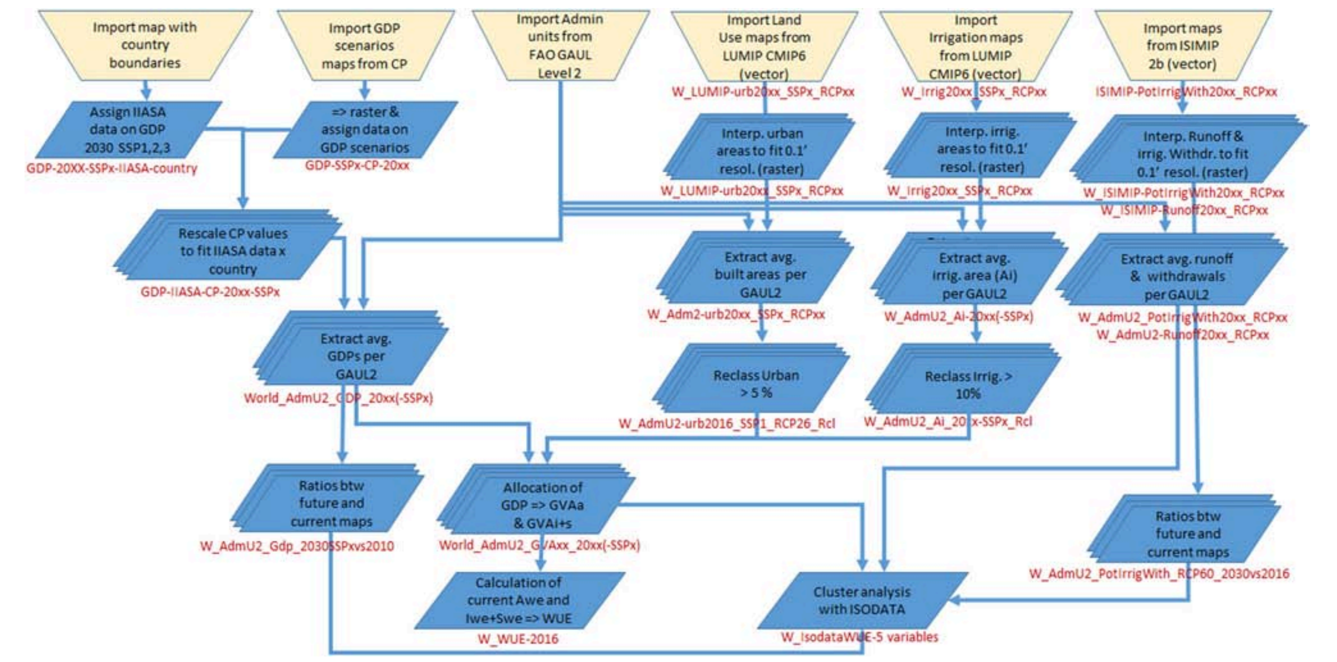

FIGURE 1 | Flow-chart of the proposed approach (file nomenclature in red).

Spatial Analysis of WUE

The gridded estimations of GDP carried out by Murakami and Yamagata (2016) in the Carbon Project[1] were used for building spatially explicit maps of the values of economic activities, going well-beyond country level. Murakami and Yamagata (2016) assessed global population and GDP scenarios in 0.5 $\times$ 0.5 degree grids between 1980 and 2100 with an interval of 10 years. For the historical period (1980–2010), the data is estimated by downscaling actual populations and GDPs by country, while for the future (2020–2100) values are estimated by downscaling projected populations and GDPs under three Shared Socioeconomic Pathways (SSP): SSP1; SSP2; and SSP3, by country (source: IIASA SSP database version 1)[2].

Using the above method, gridded GDP value in 2010 is considered as the most recent available map, while the GDP projection for 2030 (end of Agenda 2030 period) is mapped for three SSPs (SSP1 refers to "Sustainability-Taking the Green Road", SSP2 indicates "Middle of the Road," while, SSP3 refers "Regional Rivalry–A Rocky Road"). A series of tests were conducted to verify the coherence between different sources of GDP information (WB, IMF, and IPCC-SSP) and sector GVA's. Eventually, the spatially explicit maps of GDP sum up at the total GVA country values, provided by WB, thus allowing for obtaining comparable results between the country level exercise and the spatial analysis. While future projections fit the values of IIASA.

In order to increase the visibility of the maps we aggregated the cell values (ca. 80 km^2) at the level of FAO Global Administrative Unit Layers (GAUL) 2, reported in **Figure 2** (source: FAO Geonetwork)[3].

In order to allocate total GDPs per GAUL2 into agriculture as well as industry and service sectors, we have incorporated the land cover map for current and future periods (i.e., 2030) of 3 SSPs in the GIS layer. The land cover maps were collected from the Land Use Model Intercomparison Project (LUMIP) (Lawrence et al., 2016), data set prepared for the Coupled Model Intercomparison Project Phase 6 (CMIP6) (Eyring et al., 2016). In addition to a land cover map, irrigation maps for current and future periods (considering the 3 SSPs) were also imported from LUMIP. The imported land cover and irrigated agriculture maps were used to guide the allocation of GDP, to irrigated areas as the sources of agricultural value added of water withdrawn and built up areas for the allocation of industrial and services value added. By comparing GDP maps with land use and irrigation maps, we distributed total GDP estimations by the Carbon Project into 3 land typologies: (i) GDP of industrial or service origin in those areas with higher GDP and high percentages of built up areas; (ii) GDP of agricultural origin in areas with significant percentage of irrigated agriculture and intermediate GDP values; and (iii) the remaining areas where low GDP values in areas with no significant presence of irrigated agriculture.

For assessing the proportion of agricultural GVA produced by rainfed agriculture (C_r) per GAUL2, using Equation (3), the proportion of irrigated land on total arable land is extracted from LUMIP irrigation area map. Current aggregated figures of water

[1]http://www.cger.nies.go.jp/gcp/population-and-gdp.html

[2]https://secure.iiasa.ac.at/web-apps/ene/SspDb/dsd?Action=htmlpage&page=about

[3]http://www.fao.org/geonetwork/srv/en/metadata.show?id=12691

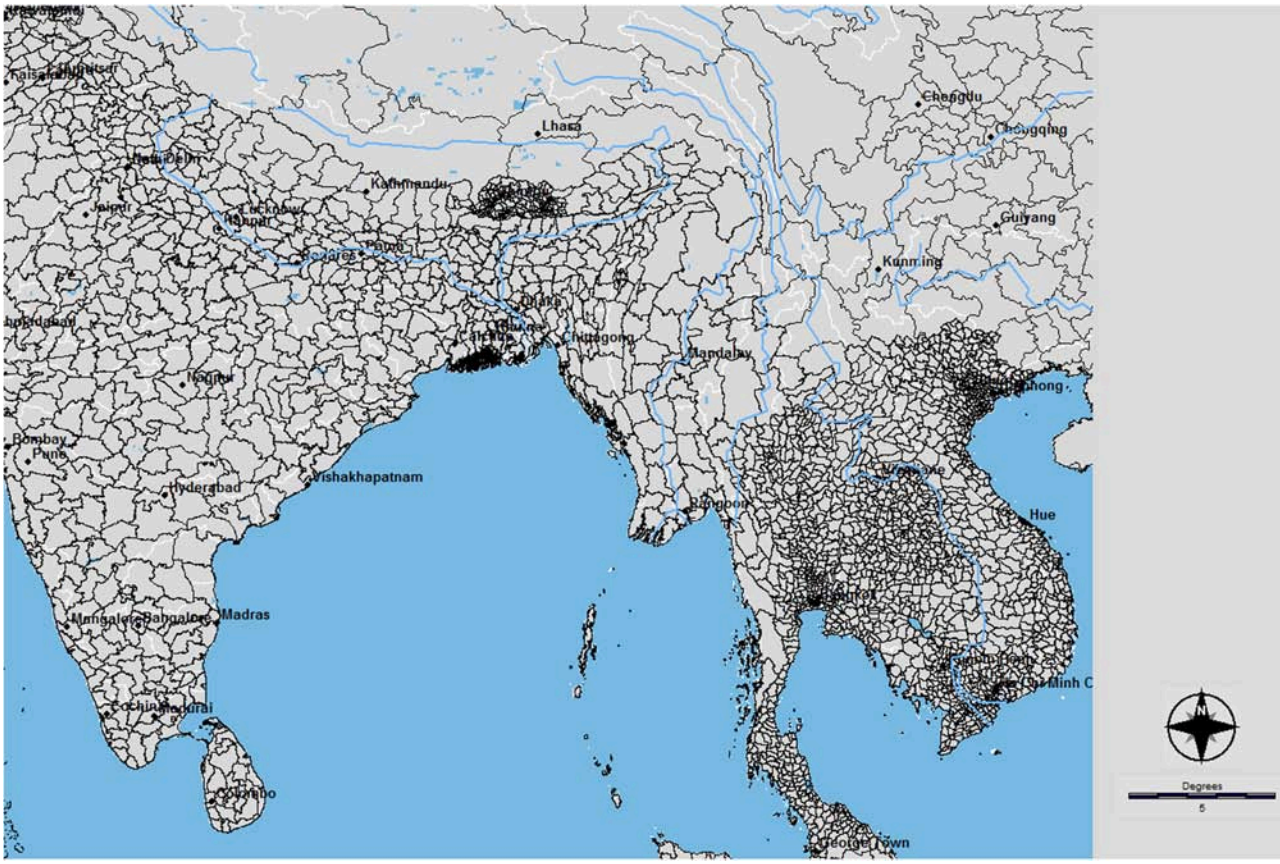

FIGURE 2 | FAO Global Administrative Unit Layer (GAUL) Level 2.

withdrawal for agriculture and other sectors are extracted from recent national statistics shown in **Table 3**.

An important caveat we would like to stress here is that the data used for this analysis, both the SSP and the LUMIP projections, are result of global scale modeling exercises affected by a certain degree of uncertainty. As stressed in the literature presenting the results of those projects (Lawrence et al., 2016; Riahi et al., 2017), the number of models used for the production of these datasets is relatively limited, and the observed data use for their calibration and validation rather scattered over space and time. Moreover, the future outcomes of current climate change adaptation and mitigation policies, or the lack of effective strategies, are likely to change the socio-economic conditions that have been hypothesized for the scenarios here utilized (Prestele et al., 2016). The uncertainty brought to the analysis presented in this paper by the use of these data is rather difficult, if not impossible, to estimate.

Assessment of Nexus Between Water and Agriculture

Given that the purpose of the work is to make use of freely available spatial information, in order to explore the nexus between water use for economic purposes in general and food production, we acquired the results of the most recent projections of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP2b) (Frieler et al., 2017).

The rationale behind the approach developed here is that having assessed the current status of economic uses of water, the strategies to be implemented to improve WUE should be tailored to the local situation in terms of: (i) potential for future economic development in general, i.e., GDP changes between future (2030) and current period; (ii) potential for future development of irrigated agriculture, in terms of changes of potential irrigation withdrawal between future (2030) and current period; and (iii) estimated future availability of water resources, using as a proxy the estimated runoff volume. Runoff volume can be considered a good indicator of the surface components of the locally generated blue water resources that, however, is limited in capturing the amount of resources flowing from upstream and fails to account for stocks of groundwater resources.

Depending on current levels of value added generated by water withdrawals and on what emerges from future scenarios (in terms of development, irrigation expansion and water availability), competent administrations can identify promising strategies for the achievement of the SDGs. For example, in areas with relatively low level of current development, but with great future potential, strategies would depend on expected water availability. They could be oriented toward infrastructural

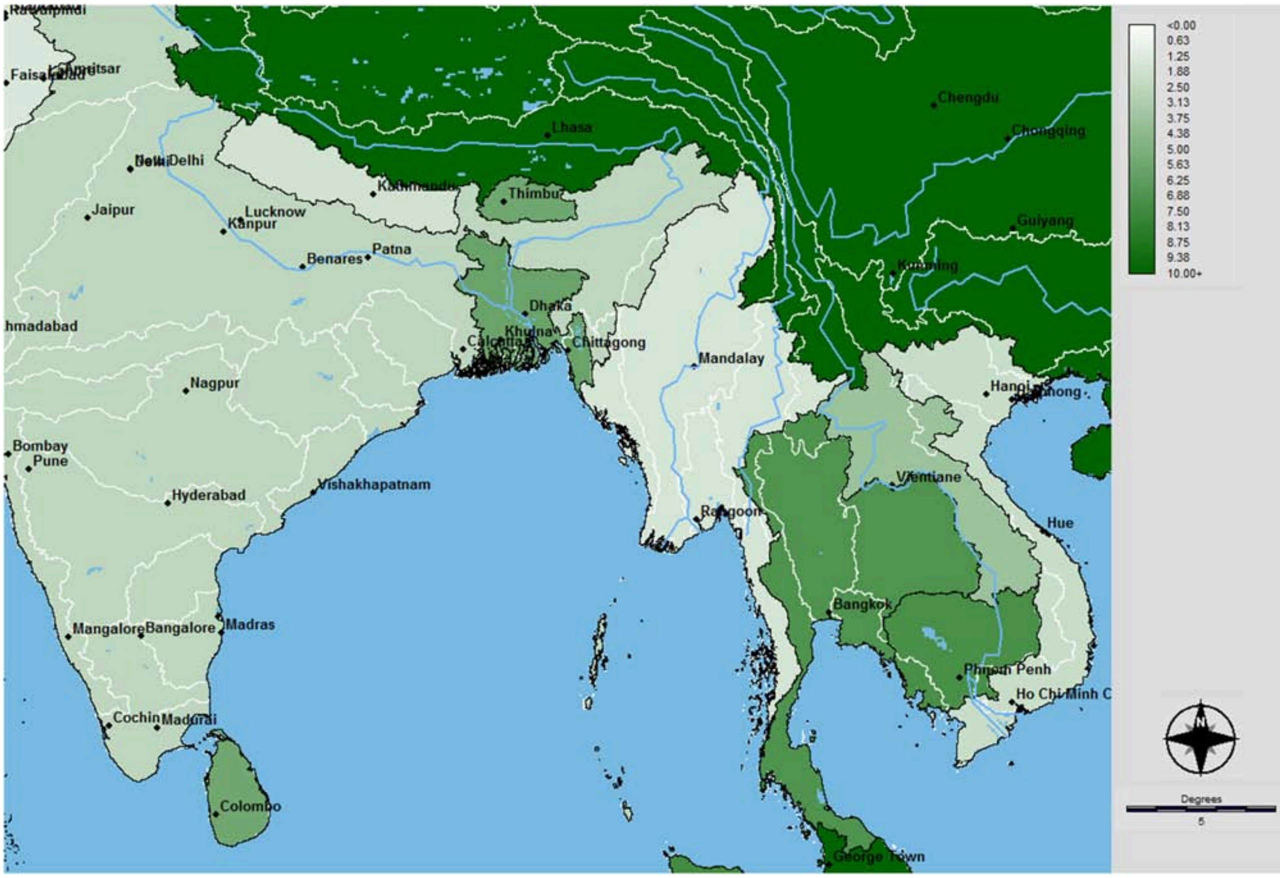

FIGURE 3 | Water use efficiency (US$ m^{-3}): current national average values of countries included in the frame of the study area.

investments, in case of high availability of water resources, or toward investments for improving the efficiency per cubic meter of water, when expected availability of water resources is low.

A very preliminary exercise of zoning in support of policy design was thus carried out by using an ISODATA cluster analysis technique (Iterative Self-Organizing Data Analysis Technique), which is a consolidated k-clustering method used for identifying land classes from stacks of multiple images in remote sensing studies (Johnson and Wichern, 2007; Richards, 2013). The map of ISODATA clusters provides a synthesis of multivariate spatial variability of the most important variables characterizing current and future WUE in the region and can be considered as a preliminary support for the identification of a series of different zones characterized by relative internal homogeneity, thus requiring different approaches in terms of policies and measures for the achievement of Target 6.4.

For assessing GDP changes, we calculated the ratio of GDP values between 2030 and current period. Similarly, the ratio of potential irrigation water withdrawal has been calculated between the values of 2030 and those of 2016. Given that runoff estimations varied a lot across the studied area, but showed only limited spatial changes in the comparison between future projection and current estimates, we preferred to use the map of future projections in the ISODATA procedure than calculating the ratio with current values.

We have considered yearly agricultural water withdrawal data for multi-model-mean of four General Circulation Models (GCMs) [GFDL-ESM2M (Donner et al., 2011), HADGEM2-ES ((Bellouin et al., 2011; Collins et al., 2011)), IPSL-CM5A-LR (Dufresne et al., 2013), MIROC5 (Watanabe et al., 2010)] under two climate scenarios (RCP 2.6 and RCP6.0) from global hydrologic model, H08 (Hanasaki et al., 2018). In order to account for inter-annual variability, water withdrawal data are calculated based on 10 years average: current period 2015 represents average yearly value of 2011–2020 and future (2030) value by averaging yearly value of 2026–2035.

RESULTS

Country Level Water Use Efficiency

The current WUE values per country, calculated with the most recent information available in the databases reported in **Table 3** is shown in **Figure 3**.

The country level results of WUE as shown in **Figure 3** are in line with those produced by international organizations (UN-Water, 2018). Only very simplistic comparisons can be derived

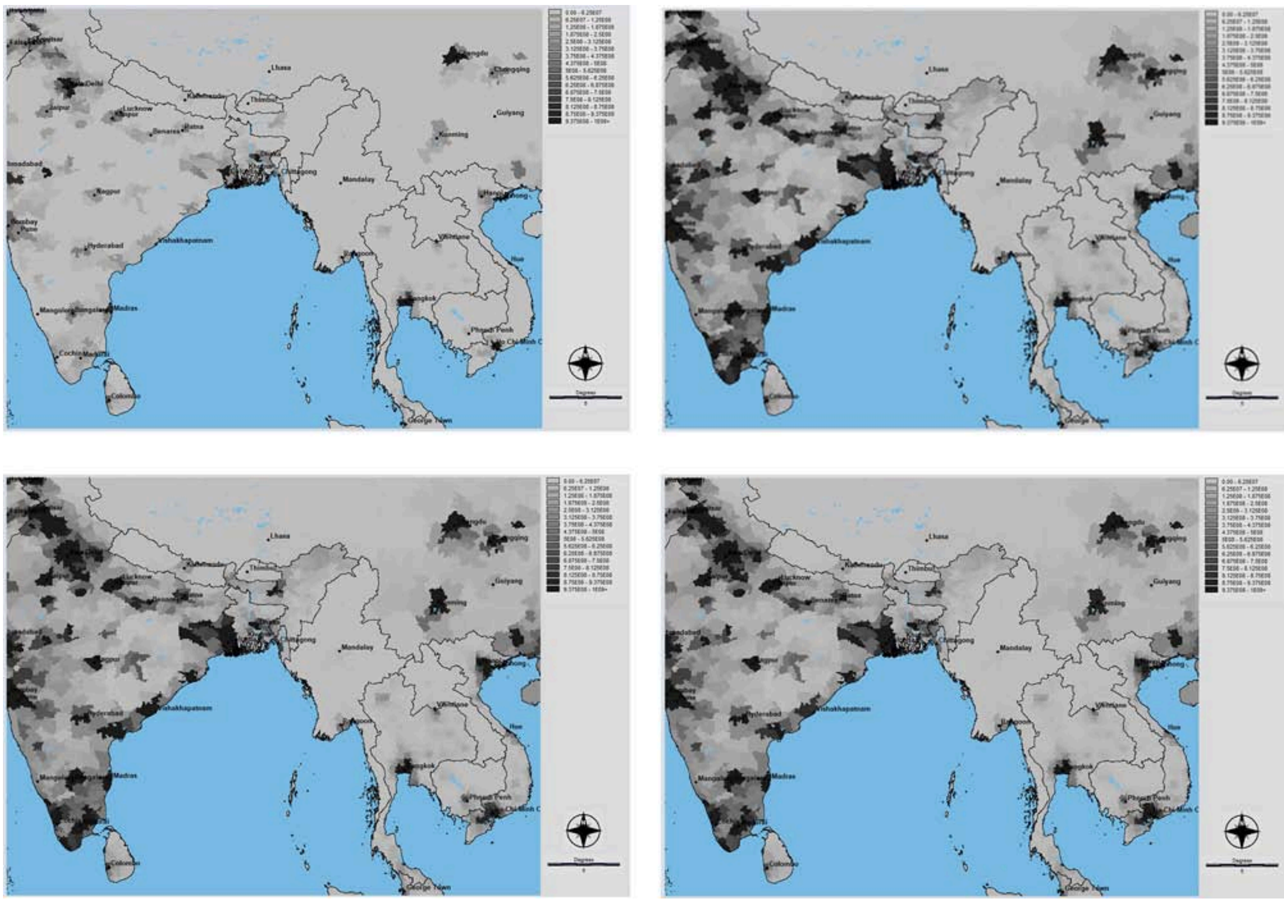

FIGURE 4 | Current GDP (top left) and projected GDP per administrative units (FAO GAUL2) in US$ per pixel (∼80 km^2): SSP1 (top right) SSP2 (lower left) and SSP3 (lower right).

from the map: e.g., the relatively high value of China, or the relatively lower value of Nepal. Evidently, values averaged at national level are too aggregated and do not present any regional and local variations and hence, there is no information useful for the analysis of the cause-effect links of the phenomena that produced such results, and thus no sound basis for the development of strategies for improving current values to meet Target 6.4, by country or regional governments. Therefore, the assessment of WUE should go beyond country boundaries, with a spatial detail that allows the identification of the combination of environmental and socio-economic drivers, determining the current situations in terms of WUE. Moreover, future projections are needed to compare the current situation with possible future trajectories of those drivers, thus being able to anticipate possible future developments and to design robust policies in view of future scenarios.

Spatial Analysis of WUE

Following the procedure concisely described above, we first mapped GDP values at 0.5° resolution from the Carbon Project as at FAO GAUL 2 level for current period and for three scenarios of SSPs of the future period of 2030. The results of aggregating GDP values at the GAUL 2 level are reported in **Figure 4**, showing, in general, projected increases in GDP for the studied area, independently from the SSP scenario, but with some differences in the allocation of economic activities moving across the SSPs.

Considering the most recent statistics on water withdrawals (agricultural, industrial and domestic) and disaggregated GDP into irrigated agriculture and built-up areas as described above, the current value added of water (in US$) at the GAUL2 has been assessed. The spatial allocation of WUE for Southeast Asia is shown in **Figure 5**. The high value of WUE (represented through deep magenta color in **Figure 5A**) is shown mainly in built-up areas where industry and urban centers are located, while intermediate levels of water value added are found in irrigated agricultural area (see also **Figure 5B,C** for more details). By comparing **Figure 5** with **Figure 3**, the potential of accurate spatial analyses clearly emerges. **Figure 4** shows all the areas in which current human activities are generating value added from water withdrawals. These are areas where policy interventions to improve WUE required by SDG Target 6.4 should find priority implementation.

Having identified the priority areas, the need emerges to identify which policies to implement, taking into consideration

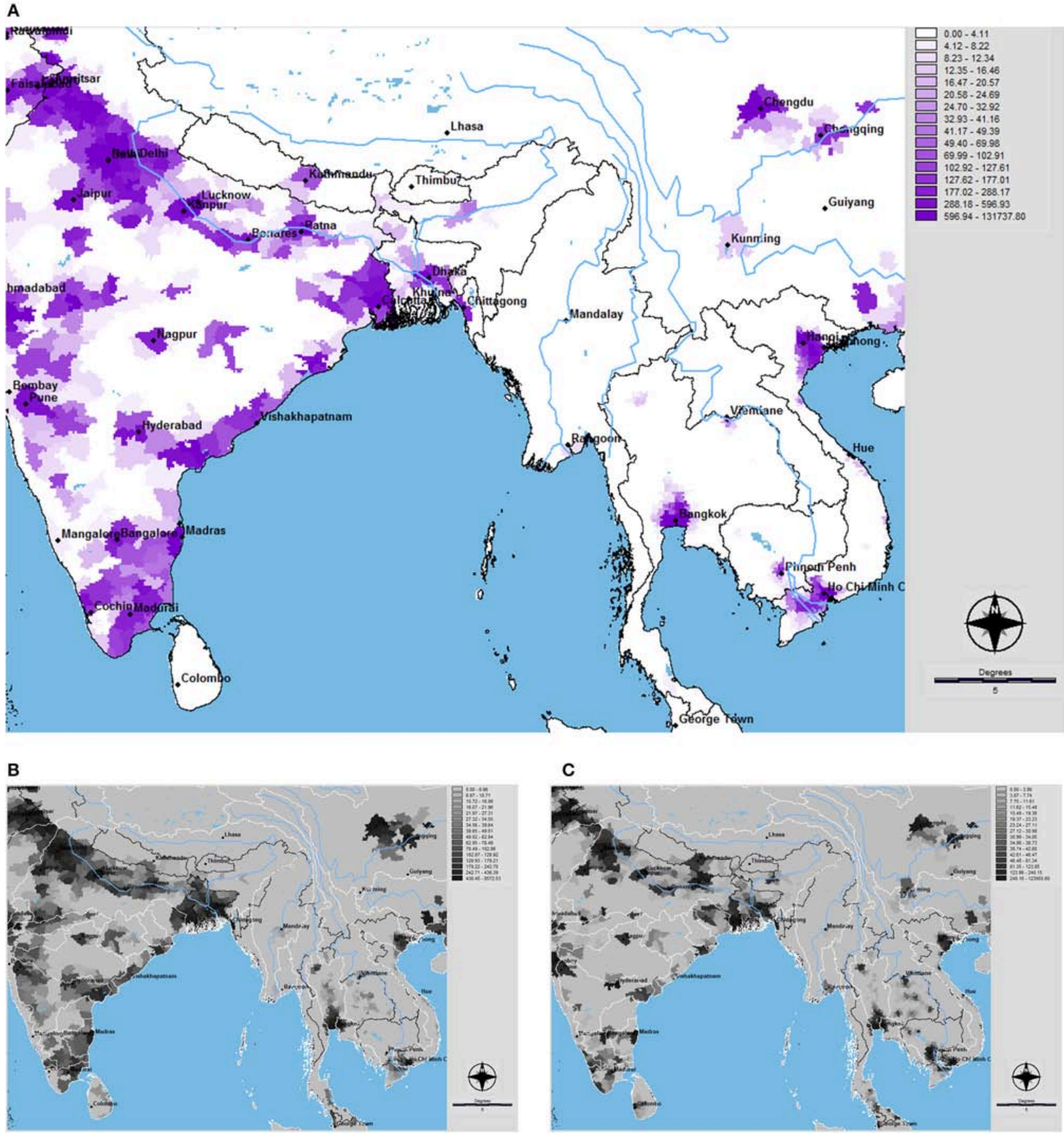

FIGURE 5 | Top **(A)**: Current value added generated by water (in US \$) per pixel (~80 km^2) at the GAUL 2 level of administrative units; bottom left **(B)**: value added from the agricultural sector; bottom-right **(C)**: value added from industrial and service sectors.

the relationships among water intensive economic activities and other environmental and socio-economic dynamics. Here, the nexus between food production–and more specifically food produced with irrigated agriculture, and other uses of water is of greater relevance. In terms of value added per unitary volume of water, the primary sector cannot compete with the secondary and tertiary ones, but strategic decisions should be taken at policy level to rule the emerging trade-offs and conflicts and exploit potential synergies, with the aim of maximizing the benefit for society as a whole.

As stated before, the policy options to be implemented will depend on how social and ecological systems will evolve

TABLE 5 | Average values of clusters.

Cluster	Current A w.e. (US$ per grid cell)	Current I + S w.e. (US$ per grid cell)	Future estimated runoff (mm yr^{-1})	Ratio of future vs. current potential irrigation withdrawals	Ratio of future vs. current GDP
1	53.1	17.4	96.1	0.472	4.767
2	12.2	8.9	1,739.6	0.983	3.459
3	633.6	3,994.6	535.1	1.010	4.118
4	38.7	15.3	641.9	0.962	4.184
5	23.3	6.5	333.8	0.919	4.263
6	23.2	11.9	1,043.1	0.996	3.969
7	7.9	6.0	2,699.0	0.921	3.596
8	746.9	9,565.4	705.1	1.061	4.292
9	5430.0	103,631.6	338.4	1.003	3.006
10	1969.2	35,625.4	627.1	1.010	4.400

FIGURE 6 | Results of ISODATA classification: normalized average values of the 10 clusters.

in the future. In this work, we considered future projections of economic growth, the expected development of irrigated agriculture and the changes in water availability as three very important drivers for policy design in water management.

As previously stated, cluster analysis was chosen as a technique to identify areas with similar combination of current and future values of driving variables. By analyzing a stack of 5 images in ISODATA, we produced a map with the identification of typologies of areas that can be used as a preliminary zoning to support the development of water management policies in the region. The five images were current value added for the agricultural sector, the value added of services and industry, future water availability (using estimated runoff volumes as a proxy), the GDP ratio (between 2030 and current period) and the potential irrigation water withdrawal ratio (between 2030 and current period). The procedure was set to obtain 10 clusters showing interesting distinctive average features (see **Table 5** and **Figure 6** with the histogram of normalized values). The description of each cluster deriving for the different combination of the five independent variables is shown in **Table 6**, while **Figure 7** shows the spatial distribution of the clusters. Indeed, the clusters produced by the ISODATA procedure depend on the specific geographical frame of analysis. With a different frame, but also with different parametrization the results will not be the same. However, the analysis of sensitivity for exploring the effects of variations on ISODATA inputs demonstrated that the main

TABLE 6 | Identification of clusters.

Cluster	Description
1	Very low levels of value added from both agriculture and other sectors, with very low water availability and–in relative terms–expected future development in the non-agricultural sectors and decreasing irrigated areas (arid areas e.g., in Rajasthan, Tibet and south India, with grasslands and rainfed crops)
2	Very low levels of current value added in both agricultural and non-agricultural sectors, as Cluster 1, but with relatively high water availability and thus expectations for future developments in particular in irrigated agriculture (forest areas scattered across the region under the influence of monsoons)
3	Low levels of value added from both agriculture and other sectors, with relatively low water availability and expectations for rather high future developments in particular in irrigated agriculture (small periurban areas)
4	Very low levels of value added from both agriculture and other sectors, with relatively low water availability and expected future development (in relative terms) in both agricultural and non-agricultural sectors (very large areas with mainly rainfed agriculture and forests)
5	Very low levels of value added from both agriculture and other sectors, with low water availability and expected future development (in relative terms) in both agricultural and non-agricultural sectors (very large agricultural areas with crops and grasslands located between cluster 1 and 4)
6	Very low levels of value added from both agriculture and other sectors, with limited water availability and expected future development (in relative terms) in both agricultural and non-agricultural sectors (large areas with high presence of forests)
7	Very low levels of value added from both agriculture and other sectors, with very high water availability and limited expected future development (mainly forests in areas close to cluster 2)
8	Rather low levels of value added from both agriculture and other sectors, with low water availability and expected high future development in the agricultural sector and not only (areas close to main cities)
9	Very high levels of value added from both agriculture and other sectors, with low water availability and expected future development only in the agricultural sector (small areas close to Delhi and Bangkok)
10	Rather high levels of value added from both agriculture and other sectors and further expectation of future development (areas around main cities)

typologies of zones concisely described in **Table 6** remain rather stable.

The results of cluster analysis briefly described in **Table 6**, point out at least three macro-areas that should be subject to different policies. Cluster 2 and 7, are mainly forested and with limited future needs of investments in water infrastructures given the current status and future prospect of availability of water resources and land uses. Cluster 1, 3, 4, 5, 6, 8 are areas of potential future development, where improvements of WUE are to be considered as a priority to avoid conflicts over water resource allocation among different economic sectors. Cluster 3 and 8 are in a peculiar situation, since they are mainly located close to very important urban areas, as are Cluster 9 and 10, where the demand and the potential value added of water are high and so are potential future conflicts for water resource allocation between agriculture and other sectors.

The uncertainty associated with the various input layers should be carefully considered, taking into account the spread of the values of the same variables in various locations. For example, scenario maps of potential irrigation withdrawals vary more in areas of active development, such as the Indo-Gangetic plain, while GDP estimation varies a lot with changing scenarios in built up areas. The robustness of proposed policies will depend on their capabilities to maintain their benefits even with varying future contexts.

CONCLUSIONS

Agenda 2030 imposes huge challenges to governments all over the world in their efforts to identify the most effective strategies and implementation measures for achieving the numerous goals and targets. These challenges are particularly strong for those countries with lower resources and more limited data. Considerable efforts have been invested by international institutions and UN agencies for facilitating the identification and access to data sources with global coverage. UN Water launched an Integrated Monitoring Guide for SDG 6 and released a series of step-by-step monitoring guidelines[4], for monitoring the various indicators, in which data sources at national level are identified. Unfortunately, the quality of available information is often not adequately documented by metadata, thus making an accurate assessment of uncertainty practically impossible as it was in this case. Moreover, the available country statistics presented are referred to different years and time series are very limited, making historical dynamic analyses impossible in vast parts of the world.

In parallel to those efforts focused on national statistics, a wealth of coordinated modeling efforts are in progress to support climate change studies and policy analyses. Here we took advantage of the Land Use Model Intercomparison Project (LUMIP) (Lawrence et al., 2016), set up for the forthcoming Coupled Model Intercomparison Project Phase 6 (CMIP6) (Eyring et al., 2016) and the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP2b) (Frieler et al., 2017). While it is evident that modeling efforts cannot replace data limitations, it seems also evident that such coordinated efforts developed upon shared scenarios and common assumptions represent a great opportunity in particular for less developed countries. In particular, they make freely available state of the art historical simulations and future projections with global coverage, which allows for global, but also regional synoptic analyses across country boundaries (e.g., transboundary river basins) with unprecedented spatial detail.

In this work we attempted the integration of available statistics with those recently released global datasets, considering that the combination of the two can substantially improve monitoring and analyses based only upon country statistics. Very importantly, the use of spatially disaggregated future projections is a prerequisite for moving from SDG monitoring, to policy support for the achievement of the Goals. The identification of effective policies is impossible without having the capability to make projections into the future, but not necessarily

[4]See http://www.unwater.org/publications/integrated-monitoring-guide-sdg-6-2/

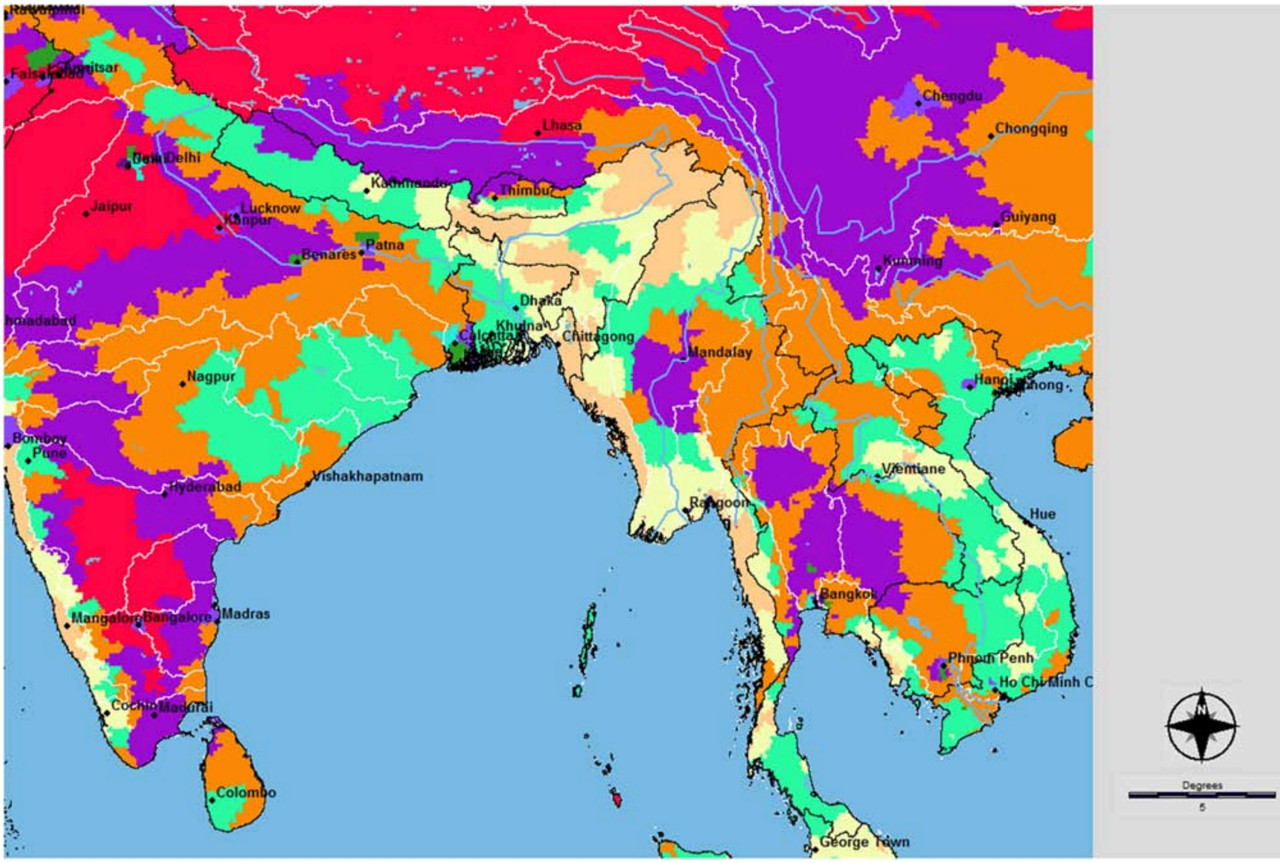

FIGURE 7 | Results of cluster analysis with five variables, to guide the identification of water management policies.

developing new models, particularly when the ambition is to explore operational solutions to current and emerging water management issues, at regional and sub-national levels, in areas where national statistical systems are less developed, as in most of developing countries.

Official documents and guidelines ask for country scale assessments, but instead the emphasis should be placed on detailed spatial analysis brought to a level of detail which allows for understanding of the mechanisms behind observed situations and thus also for the design of targeted policies to improve the current status. The first step in policy development consists in the acquisition of the information needed to develop a knowledge base, organized through a long series of indicators, but assessment procedures should go beyond national level aggregation and zoom into sub-national phenomena. Spatially explicitly future scenarios are needed to design sustainable development policies, with the required medium to long term perspectives. The proposed approach goes in that direction, while being still consistent with the approach proposed at country level by the custodian agencies, to allow for both monitoring and reporting the progress toward the meeting of the SDGs with international coordination and for supporting the identification of targeted policy measures needed at local level.

The approach is demonstrated in South and South-East Asia, an area of great relevance in addressing open issues related to sustainable development and the assessment of the indicator 6.4.1 (Change in water use efficiency), which better exemplifies the integration of socio-economic and environmental issues. Moreover, cluster analysis applied to both current estimations and future projections allows a comparison of the current state of the WUE indicator (SDG6) with future prospects of agricultural and non-agricultural development (SDG 2; 8 and others), and changes in water availability (SDG 15). For example, it allows for the identification of territorial ambits to guide tailored water management policies, with consideration of their linkages to other policy contexts, and thus also other SDGs.

Indeed, this work is focused on a single indicator, without explicit assessment of its interlinkages with others, but the calculation of Water Use Efficiency is in fact focused on the analysis of the nexus between water resources and different economic sectors, agriculture and food production in particular. Strong interlinkages are evident with several targets. In particular target 2.4 on sustainable agricultural systems, of which we analyzed the use of water for irrigation, 6.5 for the contribution of efficient water management across sectors to Integrate Water Resources Management (IWRM) policies, and 15.1 focused on the status of freshwater ecosystems. Some of the input data used for the assessment of target 6.4 can be used for the assessment of other indicators, and the flow chart designed for this work can be easily expanded to include the calculation of other indicators.

Although the kind of analysis that we proposed provides concrete support to the policy making, important limitations are still in place and should be clearly discussed. First of all, the use of modeling outputs especially in areas characterized by limited data availability is certainly a huge advantage, but, at the same time, it brings levels of error and uncertainty that are difficult to estimate and are likely to affect the conclusions of the presented and similar analyses. In this work, uncertainty has been dealt with only by means of sensitivity analysis to explore the effects of varying inputs to the final territorial clusters for policy support, obtaining results which showed limited effects on the identification of clusters. Nevertheless, further research efforts are needed to assess the uncertainty levels brought, respectively, by input data and modeling options, in order to provide an accurate estimation of the robustness of the results. Ideally, data uncertainty could be limited by a more detailed monitoring campaign that the custodian agencies should pursue: the first step toward this direction was represented by the identification of a clear set of indicators, but the course taken will surely be costly and hardly free of impediments.

The approach in this paper should be intended to be a procedure for capitalizing on existing information, applicable in different parts of the world, such as South and South-East Asia, selected in this application for the relevance of open issues related to sustainable development, but also for demonstrating the feasibility in regions with strong limitations in data availability. The same procedure (see **Figure 1**) can be easily applied to the rest of the world, even though accuracies will vary depending on the uncertainties in the input data. Cluster analysis should be carefully reconsidered at global level, for example by revising the number of clusters, in order to obtain meaningful results.

In the near future, this approach will substantially benefit from the continuous flow of new spatial information made available by the intercomparison modeling exercises mentioned above and by improved statistics. Even more, the zoning proposed here could benefit from *ad-hoc* integrated modeling exercises, but that would increase time and financial resources needed by orders of magnitude.

DATA AVAILABILITY STATEMENT

The datasets utilized as inputs for this study can be found in the repositories and links identified in the article above (see **Table 3**, in particular). Intermediate and final results, including data sets, maps and the macro file will be made available by the authors to any qualified researcher.

AUTHOR CONTRIBUTIONS

CG designed the methodological framework and conducted GIS analyses. FF and AG contributed to the development of the methodology and collected raw data. The three authors jointly wrote the article.

ACKNOWLEDGMENTS

AG is financially supported by the cluster of excellence, The Future Ocean, funded by the German Research Foundation, whose support is gratefully acknowledged.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Environmental Science

ORIGINAL RESEARCH
published: 26 November 2018
doi: 10.3389/fenvs.2018.00133

A Conceptualization of the Urban Food-Energy-Water Nexus Sustainability Paradigm: Modeling From Theory to Practice

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OPEN ACCESS

Edited by:
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Specialty section:
This article was submitted to Freshwater Science, a section of the journal Frontiers in Environmental Science

Received: *20 May 2018*
Accepted: *24 October 2018*
Published: *26 November 2018*

Citation:
Schulterbrandt Gragg R, Anandhi A, Jiru M and Usher KM (2018) A Conceptualization of the Urban Food-Energy-Water Nexus Sustainability Paradigm: Modeling From Theory to Practice. Front. Environ. Sci. 6:133. doi: 10.3389/fenvs.2018.00133

Food is the essential foundation for sustainable and healthy communities. Increasing population and urbanization, limited resources, and complexities of interactions necessitate a comprehensive and in-depth understanding of the dynamics of the global trend of urbanization. The key objective of this paper is to generate new environmental, social and economic perspectives and practices that are responsive to the rapidly urbanizing agricultural food system. We used the sustainability paradigm in the context of environmental, social, and economic sustainability to outline the three transitioning states and perspectives (unconnected/silos; interconnected/linkages; and interdependent/nested/systems) for urban agricultural food systems. We sought to ferret out the key driver/response variables and their cross-scale interactions in the urbanizing food-energy-water nexus. We used a five-step qualitative analytical method to develop a conceptual model to capture the interacting variables and their responses. The complexity in the driver/response variables and their cross-scale interactions were identified. Then three hypothetical scenarios were used to represent complexity modeling: least, medium and most complex. These variables were combined with outside dimensions (e.g., innovation, stakeholders, urbanization) for selected scenarios and deconstructed using *spider web* and *causal loop* models. The urbanizing socio-ecological systems, across various spatial (local to global) and temporal scales (days to millennium) as well as smaller temporal scales (days to decades) are described. The iterative multidimensionality of the model makes clear new ways of seeing social issues and opens opportunities for policy solutions, resources and stakeholders to be brought to bear on the issues.

Keywords: urban food, energy, water nexus, drivers/responses, sustainability paradigm, cross-scale interactions

INTRODUCTION

The worldwide trend of urbanization, characterized and shaped by socioeconomic behaviors is rapidly evolving and transitioning the urban space that is predicted to encompass 66% of the global population by 2050 compared to the present 54% (UNDESA, 2012; Dupont Advisory Committee, 2016; Richards et al., 2016). This trend is most evident in emerging markets of Africa, Asia and Latin America and presents myriad challenges and opportunities to address food and nutrition security impacted by changes in lifestyles and consumption patterns; income and population growth; and the fast-paced diversification of diets in developing countries (Richards et al., 2016). In order to feed these larger, more urban and economically diverse populations, food production must increase by 70%. The current consensus is that the world will likely exceed 9 billion people by 2050 and is unlikely to stabilize in the 21st century (Gerland et al., 2014), requiring 70–100% more food production (Tscharntke et al., 2012). Even the most optimistic scenarios require at least a 50% increase in food production (Horlings and Marsden, 2011). The availability of freshwater resources for the required production shows a similar picture. An increasing number of countries are reaching alarming levels of water scarcity creating social, economic and environmental opportunities to increase water use efficiency, quantity, quality, availability as well as adaptive characteristics (Reardon et al., 2016; Richards et al., 2016). Another emerging challenge with urbanization is the rising energy prices and the use of agricultural feedstock for biofuels, causing additional scarcity on markets for food and feed (Conforti, 2009).

Twelve percent of the world's urban population currently resides in megacities with population of more than 10 million inhabitants. By 2030 China and India will host seven and Africa will host six megacities (Dupont Advisory Committee, 2016; Reardon et al., 2016; Richards et al., 2016) urban and regional planning The notion that food production is an exclusively rural activity is negligent of the significance of urban agriculture, a continuous and ongoing activity in the cities and towns of the Global South. In the Global North food production is in the process of re-institutionalizing itself where urban planners, social entrepreneurs and technology innovators are re-imagining "the city as a farm" (Howard, 1898, 1902; Brown and Carter, 2003; Lyson, 2004; Morgan, 2009; Ikerd, 2017).

The urban socio-ecological system that is being driven by multiscale and multilevel factors and trends is actively responding to/engaging the self-organizing, transformative and resilient properties of food and nutrition systems (Magigi, 2013; Majowicz et al., 2016; Smit, 2016; Ikerd, 2017). The primary socioeconomic driver/response factors concurrent with increasing food-energy-water demands are population growth, rising incomes and urbanization (Patel, 2007; Conforti, 2009; McMichael, 2009; Holt-Giménez and Shattuck, 2011; Reardon et al., 2016; Richards et al., 2016). Additional factors include systems integration, urban and regional planning and design and technological innovations, social entrepreneurship, issues of access, environmental change, and low-wealth populations (Ernst and Young, 2015; Reardon et al., 2016; Richards et al., 2016).

Potential factor and trend outcomes of sustainably engaging food-energy-water nexus and nutrition systems include environmental, social and economic impacts. Environmental impacts include reducing urban heat island effects; mitigating stormwater impacts; lowering energy use by reducing the need for food transport; reducing urban waste streams through composting of urban organic waste (Allen and Wilson, 2012; AboElata, 2017). Social impacts include public policy, promoting paradigm shifts in environmental consciousness and awareness, reducing environmental health disparities, formation of local and regional food movements as well as food policy councils (Sumner et al., 2010; Majowicz et al., 2016). Economic impacts include access to affordable, healthy and nutritious foods, clean and safe water and access to renewable energy sources (Pothukuchi et al., 2007; Waffle et al., 2017). Food hubs and incubators provide living wage jobs for community development and resilience (Reardon et al., 2016; Richards et al., 2016; Juncos A. E., 2017).

According to Kahn's elaboration of Agenda 21 (Basiago, 1999), the paradigm of sustainable development rests on the three conceptual pillars of economic, social and environmental sustainability. "Only by 'integrating' and 'interlinking' economic, social and environmental 'sustainability' can negative synergies be arrested, positive synergies fostered and *real* development encouraged. Economic, social, and environmental sustainability form elements of a dynamic system (McClintock, 2010). They cannot be pursued in isolation for 'sustainable development' to flourish" (Basiago, 1999). We observe that in the context of environmental, social, and economic sustainability, urban food and nutrition systems are simultaneously transitioning between states and perspectives of unconnected/silos (**Figure 1A**); interconnected/linkages (**Figure 1B**); and interdependent/nested/systems (**Figure 1C**), (Hembd, 2014). Essentially urban space or the built environment is evolving to fully mimic and integrate the natural system in action (McClintock, 2010; Kenyeres, 2017).

The purpose of this paper is to conceptualize the rapidly transitioning and evolving urban agricultural food and nutrition system (**Figure 8**). The model will generate new environmental, social, and economic perspectives and practices that are responsive to the rapidly urbanizing agricultural food system. This in turn will enhance our understanding of the dynamics of the key driver/response variables in the food-energy-water nexus under the sustainability paradigm.

METHODS

We followed the following steps to develop a conceptual model for the urbanizing food-energy-water nexus based on the economic, social and environmental sustainability paradigm (**Figures 1A–C**).

Step 1: Schematic of methodology followed in the study and review existing conceptual models from literature and what's trending agriculturally (**Figures 2**, **3**, respectively).
Step 2: Develop spider web diagrams (**Figure 4**). Spider web diagrams show the scale and level interactions of multiscale and multilevel factors and trends due to feedbacks between

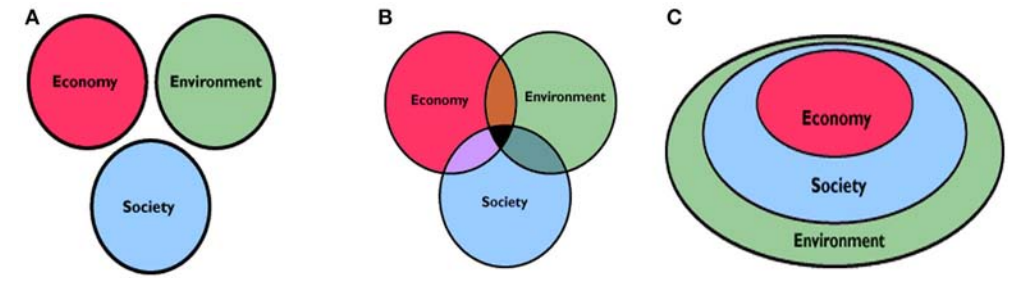

FIGURE 1 | Transitioning between states and perspectives for urban food and nutrition systems in the context of environmental, social, and economic sustainability, **(A)** unconnected/silos; **(B)** interconnected/linkages; **(C)** interdependent/nested/systems (Hembd, 2014).

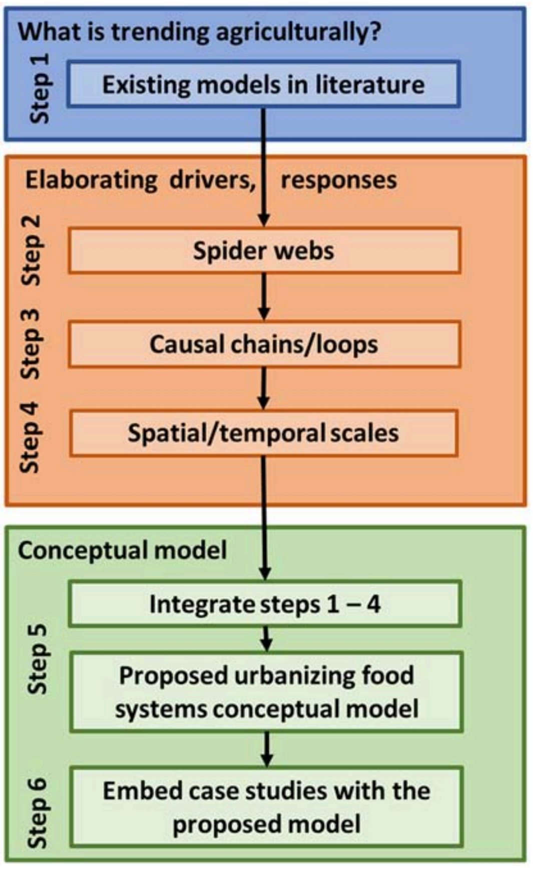

FIGURE 2 | Schematic of methodology followed in the study.

driver and response variables in the context of unconnected; interconnected; and interdependent nested sustainability scenarios.

Step 3: Develop causal chain and loops diagram (**Figure 5**). Causal chain is a finite ordered sequence of actual events in which any one event in the chain causes the next (Menzies, 2017). Causal loop is when an event in the chain causes an earlier event in the chain then the loop developed is referred to as causal loop (Bures, 2017). Describing the causal chain from driving forces to impacts and response is a complex task, and needs to be broken down into sub-tasks (Kristensen, 2004). These diagrams explain the cause and effect behavior from the systems (e.g., ecosystems) standpoint to assess the impacts of climate change on multiple ecosystems.

Step 4: Develop interactions across spatial, organizational, and temporal scales (Cash et al., 2006). This schematic diagram (**Figures 6**, **7**) can be used to illustrate the dimensions of socioecological phenomena and the interaction of two human domains: microclimate research and regional energy/water management.

Step 5: Integrate steps 1–4 and develop, explain and discuss the conceptual model (**Figure 8**). The FEW nexus refers to intersections among food, energy, and water systems that have large impacts on natural resources (e.g., water, energy), on pollution and greenhouse gas emissions (GHG), and on the security of FEW supplies (availability, affordability, quality) essential to the well-being of the world's population (Ramaswami et al., 2017). Our model is housed in the sustainability paradigm.

Step 6: Embed case studies with the proposed model (**Figure 2**).

RESULTS AND DISCUSSION

What's Trending Agriculturally? (Step 1)

The adaptive capacity and resiliency of the agriculture and nutrition system along with its associated sectors in the food-water-energy nexus to ensure food and nutritional security for a growing global population is closely tied to improved stewardship of the transitioning urban-ecological system (Reardon et al., 2016; Richards et al., 2016). Major multilevel and multiscale reforms and investments are needed in city-region systems due to the increasing scarcity and degradation of land, water and biodiversity with the added pressures of rising incomes, climate change, and energy demands especially in developing countries (Conforti, 2009; Reardon et al., 2016; Richards et al., 2016). When we acknowledge food as the foundation for healthy and viable communities then we must consider and explore its broader social, economic and environmental impacts, connections and pathways (Reardon et al., 2016; Richards et al., 2016).

Urban agriculture is an evolving and complex activity "located within (intra-urban) and/or on the fringe (peri-urban) of a city or metropolitan region, which grows, raises, processes and distributes a diversity of food and non-food products, (re-)using largely human and material resources, products and services found in and around that urban area, and in turn supplying human and material resources, products and services largely to that urban area" (Mougeot, 2005, 2006; Dubbeling, 2013). These interactions are governed by multiscale/multilevel driver/response variables: dynamic, interactive, and spatial, temporal, jurisdictional, institutional, management, stakeholder network and knowledge (Grimm et al., 2000; Mougeot, 2005; Cash et al., 2006; Dubbeling and Merzthal, 2006; Golden, 2013; Koopmans et al., 2017).

One of the most encouraging trends is that the evolution and transition of the integrated urban agriculture food and nutrition system is rooted in community based action organizations and initiatives responsive to various socioeconomic drivers and impacts: i.e., urbanization; under-/over-nutrition; environmental justice; climate justice; health disparities; income and employment; and food-access especially amongst minority and low-wealth populations (Gragg et al., 1997, 2002; Sobal et al., 1998; Gee and Payne-Sturges, 2004; Hicken et al., 2011; White and Hamm, 2014; Posts and Campbell, 2017). Furthermore, these urban agricultural food system drivers are fostering collaborative, functional and transformative responses in the contexts of institutional interplay; co-management, boundary or bridging organizations and social entrepreneurship amongst stakeholders at various socioeconomic and intra-urban and peri-urban scales and levels (Lee et al., 2006; Sekovski et al., 2012; Gragg et al., 2015; Jessee et al., 2015). Results include but are not limited to: food-networks (Arndt et al., 2009; Allen, 2010; Koopmans et al., 2017); community-food gardens and farms (Lovell, 2010; Hirsch et al., 2016); urban agriculture and food systems planning; local, regional, national and global food systems; food-policy councils; treating the city as if it were an ecosystem in the urban planning and design process; "bioreactor-based, distributed manufacturing systems to close the urban, water, food, waste and energy loops, that fit seamlessly into the urban environment" (Coelho and Ruth, 2006; Ericksen, 2008; Padoch et al., 2008; Sterman, 2011; Armendáriz et al., 2016); rooftop gardening; indoor vertical commercial farming; food systems architecture; design; and tech innovation with many opportunities for enhancing food and nutritional security—and increasing productivity and down-stream, value-chain entrepreneurial opportunities—particularly with more efficient use of technology the interconnectivity of the cloud, ubiquitous cell phone coverage, uberization of goods and service—from mechanization, to urban cloud-kitchens to customer delivery (Lovell, 2010; Knizhnik, 2012; Fung and Jim, 2017) for the evolving integrated urban regional food and nutrition system (Alberti et al., 2003; Lovell, 2010; Dubbeling, 2013; Hirsch et al., 2016).

There are existing frameworks that utilize various multiscale and multilevel factors, trends and outcomes in urban social–ecological–technological systems. In these frameworks, factors such as disturbance have been observed as crucial drivers to different elements of these systems at different interactive scales and levels. It has long been recognized that disturbance as a concept applies to the coupled human and natural systems of urban environments (Peters et al., 2011; Grimm et al., 2017). The observed social and technological drivers and responders can contribute additional insights to disturbance research beyond urban systems. These integrated frameworks facilitate quantitative comparisons of disturbance effects on different types of ecosystems (Peters et al., 2011). Ramaswami et al. (2017), developed a generalizable systems framework and cross disciplinary approach in the analysis of the food-energy-water nexus from an urban ecosystems perspective. They also quantified multiple environmental impacts of community-wide FEW provisioning to cities, and visualized FEW supply-chain risks posed to cities by the environment using the supply-chain informed coupled water-, energy- and GHG footprints.

Spider Web and Causal Chain Diagrams (Steps 2 and 3)

To explain the conceptual model within a sustainability paradigm of the rapidly transitioning and evolving integrated urban agricultural food and nutrition (food-energy-water nexus) system, scale diagrams (spider and causal chains) are used as a way of showing complexity in the columns. Spider web diagrams provide a visual way of showing the three ways of sustainability paradigms with several trade-off criteria sets.

The urban food and nutrition system paradigm is rooted in Basiago's examination and advocacy of imaginative policies that any society must foster if it is to achieve "urban sustainability" (Basiago, 1999). As it pertains to urban agriculture, sustainability describes food and nutrition systems that are "capable of maintaining their productivity and usefulness to society indefinitely. Such systems must be resource-conserving, socially supportive, commercially competitive, and environmentally sound" (Gold, 2007; McClintock, 2010; Majowicz et al., 2016).

"As consumer diets change in more urban environments, the double burden of undernutrition and overnutrition continues to place a significant human and economic toll on cities in both developing and developed countries" (Dupont Advisory Committee, 2016). The co-evolution and integration of urbanization, urban design, urban and regional planning and agricultural food systems call for an understanding of these intersectionalities in the context of community-based participatory action, shared governance, information, innovation, human health and wellbeing, and a sustainable food energy water system (Grimm et al., 2000; Mougeot, 2006; Cassidy and Patterson, 2008; Allen and Wilson, 2012; Allen and Prosperi, 2016; Armendáriz et al., 2016; Koopmans et al., 2017).

In **Figures 4A–C**, the potential tradeoffs among eight different food system outcomes are shown in spider diagrams and are compared among three different hypothetical scenarios to inform the conceptual model. The scenario in **Figure 4A** exhibits the least complexity because of no cross-scale interactions between drivers. The unconnected silos of the food, water and energy system, production of food, sanitation and human health is least supported, resulting in least agricultural incomes and utilization

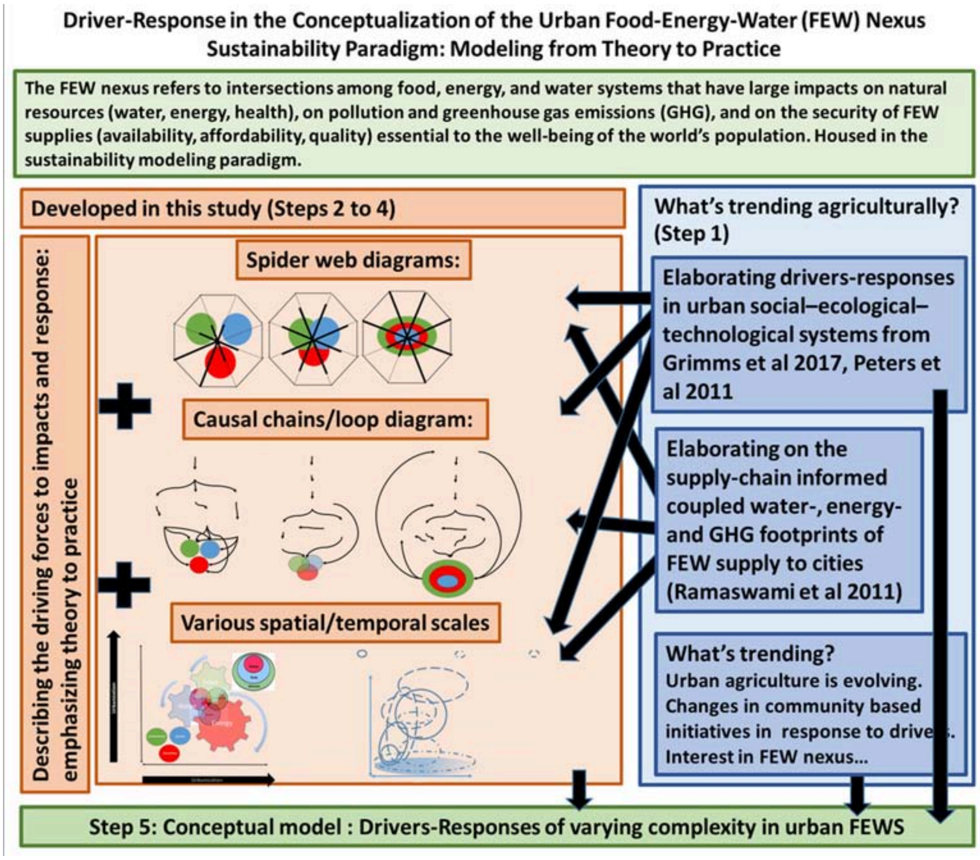

FIGURE 3 | Schematic that depicts the flow and connectivity between review of existing conceptual models from literature, what's trending agriculturally and those developed in this study (spider, causal chain/loop, spatial/temporal scale diagrams) that were used in developing the conceptual model. Methodology followed in the study (**Figure 2**) is elaborated here.

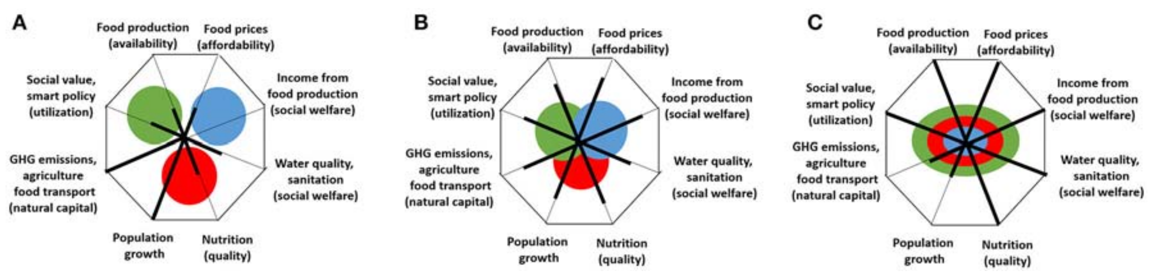

FIGURE 4 | Trade-offs among example environmental outcomes (GHG emissions), social welfare outcomes (income), food security outcomes and population growth for a given food system that have **(A)** no cross-scale interactions occurring between driver variables from broader to finer scales and levels with minimal multidimensional effects; **(B)** driver variables interactions across scales and levels; **(C)** cross-scale interaction due to feedbacks between driver and response variables. This figure is adapted from Ericksen (2008).

of social values. This leads to high food prices resulting in least affordability and low nutrition. Greenhouse gas emissions from agriculture and transporting food are highest (Musy et al., 2017).

The second scenario (**Figure 4B**) shows medium complexity because of cross-scale interactions between drivers and interconnectedness among the systems of food, water and energy. Food production, sanitation and human health are midway supported, resulting in medium agricultural incomes and utilization of social values. This leads to medium food prices resulting in midway affordability and nutrition. Greenhouse gas emissions from agriculture and food transportation are also medium (Satterthwaite et al., 2010).

The third scenario (**Figure 4C**) is the most complex because of cross-scale interactions between drivers and

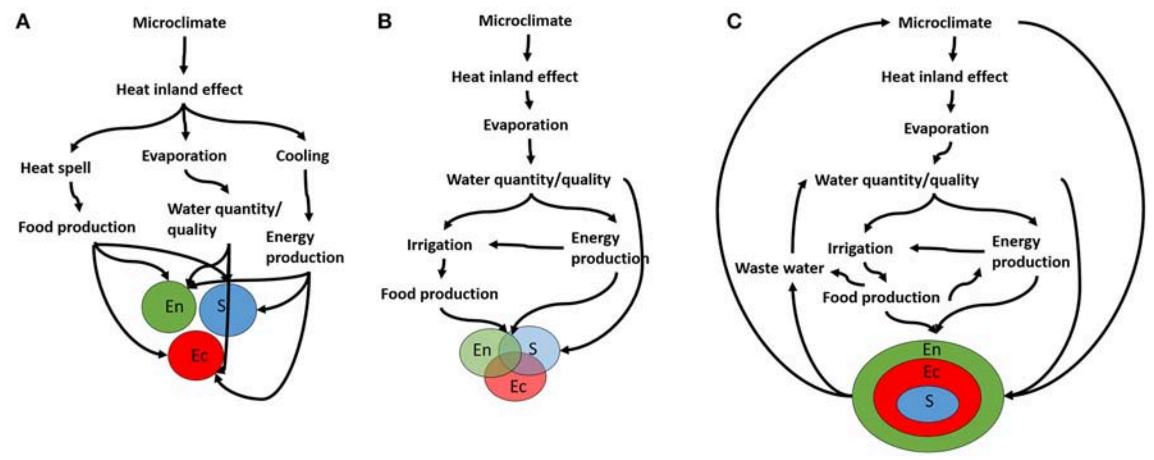

FIGURE 5 | Example causal loop shows the complexity in the columns as well as combining it with outside dimensions for the three scenarios. Examines three causal chain and loop scenarios. **(A)** The output is the microclimate temperature changes affect the food system and impact crop yield and food production; **(B)** The output is the integrated socio-ecological food-energy-water system; **(C)** The response from the FEWS affects the causal chains through feedback or causal loops. In the figure, acronyms En, S and Ec represent environment, society and economy, respectively.

interdependent/nested systems of food, energy, and water nexus. Food production, sanitation and human health are most supported, resulting in highest agricultural incomes and utilization of social values. This leads to lowest food prices resulting in highest affordability and nutrition. Greenhouse gas emissions from agriculture and transporting food are also lowest (Meybeck and Gitz, 2017). The population growth is assumed to follow the urbanization trend (UNDESA, 2012; Dupont Advisory Committee, 2016).

The multifunctional character of the urban socio-ecological system has profound effects on a host of other sectors—including public health, social justice, food, energy, water, land, transportation, economic development and innovation (Moragues-Faus and Morgan, 2015; Armendáriz et al., 2016; Dupont Advisory Committee, 2016); responsive to globalization, urbanization and national, regional, and local food system dynamics. Beyond its nutritional value, food can frame "multilayered challenges" in urban environments while providing an integrative foundation for diverse stakeholders to collaboratively address social, environmental and economic problems in the creation of just and sustainable cities (Dubbeling and Merzthal, 2006; Gottlieb and Joshi, 2010; Alkon and Agyeman, 2011; Koopmans et al., 2017). Community-based participatory urban food initiatives and research create jobs, stimulate innovation and entrepreneurship, reduce food expenditures, improves access to fresh and healthy food; mitigate "food deserts" and health disparities along with environmental and climate justice impacts; and promote physical activity associated with food production as well as collaboration of community and academic scholars and subject matter experts (Gragg et al., 2015; Usher, 2015; Koopmans et al., 2017). These multi-cross scale and level interactions enhance social and cultural identities and interactions further enriching local communities and their social capital. They also inform transdisciplinary, systems, and culturally responsive teaching methods and practices, research and community engagement (Gragg et al., 2015; Jessee et al., 2015).

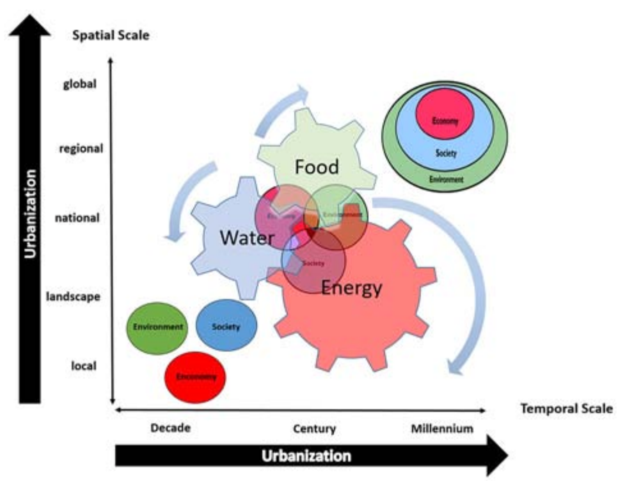

FIGURE 6 | The Transitioning Urban Socio-Ecological Nexus across spatial and temporal scales and levels under the primary driver of urbanization. This schematic diagram can be used to illustrate the integrated spatial and temporal transitions from unconnected to an interdependent/nested urban food-energy-water nexus in the contexts of urbanization and the associated social, economic and environmental complexities and innovations.

Figure 5A examines three causal chain and loop scenarios to further explain the complexity and differences of the driver response variables and their cross-scale interactions in the unconnected, connected, and nested sustainability scenarios. In **Figure 5A**, the output is the microclimate temperature changes affect the food system and impact crop yield and food production. Increasing temperatures causes increased evaporation of water and together with changes in heat spells affects water quantity that in turn affects the water system. The changes in water quantity as well as the need for more energy required for cooling in the microclimate impacts energy production and systems (e.g., power generation).

In **Figure 5B**, the output is the integrated socio-ecological food-energy-water system. This scenario can be explained by taking a perspective from one system where the other two systems are users. For example, here by taking a water perspective, the food and energy systems are inputs or users of the water resource. Water is a resource which can directly/indirectly impact the FEWS by quantity, quality, availability, irrigation and energy. Similarly, food as well as energy perspectives can be used.

Figure 5C has all causal chains from **Figure 5B** in addition, the response from the FEWS affects the causal chains. The chains run in circles known as feedback loops or causal loops. For example, the sustainability nested silos of FEW systems response can result in wastewater treatments, which in turn impacts the water quantity. The other responses can result in land management practices that impact irrigation and developing energy production from biomass (Arnfield, 2003; Dimoudi et al., 2013; Golden, 2013; Waffle et al., 2017).

Develop Interaction Across Spatial, Organizational, and Temporal Scales (Step 4)

The urbanizing food, energy and water nexus is fostering an interdependent/nested/embedded/systems perspective and practice of the environmental, social and economic sustainability paradigm (see **Figure 1C**). The movement toward a sustainability paradigm has brought into focus the centrality of food in our everyday lives, and its myriad social, economic and environmental connections (Gragg et al., 2017). This paper presents a conceptualization of the urban food and nutrition system based on the theory and practices of food as the foundation for healthy and sustainable communities (Gragg et al., 2017). The framework of this proposed sustainability-in-action model is rooted in the idea that urban socio-ecological systems are self-organizing, resilient and transformative "in which patterns at higher levels emerge from localized interactions and selection processes acting at lower levels" (Coelho and Ruth, 2006). This "unified urban systems theory" provides a flexible framework responsive to issues of scale and changing social and environmental conditions over time, within which to study urban systems (Coelho and Ruth, 2006). The grand challenge is for stakeholders to understand and embrace the scale and cross scale human–environment interactions that are taking us "back to the future" way of living in harmony with the natural environment and its offerings.

In **Figure 6**, the first scenario exemplifies the least complexity because of no cross-scale interactions between the drivers and the unconnected silos of environmental, social and economic sustainability. Here the research on the food-water-energy nexus and decision-making are at these finer spatial scales too. While on the other hand the most complex third scenario with cross-scale interactions between drivers and nested food-energy-water and systems generally occur at slower timescales.

The urbanizing food energy water nexus factors and trends are discussed across various spatial and temporal scales (**Figure 7**). Schematic examples of interactions across spatial, organizational, and temporal scales and levels at finer time scales (days to decades) are illustrated using a spatial and temporal scale diagram (**Figure 7**). The interactions include socio-ecological phenomena (the microclimate-related system represented as a solid line) and the interaction of two human domains: microclimate research (the long hashed line) and regional energy/water management (hash-dotted lines). These figures are adapted from (Cash et al., 2006).

In this case, gaps exist in the human systems across levels within domains, e.g., microclimate research is not interactive across international and national scales; is not linked to national energy/water policy and/or national microclimate and urban agriculture research; nor is forecasting and national food-energy-water policy linked to urban/regional planning & development across scales and levels. This diagram is based on figure by Cash et al. (2006).

Proposed Conceptual Model (Step 5)

Our multidimensional model (**Figures 8a–c**), seeks to identify, characterize and deconstruct the environmental, social, and economic driver/response variables and their interactions/feedbacks for the transitioning integrated urban regional food and nutrition system that for the purpose of this food/ecological model (Sobal et al., 1998), is referred to as the "food-energy-water nexus." The nexus is a dynamic interaction among humans, agriculture and the environment; it integrates physical (such as built infrastructure and new technologies), natural (such as biogeochemical and hydrological cycles), biological (such as agroecosystem structure and productivity), and social and behavioral entities (such as decision making and governance); (NIFA Research Addresses, 2016).

"Urban agricultural food and nutrition macrosystems" are made up of biophysical, socio-ecological, and socio-cultural drivers/responses that exhibit local to global variations (Sobal et al., 1998; Heffernan et al., 2014). For simplification, the term "Urban macrosystems" is used here to include four dominant spatial "scales" (interpreted as spatial extents, but which can be interchanged with temporal extents), and the potential driver response interactions that make up the urban regional food-energy-water system are arrayed along multidimensional gradients of complexity. Unidirectional interactions from broader- to finer-scale drivers or explanatory variables (**Figure 8a**); bidirectional interactions between variables within a scale (arrows in **Figures 8b,c**) and cross-scale interactions and feedback loops are perhaps the three interaction types of most important scenarios (Heffernan et al., 2014).

Variations in both temporal (e.g., daily, monthly, seasonal, and annual, decadal) and spatial (e.g., local, regional, national, and global) scales and data sources are arrayed along multidimensional gradients of scenario complexity in this multidimensional conceptual model. Initially, driver variables are grouped into appropriate scales and levels, and three scenarios of causal chains and feedback loops are

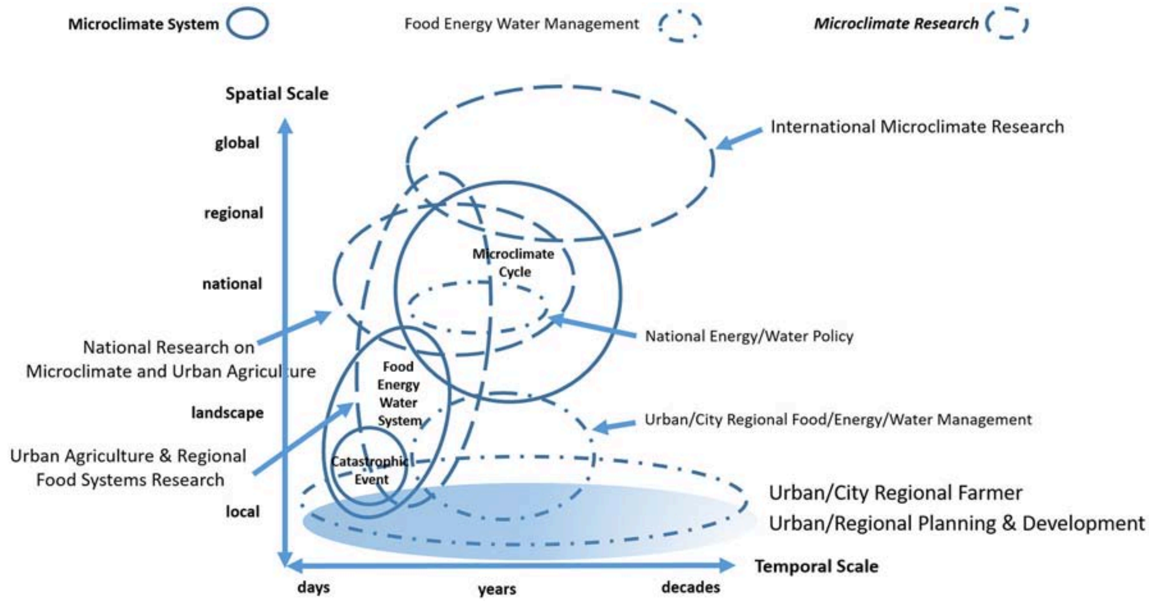

FIGURE 7 | Schematic example of urbanizing food-energy-water nexus factors and trends across spatial, organizational, and temporal scales and levels. This schematic diagram can be used to illustrate the spatial and temporal dimensions of socio ecological phenomena (the microclimate-related system represented as a solid line) and the interaction of two human domains: microclimate research (hashed line) and regional energy/water management (hash-dotted lines). These figures are adapted from Cash et al. (2006).

identified (see **Figures 8a–c**). These observable, measurable and trackable driver/response variables are governed as well by various underlying multidimensional socioecological and biophysical influences and effects: scale and cross scale dynamics; stakeholder networks; macrosystem complexity; resiliency and adaptive capacity (Alberti et al., 2003; Seto and Kaufmann, 2003; Sumner et al., 2010; Neumann et al., 2015; Weiler et al., 2015; Allen and Prosperi, 2016; Armendáriz et al., 2016; Richards et al., 2016; Sharifi and Yamagata, 2016; Juncos A. E., 2017; Li et al., 2017; Stringer et al., 2018).

Group one scenarios (see **Figure 8a**) have the least complexity and no cross-scale interactions occurring between driver variables from broader to finer scales and levels with minimal multidimensional effects. This scenario represents the disaggregated (unconnected/silos; see **Figure 1A**) socioecological drivers and focal response variables of the urban agricultural food system in transition initiated by local drivers (Sterman, 2011).

Group two scenarios (see **Figure 8b**) have medium complexity, interactions, and dimensional effects; where driver variables interact across scales and levels; and more complex interactions occur; with the driver variable at different scales influencing the transition of the food-energy-water system in the urban space (**Figure 8b**, interactions between driver and response variables). This scenario represents the aggregation (interconnected/linkages; see **Figure 1B**) of the socioecological drivers and focal response variables, and their cross-scale interactions, under increasing underlying multidimensional socioecological and biophysical influences and effects (James and Friel, 2015; Passe et al., 2016).

Group three scenarios (see **Figure 8c**) have the most complex interactions (interdependent/nested/systems; see **Figure 1C**) and multidimensional influences and effects; representing cross-scale interaction due to feedbacks between driver and focal response variables (**Figure 6C**, driver/ focal response variables interactions). The multiple dimensions outside the columns (e.g., spatial scales and levels; science, technology, and innovation; macrosystem complexity; and measurable, trackable, and observable drivers/responses) impact all three scenarios at increasing levels of influence and effects and assessment. The integration of the underlying multidimensional socioecological and biophysical influences and effects and the sustainability paradigm are distinguishing aspects and components of this conceptual model (Cash et al., 2006; Ericksen, 2008; Hazell and Wood, 2008; Sterman, 2011; Sekovski et al., 2012; Majowicz et al., 2016; Blake, 2017; Musy et al., 2017).

This multidimensional conceptual model will improve our understanding and development of the key driver/response variables and interactions of the food-energy-water nexus; their sensitivities to human economic development and building social capital; resiliency and adaptive capacity; and the causal chains and feedback loops linking non-uniform changes and ecosystem functions in rapidly evolving and transitioning urban socio-ecological infrastructural systems such as urban agricultural food (Armendáriz et al., 2016; Richards et al., 2016; Ramaswami et al., 2017).

Thus, the urban socio-ecological infrastructural system influenced by these cross-scale interactions and feedbacks can be observed, assessed, operationalized and integrated by stakeholders. This approach is iterative. Interactions and

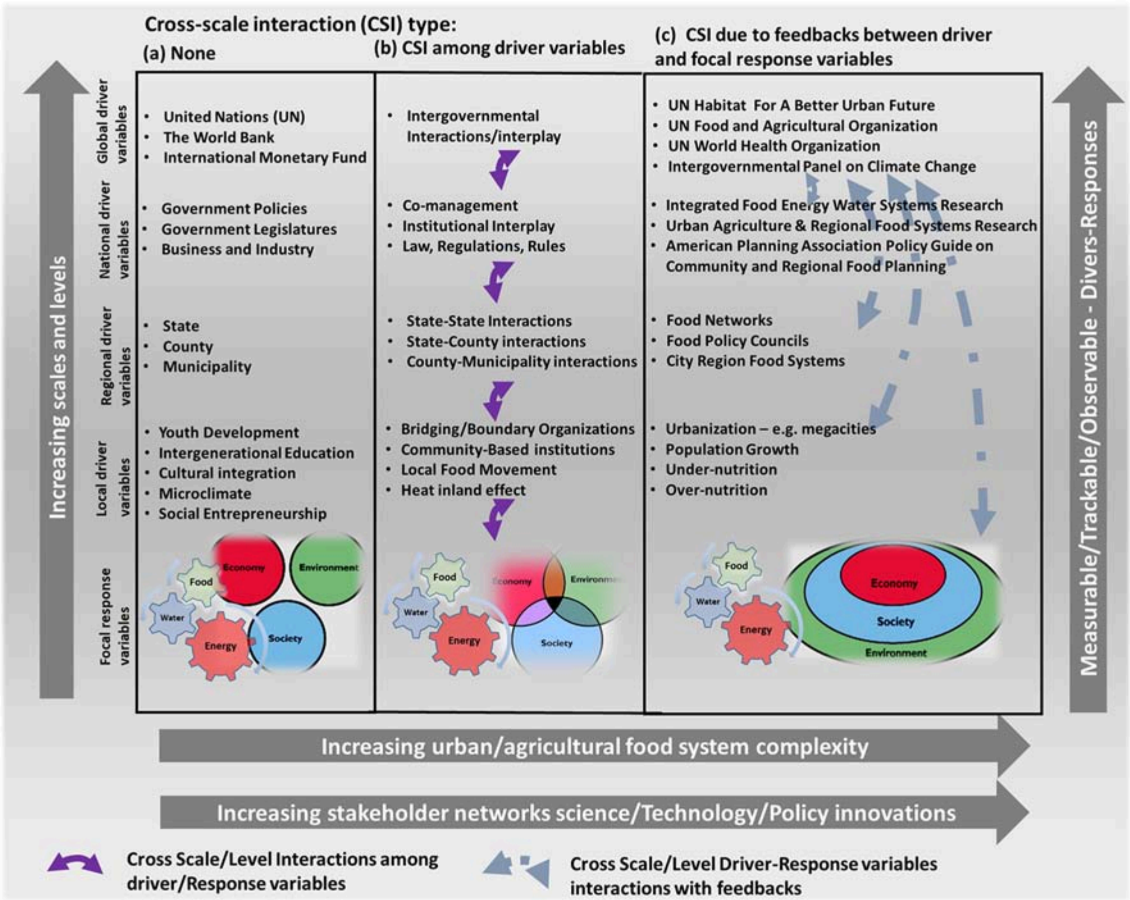

FIGURE 8 | Urbanizing food-energy-water nexus conceptual model.

feedbacks can be refined and new relationships added in subsequent model iterations. These include documenting uncertainties in the interactions and feedbacks. If stakeholders observe no change in the system functions, then they can identify other human-environment indicators, processes and scenario generation methods that are dampening the relationship exhibited by the driver/response variables. The better identification of causal chains and feedbacks underlying the scale and cross-scale dynamics in the urban agricultural food system plays an important role in developing sound sustainable urban agricultural food systems (Armendáriz et al., 2016), policy and management strategies amid rapidly evolving urbanization accompanied by over- and under-nutrition (Dubbeling, 2013; Weiler et al., 2015; Dupont Advisory Committee, 2016; Majowicz et al., 2016; Schipanski et al., 2016; Smit, 2016).

TABLE 1 | Sustainable development goals in action.

Case studies	United nations - sustainable development goals
Belize-Maya	2 - Zero Hunger, 3 - Good Health and Well-being, 8 - Decent Work and Economic Growth, 13 - Climate Change
MXCY-ViaVerde	3 - Good Health and Well-being, 9 - Industry, Innovation and Infrastructure, 11 - Sustainable Cities and Communities, 13 - Climate Change
Detroit-Green Collar Foods	3 - Good Health and Well-being, 8 - Decent Work and Economic Growth, 9 - Industry, Innovation and Infrastructure, 10 - Reduced Inequalities, 11 - Sustainable Cities and Communities
NJ-AeroFarms	3 - Good Health and Well-being, 9 - Industry, Innovation and Infrastructure, 10 - Reduced Inequalities, 11 - Sustainable Cities and Communities

Case Studies: Urbanizing Food-Energy-Water Nexus (see the Model Figure 8)

The following four case studies were selected because they were each unique in their social, economic, and environmental depiction of the transitioning urban agriculture and nutrition system and they are at the same time broadly representative as seen when associated with their corresponding United Nations Sustainable Development Goals (see **Table 1**) created in-part to meet the grand challenges and opportunities of urbanization, population growth and food security (Griggs et al., 2013).

Southern Belize

Perhaps a useful case study could be found in urbanizing, southern Belize where Maya farmers from three villages shared their experiences with yields of corn types, the effects of climate change on the growing season and milpa productivity, and on socio-cultural impacts on farming. This case study example highlights work being accomplished to improve food security. Plans for sustainable water and energy practices will be addressed in the future. In many communities across the developing world, households continue to produce most of their own food (Wilk, 1997). In these settings, improving food security depends upon increasing local agricultural productivity, while maintaining household access to productive land and avoiding environmental degradation (Rosset, 1999; Perfecto et al., 2009; Herrero et al., 2017). The Maya milpa[1] study explored the drivers influencing the change in forest ecology, its effects on milpa production and practices and food security in three Mopan-Q'eqchi' Maya villages in the Toledo District of southern Belize: Santa Cruz, Aguacate and Jalacte (author's fieldnotes, March, 2018). Some of the stated objectives of the project were to study soil fertility, water quality, weed ecology, farming practices, land use change and food insecurity.

Several focus groups were held with participants (farmers) from all three villages. They were asked three questions: What did they see as the drivers of forest change? What factors are affecting the changes in milpa? And, how were these changes affecting household food security[2]? Many of the responses highlighted the effects of climate change and weather patterns as affecting dry and wet seasons. This shortens the growing season, affects yields and promotes the invasion of grasses that reduces corn production. In addition, food security was affected by more young people in the villages "jobbing out," or preferring to find work in the larger towns and not farming in the villages (author Usher fieldnotes, March, 2018).

This case study relates to the Sustainability Paradigm and connects with the Spider Web **Figures 4A–C**; Causal Loop **Figures 5A–C**; and Spatio-Temporal scale diagrams **Figures 6**, **7**. This example case shows the trade off in food security outcomes within the Spider Web diagram (when the environment—which is affected by climate change, the social—affected by urbanization/less farmers and economic—affected by urbanization/pre-packaged processed foods). That is, with increase impacts of urbanization and climate change, milpa yields are diminished and the communities' way of life become less sustainable. Examining the Causal Loop diagram, we understand the impact of the three villages coming together to share resources such as more adaptive seeds and planting techniques to address the impacts of climate change.

Mexico City, Mexico

Increasingly, cities around the world are enacting food and urban agricultural initiatives to increase food security among its vulnerable and marginalized populations, and stimulate local economic development. In the case of Mexico City, one of the world's mega-cities, Vertical Gardens act as air filters and reduce heat island effects in urban areas when implemented at massive urban scale. The water source is recycled and harvested rainwater is used for irrigating the gardens. The "Via Verde" (Green Way) is an innovative urban greening project where approximately 60,000 sq. m. (15 acres) of vertical gardens were installed around more than 1,000 highway pillars covering nearly 17 miles (27 km) of space. In addition to growing food, the project will improve air quality, reduce traffic noise pollution, beautify the urban landscape, and reduce heat-island effects caused by air pollution and the effects of climate change. Along with those functions, the project has created jobs, uses an automated irrigation system for efficient water usage, and improves the emotional well-being of citizens.

This project is an exemplar case of the nested scenario of the Social, Environmental and Economic states in an urbanized area within the Spider Web and Causal Loop diagrams. Due to the effects of the changing climate and urbanization, microclimates develop that create heat-islands. Referring to **Figure 5C**, as this project incorporates the nested scenarios, it is able to respond appropriately to the issue of the microclimate with the use of vertical gardens, the efficient use of water, and by also creating jobs for the local economy and improving social welfare by improving urban aesthetics. (http://viaverde.com.mx/v2/).

Detroit, Michigan

Once thriving mid-western cities in the United States are thinking creatively about ways to increase employment and putting abandoned property to productive use. Green City Growers, a subsidiary of Evergreen Cooperative in Cleveland, Ohio has been able to provide fresh, local food all-year round while providing employment to its worker-owners some of whom are immigrants and new Americans and returning citizens. Retrieved from https://www.clevescene.com/cleveland/worker-owned-green-city-growers-is-on-the-path-to-profits-while-giving-refugees-and-ex-cons-gainful-employment/Content?oid=5740258.

Green Collar Foods (GCF) is building a franchise of small-scale, low-cost, and locally-owned controlled environmental agriculture production facilities in inner cities across the US and the UK. This social entrepreneurship model uniquely targets urban populations in the midst of multilevel and multiscale socioeconomic challenges such as food insecurity; health disparities; and low-wealth. (www.greencollarfoods.com). This project resonates with the nested sustainability paradigm in the **Figure 4C** Spider Web. It incorporates social, economic and environmental components to address nutrition, income from food production, food prices, food production, and it limits GHG emissions by using aeroponics technology.

Newark, New Jersey

AeroFarms, has built the world's largest vertical garden without soil, water or sunlight. The process uses technology in what it calls "precision agriculture" to increase crop yields by as

[1] The word *milpa* is derived from the Nahuatl word phrase **mil-pa**, which translates into "maize field."

[2] Food security is defined as having reliable access to a sufficient quantity of affordable, nutritious, culturally appropriate, non-emergency food at all times to maintain a healthy and active life.

much as 70 times that of traditional farming. Growing crops this way produces no pollution from runoff and their use of L.E.D. lights reduces energy consumption significantly. (http://aerofarms.com). This example embeds with our Spider Web diagram in **Figure 4C**. The company has 120 employs, produces affordable food which improves food access, and GHG emissions are low due to no agricultural runoffs.

CONCLUSIONS

In this paper we presented a conceptual model of the urbanizing food-water-energy nexus developed on the notion of "food as the foundation for sustainable and healthy communities". This is the idea that food is not only the primary element in the formation of human settlements (Mumford, 1961; Steel, 2008), but also that food as a component of the water and energy cycle is vital for all life on our planet. Compared to other models our multidimensional sustainability paradigm iterative model is framed using a unified urban systems theory. The model is aligned with the three social, economic and environmental corners of the "Planner's Triangle" (Campbell, 2013)—in unconnected, interconnected and interdependent nested systems, with increasing complexities and constraints to model three broad food-energy-water scenarios. This model presents a simplistic scenario with no cross-scale interactions between drivers and unconnected silos of food, energy and water. Therefore the decision-making process is not integrated across spatial and temporal scales as demonstrated in the Belize case study. However, in the most complex third scenario with cross-scale interactions between drivers in nested food, energy and water systems, integrated decision-making occurs due to multiple and highly complex interactions and feedbacks. This is demonstrated in varying degrees of complexity in the Detroit, New Jersey and Mexico City case studies.

This conceptual model holds saliency for public decision-makers and policy analysts, urban planners, public health professionals, as well as community and non-profit organizations concerned with food access, social and environmental justice, land use and employment, and sustainable economic development. It can serve as an educational tool to inform the connections and interactions between economic, social and environmental sustainability and the food-energy-water nexus in a urbanizing world. It makes clear new ways of seeing, learning and understanding opportunities for policy solutions, resources and stakeholders to be brought to bear on the issues. The systems thinking approach utilized in this model provides an easy way to understand the integration of components, connections and interactions in the sustainability nexus. This decreases waste, builds resiliency and adaptive capacity while improving access, sanitation, nutrition, human and animal health. Ultimately it develops smart policy around land use, land ownership, trade, and economic policy that encourages entrepreneurship and access to credit, access to markets, cooperatives, transparency in government, rule of law, and basic infrastructure (all-weather roads, reliable electricity, etc.).

Future work will elaborate the Urban Agricultural Food and Nutrition System in Action, discussing the next steps in moving beyond the conceptual model using new intra- and peri-urban processes, materials and paradigms can arise from these integrated urban biomanufacturing/production systems. Further development of the model includes deploying the model in urban food system scenarios, gathering qualitative and quantitative input from urban food system and sustainability stakeholders and practitioners. The field testing of the model was not carried out in this study. The validation and field testing of the conceptual model are the next steps. Dimensions such as sociocultural settings, socioeconomics gradients can be incorporated in the current conceptual model. The other model limitations are that we are unable to identify and represent every driver variable and their interactions and feedbacks in the present or in the future. Nor can we account for the compounding effects of two or more variables. As such, the model attempts to address the grand challenge for stakeholders to understand and embrace the scale and cross-scale human–environment interactions by taking us "back to the future" way of living in harmony with the natural environment and its offerings.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

ACKNOWLEDGMENTS

This material is based upon work partially supported from the USDA-NIFA's capacity-building grant 2017-38821-26405, USDA-NIFA Grant 2018-68002-27920 as well as the National Science Foundation under Grant No. 1735235 awarded as part of the National Science Foundation Research Traineeship and DUE-1125331 awarded as part of the Science, Technology, Engineering, and Mathematics Talent Expansion Program.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Sustainable Food Systems

PERSPECTIVE
published: 04 December 2018
doi: 10.3389/fsufs.2018.00084

Technology for Sustainable Urban Food Ecosystems in the Developing World: Strengthening the Nexus of Food–Water–Energy–Nutrition

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Smart integration of technology can help create sustainable urban food ecosystems (UFEs) for the rapidly expanding urban population in the developing world. Technology, especially recent advances in digital-enabled devices based on internet connectivity, are essential for building UFEs at a time when food production is increasingly limited on a global scale by the availability of land, water, and energy. By 2050, two-thirds of the world will be urban—and most of the net world population growth will occur in urban regions in the developing world. A food crisis is looming, with the developing world ill-prepared to sustainably feed itself. We identify 12 innovative technology platforms to advance the UFEs of the developing world: (1) connectivity—information delivery and digital technology platforms; (2) uberized services; (3) precision agriculture (GPS, IoT—Internet of things, AI—artificial intelligence, sensing technology); (4) CEA—controlled environment agriculture, including vertical farms; (5) blockchain for greater transparency, food safety, and identification; (6) solar and wind power connected to microgrids; (7) high-quality, enhanced seeds for greater yield, nutrition, climate, and pest resistance; (8) advanced genetics, including gene editing, synthetic biology, and cloud biology; (9) biotechnology, including microbiome editing, soil biologicals, cultured meat, alternative proteins to meat and dairy; (10) nanotechnology and advanced materials; (11) 3-D printing/additive manufacturing; and (12) integration of new tech to scale-up underutilized, existing technologies. The new tech-enabled UFEs, linked to value-chains, will create entrepreneurial opportunities—and more efficiently use resources and people to connect the nexus of food, water, energy, and nutrition.

Keywords: FWEN, nexus, technology, value chain, sustainability, developing world, urban food ecosystems

OPEN ACCESS

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Specialty section:
This article was submitted to Nutrition and Environmental Sustainability, a section of the journal Frontiers in Sustainable Food Systems

Received: *23 August 2018*
Accepted: *20 November 2018*
Published: *04 December 2018*

Citation:
Davies FT and Garrett B (2018) Technology for Sustainable Urban Food Ecosystems in the Developing World: Strengthening the Nexus of Food–Water–Energy–Nutrition. Front. Sustain. Food Syst. 2:84. doi: 10.3389/fsufs.2018.00084

INTRODUCTION

Smart integration of technology can help create sustainable urban food ecosystems (UFEs) for the rapidly expanding urban population in the developing world (Orsini et al., 2013). Technology, especially recent advances in digital-enabled devices based on internet connectivity, are essential for building sustainable UFEs at a time when food production is increasingly limited on a global scale by the availability of land, water and energy. By 2050, two-third of the world will be urban—and most of the net world population growth will occur in urban regions in the developing world (UN-DESAPD, 2018). Yet the developing world is ill-prepared to feed itself: agricultural production in West Africa remains anemic—its population is doubling in 20 years—and two of the six largest global cities will be in West and Central Africa (UN-Habitat, 2014; FAO, IFAD, and WFP, 2015). In the developing world, there is chronic underuse of mechanization, basic fertilizer, and irrigation inputs—and adaption of modern agricultural and food technologies needed for sustainable intensification (Binswanger-Mkhizea and Savastanob, 2017; see **Appendix 1** in the Supplementary material).

More than a billion people live in developing world slums—which could double by 2030. Furthermore, the poorest urban households spend 60–80% of their income on food (Reardon, 2016). A food crisis is looming, exacerbated in coming decades by the impact of climate change, bulging youth populations, large migrations from rural areas to cities—and inadequate infrastructure, education, and economic opportunities (Chatterjee, 2015; Hamm et al., 2018). Current UFEs in the developing world are inefficient and critically inadequate to meet the challenges of the future (van Ittersum et al., 2016). This could have catastrophic economic, social and political consequences.

TECHNOLOGY KEY TO SUSTAINABLE URBAN FOOD SYSTEMS (UFES)

A new path forward for UFEs needs to be found. The advancement should include increased productivity and environmental sustainability that links rural, peri-urban, and urban producers and consumers and increases overall urban region food production (Addo, 2010) (**Figure 1**). Connecting food production and distribution to urban and peri-urban markets has many advantages. Road systems are better with closer proximity to markets, reducing problems with perishability, and unreliable electricity for refrigerated storage (cold-chain). These regions and markets favor high-value (cash), nutrient-dense crops (vegetables and fruits), which require smaller acreage, and are more profitable per square meter than agronomic crops such as rice, corn, and wheat (Davies and Bowman, 2016). This creates market niche opportunities for smallholders, many of whom are women (FAO, 2011a). New technologies, coupled with new business models and supportive government policies, can revolutionize and create more resilient and productive UFEs for the twenty-first century. It will generate opportunities for entrepreneurs to create many new businesses and jobs.

These new UFEs also will create unprecedented opportunities for smallholders to progress from subsistence farming to commercially producing niche, cash crops (horticulture), and animal protein (poultry, fish, pork, insects) (McCaffrey, 2012; Davies and Bowman, 2016). There will be new opportunities within cities in creation of "vertical farms" and other controlled environment agricultural (CEA) systems as well as production of plant-based and 3D printed foods and cultured meat (Benke and Tomkins, 2017; Chadwick, 2017; Simon, 2018). Uberized facilitation of production and distribution of food will reduce bottlenecks and provide new business opportunities and jobs. "Off the shelf" precision agriculture technology will increasingly be the new norm, for smallholders to larger producers (Kite-Powell, 2018).

Rapid growth of urban markets is providing opportunities for new entrepreneurs and young people who have technological, business, and interpersonal skills—to build food production and distribution businesses based on new technologies (Reardon, 2016). These new entrepreneurs do not necessarily need a college education—but rather the ability to continually retool and keep up with technology and market opportunities. Moreover, technology is making UFEs exciting for young people to develop successful businesses that will enable them to "take ownership," innovate, make money, and have meaningful careers. And it involves more than developing apps. Rather, the challenge is understanding weak links along the value chain and exploiting innovative use of technology to create new businesses.

Middle class consumers in the developing world have greater disposable income and want better, safer, fresh, healthy, *sustainably produced* food—including more protein-rich meat, poultry, and fish (Burlingame and Dernini, 2012). They also desire new services to facilitate merchandising, purchasing, and delivering food to their doorsteps. Urban consumers are also seeking more convenient food for consumption. This creates new product and market opportunities for producing nutritionally fortified, processed food (Darton-Hill et al., 2017).

These opportunities can also extend to rural and peri-urban regions where technology can eliminate drudgery. A subsistence farmer's life of hoeing weeds and carrying jerry-cans full of water to irrigate does not attract young entrepreneurs. They quickly see the "Red Queen dilemma" of *Alice in Wonderland*: running just to stay in place and never advancing. Technology can enable rural, peri-urban, and urban producers to have better market and income-stream opportunities by servicing larger urban markets (UN-SD, 2017). Technology that enables smallholder producers to increase productivity without increasing labor—is critical to food security for UFEs. This includes integrating technology to enable smallholders to rise above subsistence and become commercially successful.

New urban and peri-urban market opportunities also are being created in the developing world by supermarket chains (Walmart, Carrefour, Pick-N-Pay, Shoprite, Tesco, Metro, Pingo Doce, etc.). They are looking for locally-sourced, high-value fruits, vegetables, flowering plants, and animal protein to service rapidly growing urban populations. Walmart and its local affiliate, Hortifruiti, for example, have small-farmer-direct programs with strict product standards servicing larger cities in Central America (Anon, 2018a). New technologies and business models are making such synergistic relationships increasingly viable.

The next generation UFEs, part of Agricultural Revolution 4.0 (see **Appendix 1** in the Supplemental Material), will be integrated with the larger collaborative economy that is connected by digital platforms, the cloud, and the internet of things, and powered

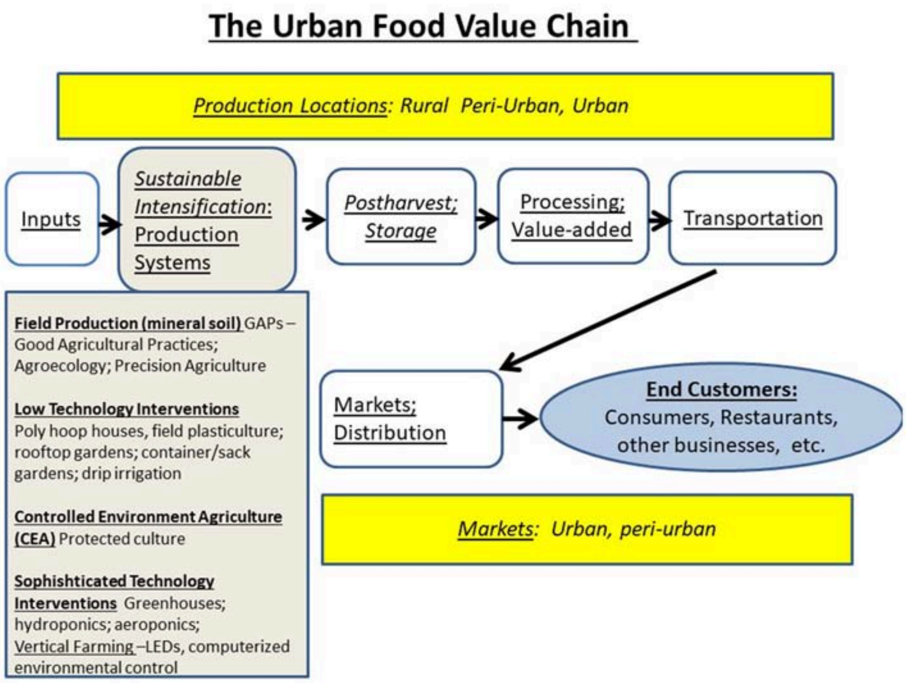

FIGURE 1 | The urban food value chain nodes from rural, peri-urban, and urban producers to servicing end customers in urban and peri-urban markets.

by artificial intelligence (De Clercq et al., 2018). The new tech-enabled UFEs will more efficiently and effectively use resources and people to connect the nexus of food, water, energy, nutrition, and human health. This will also contribute development of a circular economy that is designed to be restorative and regenerative—minimizing waste and maximizing recycling and reuse to build economic, natural, and social capital (Anon, 2018b).

We have identified 12 innovative technology platforms to advance the food ecosystems of the developing world that include: (1) connectivity: information delivery and digital technology platforms; (2) uberized services from producers to consumers; (3) precision agriculture (GPS, IoT—Internet of things, AI—artificial intelligence, sensing technology); (4) CEA—controlled environment agriculture, including vertical farms; (5) blockchain for greater transparency, food safety, identification; (6) solar and wind power connected to microgrids and storage; (7) high-quality, enhanced seeds for greater yield, nutrition, climate, and pest resistance; (8) advanced genetics, including gene editing, synthetic biology, and cloud biology; (9) biotechnology, including microbiome editing, soil biologicals, cultured meat, alternative proteins to meat and dairy; (10) nanotechnology and advanced materials; (11) 3-D printing/ additive manufacturing; and (12) integration of new tech to scale-up underutilized, existing technologies—such as efficient drip-irrigation with new precision soil sensors and solar-electric pumps—allowing both "on" and "off-grid" usage; "packaging technologies" (**Figure 2**).

The tech-enhanced UFEs will make on-farm production more resilient and more closely tied to urban food systems. It will also create off-farm opportunities in the value chain, including food production in cities and serving customers with new goods and services. Technology can enable transformation of UFEs, from expanded production in cities to more efficient and inclusive distribution and closer connections with rural farmers. See **Appendix 2** in the Supplementary material, which includes currently available, soon-to-be available, and prospective commercialized technologies for creating more sustainable UFEs in the developing world. Examples are as follows.

CONNECTIVITY FOR INFORMATION, LEARNING, AND MARKETS

Connectivity, from simple cell phone SMS communication to internet-enabled smart phones and cloud services, is providing platforms for increasingly powerful technologies that are enabling development of a new agricultural revolution. Internet connections currently reach more than 4 billion people, about 55% of the global population (Kemp, 2018).

Smart phones are often the first and only computer available to a producer or a consumer in developing countries. It becomes their gateway to the world, from accessing relevant business and weather information to participating in on-line learning and acquiring data on their health. All of this can radically transform a family's economic and educational opportunities. More than 2 billion people actively use Facebook, which is often a platform for conducting business. Indonesia, a developing country, is the fourth largest Facebook user, while India has twice as many users

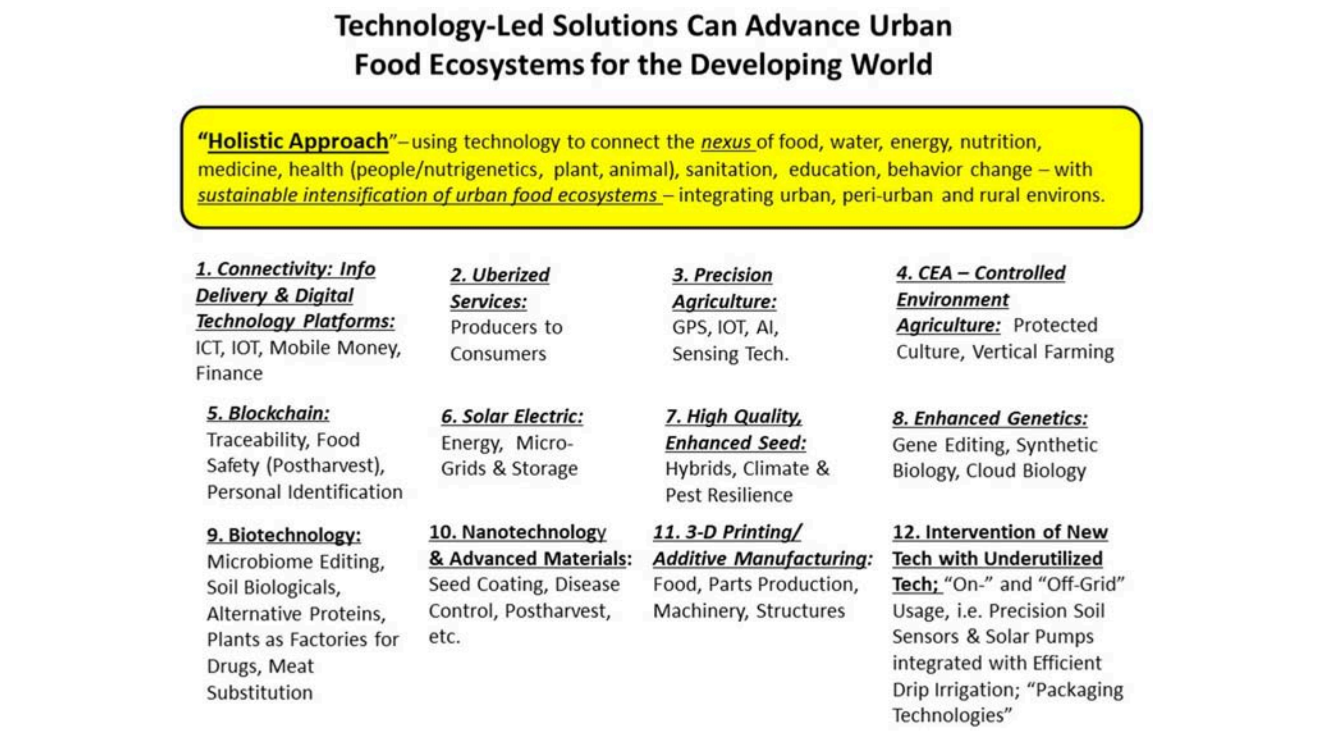

FIGURE 2 | Twelve innovative technology platforms to sustainably intensify urban food ecosystems (UFEs) of the developing world.

as the United States. Some 48% of Kenya GDP flows through mobile money (M-Pesa) and 31% of eCommerce comes from mobile devices (Munda, 2017). More sub-Saharan African adults (12%) have mobile money accounts compared to just 2% global usage (Lewis et al., 2016).

These information and communications technologies (ICT) connect food value-chain actors, from producers to consumers, with just-in-time data; enhanced good agricultural practices (GAPs); mobile money and credit; telecommunications; market information and merchandising; and greater transparency and traceability of goods and services throughout the value chain (Ekekwe, 2018; USDA, 2018). The smartphone and basic cell phones using SMS have become the one-stop-shop for a smallholder to place orders, gain technology information for "best management practices" (BMPs), and access market information to increase profitability (EPA, 2018). Hershey's CocoaLink in Ghana uses SMS text and voice messages with cocoa industry experts and smallholder producers (Anon, 2018c). Digital Green is a low cost, technology-enabled communication system in Asia and Africa to bring needed GAPs and BMPs to smallholder farmers in their own language and dialects through filming and recording successful farmers within their own communities (Harwin and Gandhi, 2016). MFarm is a mobile app that connects Kenyan farmers with urban markets via SMS messaging (Solon, 2013). Farmerline and AgroCentral use mobile and the web as part of their business model in Africa to connect farmers with the services they need (Anon, 2018d). This includes weather forecasts, market prices, and GAPs.

The internet currently remains slow and expensive in parts of Africa, affecting the ability of Africans to use the web and connect globally. However, advances such as the Google Go app will make it easier to browse the web. The app will be available in 26 sub-Saharan African countries, and will function on Android devices that have low storage capability and slow, unstable connections, including 2G networks. The app includes voice recognition for searches, instead of typing - enabling literate literate and semi-illiterate users; it can switch between languages, including Swahili (Dahir, 2018).

To further enhance Wi-Fi, while increasing their bottom line: Google Station is a free, public Wi-Fi service in Nigeria, India, Indonesia, Thailand, and Mexico. Essentially Google partners with local service providers for infrastructure and locations and offers a cloud-based platform and devices to provide and manage the Wi-Fi hot-spots (Kazeem, 2018). Google is also building fiber-optic networks through *Project Link* to help local internet service providers and mobile operators provide faster broadband in the developing world. Furthermore, Google is partnering with telecom operators in Kenya to launch *Project Loon* to connect users to the internet using solar-powered, high-altitude balloons. Facebook also has internet access projects in Africa, including Express Wi-Fi and Free Basics (Kazeem, 2018).

UBERIZED CONNECTIVITY FOR A COLLABORATIVE ECONOMY

Uberized services can advance development of the UFE across the spectrum, from rural to peri-urban to urban food production and distribution. These facilitators—using mobile devices and mobile money transactions, and connected to the cloud for on-demand goods and services for producers, value-chain actors, and consumers—can strengthen the many weak links in the UFE. This includes uberized: planting and harvesting equipment; transportation vehicles; cold-chain facilities for temporary storage of perishable product; and "cloud kitchens" that produce fresh meals to be delivered to urban customers, enabling young people with motorbikes, and cell phones to become entrepreneurs or contractors delivering meals to urban customers.

Uberization of the UFE can begin with rural producers. "Custom harvesting" (renting) farm equipment creates business-to-business (B-to-B) opportunities for the developing world. Mechanization and automation are vitally needed to reduce drudgery, increase efficiency, and enhance profitability. Hello Tractor is an example of a custom harvesting company and is the "Uber" of small, 2-wheel tractors (Otufodunrin, 2017). It is a business platform of entrepreneurs operating in Africa and Central America. Smallholders use their cellphones to contract with Hello Tractor for tractors to plow and harvest their fields, track when they will arrive, and make mobile money payments. Hello Tractor uses smart tractors linked to the cloud with a GPS antenna and international SIM card for remote monitoring.

The global trend in urban regions of using mobile phones to order food delivery is spreading to the developing world. Just as Airbnb owns no hotels but provides more than one million "hotel rooms" and Uber owns no taxies but provides urban mobility in hundreds of cities, GrubHub has no takeout restaurants; it supplies restaurant food to over 10 million customers in more than 1,300 cities in the US and the UK. Online food-delivery platforms are increasing efficiency, expanding choice, and convenience, allowing customers to order from a wide array of restaurants with a single tap of their mobile phone (Hirschberg et al., 2016). Africa has a number of local, indigenous, on-line-delivery services, from SoupDirect and EasyAppetite in Nigeria to FoodCourt in Rwanda. In India, food delivery apps, including Google's Aero, Uber Eats, and Indian startups such as Swiggy and Zomato, are competing to gain market share (Kashyap, 2017). The Indian online delivery market is composed of aggregators and cloud kitchens where chefs prepare food at a physical outlet. The congestion of India's roads has created another down-stream, business opportunity to service Indian consumers who do not want to cook at home, but do not want to get stuck in traffic going to a restaurant.

About a third of the world's food goes to waste, often because of appearance; this is enough to feed two billion people (Royte, 2016). The businesses "Imperfect Produce" and "Imperfect Picks" use market opportunities to reduce food waste by creating a service of marketing and distributing "ugly food" (Helbig, 2018). Such services supply consumers with cheaper, nutritious, tasty, healthy fruits, and vegetables that would normally be discarded as culls due to imperfections in shape or size. Services supplying "ugly food" utilize land and resources more efficiently. Companies source directly from farms and deliver produce to customers' doorsteps for 30–50% less than grocery store prices. Farmers sell more produce, down-stream service/delivery jobs are created, and consumers have access to more affordable, healthy, and nutrient-dense food. Similar models could be used in the developing world.

PRECISION AGRICULTURE AND CONTROLLED ENVIRONMENTAL AGRICULTURE (CEA)

UFEs production systems rely not only on field-grown crops, but also on production of food within cities (Hallett et al., 2016).There are a host of new, alternative production systems using "controlled environmental agriculture" (CEA). These range from low-cost, protected "poly hoop" houses, greenhouses, and roof-top and sack/container gardens, to vertical farms in buildings using artificial lighting (FAO, 2011b; Black, 2018; Coffman, 2018). Many vegetables, greens, herbs, and flowering plants can be commercially grown in containerized or trough/tubing systems using "synthetic" high organic media as a solid substrate or in aeroponic and hydroponic environments, which require no media support. Vertical farms enable year-round production, regardless of weather, which will be an increasingly important with global warming (Esposito et al., 2017). LED lighting provides 24/7 production with the optimal amount of light quality and quantity for specific crop production requirements (Kozai et al., 2016). Sensors and robotics provide the root system with the exact pH and micronutrients. Such precision farming can generate yields 200–400% above normal field production (Blomqvist, 2018). In addition, vertical farms *reduce land and water* usage by as much as 95%, and energy usage by 50% (Esposito et al., 2017). Although vertical farming has great potential in the developing world for the production of selected greens and vegetables for urban markets, it is generally not cost-effective for producing all agricultural products, such as field crops, fruits, and nuts.

BLOCKCHAIN TECHNOLOGY

ICT technology can now address gaining access to credit and executing financial transactions, which has been an especially persistent constraint for smallholder producers. The Gates Foundation has released an open source platform, Mojaloop, to allow software producers, banks, and financial service providers to build secure digital payment platforms at scale (Galeon, 2017). Mojaloop software uses more secure blockchain technology to enable urban food system players in the developing world to conduct business and trade (Tapscott and Tapscott, 2016). The free software reduces complexity and cost in building payment platforms to connect smallholders with customers, merchants, banks, and mobile money providers. These digital financial services allow smallholder producers in the developing world to conduct business—without a brick-and-mortar bank.

Blockchain is also important for traceability and transparency requirements to meet food regulatory and consumer requirement during the production, post-harvest, shipping, processing, and distribution to consumers (Helmstetter, 2018). Urban consumers and regulators are expected to require more product information and labeling from listing the sustainable production system utilized, chemical applications, GMO status, handling, and transportation. Combining blockchain with RFID technologies also will enhance food safety (Costa et al., 2013).

ENHANCED GENETICS, BIOTECHNOLOGY, AND NANOTECHNOLOGY FOR SUSTAINABLE INTENSIFICATION OF UFEs

CRISPR is a promising gene editing technology that can be used to enhance crop productivity while avoiding societal concerns of GMOs (Servick, 2016; Regalado, 2017a; Rotman, 2017). The technology allows genes to be added and deleted, much like using word-processing software, but does not incorporate "foreign" genes (utilized in GMO-produced plants and animals)[1]. CRISPR can accelerate traditional breeding and selection programs for developing new climate and disease-resistant, higher-yielding, nutritious, biofortified crops, and animals. It provides a pathway for plant and animal breeding that is more reliable, cheaper, and faster than traditional methods.

Post-harvest losses of perishable fruits and vegetables during harvest, transportation, and delivery to consumers can be as high as 50% in the developing world (Kader, 2005). Plant derived coating materials, developed with nanotechnology, can reduce waste, enhance freshness, nutrition, extend shelf-life, and transportability of fruits and vegetables (Rowland, 2017). The nanotechnology coating could significantly reduce post-harvest crop loss in developing countries that lack adequate cold-chains (refrigeration). New post-harvest technologies using nanotechnology and packaging materials can dramatically enhance shelf-life, nutrition, and reduce unacceptable food losses (Flores-Lopez et al., 2016; Helmstetter, 2018). Nanotechnology is also used in polymers to coat seeds to increase their shelf-life and increase their germination success and production for niche, high-value crops (Davies et al., 2018).

Just as humans have a gut microbiome, plants have a root microbiome that offers much potential in integrated pest management (IPM) systems for increased plant resistance to environmental and pathogen stress (Fitzpatrick et al., 2018). These rhizosphere microorganisms (bacteria, beneficial fungi) can enhance plant nutrient uptake, drought resistance, and signaling important to plant development (Fitzpatrick et al., 2018; Ingham, 2018). The Earth Microbiome Project is just beginning to address how to better utilize these rhizosphere organisms (Gilbert et al., 2014). This could lead to a new, environmentally friendly, naturally produced, biological fertilizers, herbicides, fungicides, and pesticides (Davies et al., 2005).

IPM can increase vegetable and fruit yield while reducing chemical usage (Parsa et al., 2014). Furthermore, the use of IPM can be enhanced by portable, hand-held, genomic sequencing technology, available in Africa and other developing regions, to identify in the field beneficial root microbiome organisms, plant pathogens, or food contaminants (Craighead, 2009; Regalado, 2017b). For example, there are portable sequencing devices, the size of USB sticks that are connected to a smart-phone that is in turn connected to the cloud to stream data in real time. It enables cost-effective, "lab-in-the-hand" genomic sequencing without requiring a physical lab and elaborate equipment to be located in the developing country where the devices would be used.

Sustainable intensification of agriculture is smart agriculture that uses agroecology, inorganic, and organic farming, and IPM through judicious use of chemicals, including fertilizers, and pesticides (Altieri, 1992; Garnett et al., 2013). Organic agriculture alone is insufficient to feed the world, although it is an important part of the matrix of different agricultural production systems. Many of the newest pesticides are very targeted to specific pests, not harmful to the ecosystem, and enable beneficial, predatory insects to thrive. Good agricultural practices (GAPs) imply smart use of chemicals, pesticides, and fossil fuels that are environmentally and economically sustainable. According to Wilcox (2011), a world without inorganic, chemical usage is neither "greener" nor sustainable.

TECHNOLOGY FOR IN CITY PRODUCTION OF PLANT-BASED FOODS, CELLULAR AGRICULTURE, LAB-GROWN MEAT, AND 3D PRINTED FOOD

Lab grown meat, plant-based meat substitutes, and the technology for 3-D printing food may radically change where and how protein and food is produced, including in the cities where it is consumed (Card, 2017). There are a wide range of innovative food alternatives to traditional meats that can supplement or offset the need for livestock, farms, and butchers. The history of innovation is about getting rid of the bottle neck in the system, and with meat, the bottleneck is the animal. Finless Foods is a new company trying to reduce use of fish by replicating fish filets (Lamb, 2018). Rather than giving up the experience of eating red meat, technology is enabling marketable, attractive plant-based meat substitutes, and lab-grown meat that can potentially drastically reduce world per capita consumption of animal-produced red meat. It turns out that current agricultural production systems for "red meat" have a far greater detrimental impact on the environment than automobiles (Weber and Matthews, 2008; Ritchie et al., 2018).

There have been significant advances in plant-based foods, like the "Impossible Burger" and "Beyond Meat," that can satisfy the consumer's experience and perception of meat (Kummer,

[1]While there is much disinformation about genetically modified crops (GMOs), they are no less safe than sustainably produced plants and animals using traditional systems. CRISPR uses modern biotechnology without introducing "foreign genes"—hence the end-product is a non-GMO. There is no ethical justification for not incorporating CRISPR technology with traditional breeding and selection systems to speed up the introduction of drought, disease, and climate-resistant, biofortified crops, and animals that are essential for sustainably feeding the world. Humankind has been genetically modifying plants and animals, which was critical for the first Agricultural Revolution. The mule is a cross between a donkey and a horse. None of the original parents of corn, rice, wheat resemble today's modern genotypes. The commercial banana is a clonally produced, sterile triploid, and the modern apple is clonally grafted on dwarfing rootstock.

2015; Calderone, 2016). There have also been major advances in "growing" real meat in labs using animal cells.

To eliminate the inefficiency in raising animals for slaughter—scientific teams and startups are developing laboratory produced meat for animal-free burgers, chicken, turkey, and fish to create new sustainable, commercial industries (Card, 2017). In the future, "clean meat" can be produced starting with muscle stem cells from live cattle, using what is called "cellular agriculture" (Shapiro, 2018). Several startups, including Memphis Meats, are pioneering "clean meat" or cultured meat, ranging from beef to chicken. Cells of live animals can be cultured in urban "breweries" that subsequently reduce the use of land, water, and greenhouse gas emissions by more than 90%, and produce significant health benefits (Zaraska, 2016). These meat-producing breweries could become nodes in UFEs throughout the world.

3D printing or additive manufacturing is a "general purpose technology" that is being used for making everything from plastic toys and human tissues to aircraft parts, buildings, and on-demand replacement parts—which are badly needed in the developing world for tractors, pumps, and other equipment (Campbell et al., 2011). Catapult Design (https://catapultdesign.org/) 3D prints tractor replacement parts as well as corn shellers, cart designs, prosthetic limbs, and rolling water barrels for the Indian market. 3D printing also can be used to convert alternative ingredients such as proteins from algae, beet leaves, or insects into tasty and healthy products that can produced by small, inexpensive printers in home kitchens (https://foodink.naturalmachines.com/) (Chadwick, 2017). The food can be customized for individual health needs as well as preferences.

Acceptance of these plant-based, lab-grown, and 3D printed foods, will require changing diet choices through education, marketing, and developing affordable, tasty, plant-based substitutes through technology. This is not only critical for environmental sustainability, but also offers opportunities for new businesses and services.

DEVELOPING NEXT GENERATION URBAN AND RURAL PRODUCERS AND PLAYERS—INTEGRATING NEW WITH UNDERUTILIZED TECHNOLOGIES

The key to advancing UFEs will be educating, developing and mentoring a new generation of urban producers and value chain players (Christiaensen, 2017; Townsend et al., 2017). They will not necessarily have grown up on a farm but rather learned their trades within the growing UFEs. They will be part of the collaborative economy connected to digital platforms, artificial intelligence, the cloud, and the internet of things (Lohr, 2015; Ray, 2017). The new UFEs will connect producers, horticulturists, agronomists, plant biologists, distributers, traders, marketers, urban planners, nutritionists, chefs, educators, food processors, computer programmers, engineers (chemical, mechanical, electrical, environmental), and social scientists. As an example, MIT's OpenAg is committed to developing a new generation of farmers (England, 2017; Ferrer et al., 2019). It is doing so by targeting schools. "I want kids to see agriculture as an exciting field where they can innovate, explore, and make a real impact on their communities and on the world," OpenAg founder Harper says; "Creating an exciting technology platform that inspires students to innovate and explore is our best bet toward a better future of food."

There are niche market opportunities in Africa for farmers to service urban markets with high-value, vegetable crops. But lack of access to credit and insurance, low-quality seed, lack of technical assistance, and direct links to markets limit the ability of smallholder farmers to become more commercially successful. Efforts to address this problem include Amiran, which is a commercial greenhouse supplier in Kenya. It has developed Amiran "farmer kits "to improve the livelihoods of smallholders." It is a micro-niche, "packaging technology" approach—using technology for producing high-value horticulture crops with smallholders linked to markets http://www.amirankenya.com/agribusiness2/agribusiness-afk/imp-afk-2 (Chao-Blasto, 2014). There is also support from the Kenyan government, and commercial banks in Kenya supply low-interest loans and reinsurance that is used for micro-insurance of production inputs (e.g., high-value horticulture seed, greenhouse materials, drip-irrigation, chemicals, etc.). The $4,000 micro-loan package is to be paid off over a period of several seasons, based on the high-value vegetable crop cash flow.

The Amiran program targets young producers and technologically savvy entrepreneurs (both from on- and off-farm) who are 35-years-old and younger. They are required to contribute 10% collateral, so they have "skin in the game." The vegetable production system utilizes low-cost, insect-screened greenhouse structures, outdoor drip irrigation and high quality (hybrid) seed. There is access to trainers, pest-certification, and assistance to forge direct links to markets. These technologies are appropriate for urban, peri-urban, and rural producers in the developing world for servicing urban markets with high-value, horticultural product.

Modern UFE technologies—can help smallholder farmers create viable businesses. This includes developing business-to-business (B-to-B) down-stream opportunities, linked to markets. For instance, custom seed propagators of high value vegetable and floriculture crops can raise seedlings to the "plug stage" in seedling tray systems—and sell them to producers/farmers (Davies et al., 2018). While it is more expensive for farmers to buy the "plugs" rather than propagate their crops, the seedling plugs assure farmers they will have successful crops that will be of high quality, and be produced more quickly to meet market demands. Amiran has a partnership with Plantech to supply seedling vegetable plugs to its growers who transplant them and finish off the crop (de Nijs, 2016). In Vietnam there are also custom propagators of grafted vegetable seedling plugs with greater yields and pest resistance. This is another B-to-B technology, selling directly to farmers to transplant in their fields, and CEA- hoop-house tunnels to grow and "finish off" marketable vegetable crops.

Less than five percent of the African agriculture is irrigated. This is a recipe for disaster. You cannot reliably grow quality vegetables and fruits without irrigation, which becomes even more critical with the impact of extreme climate change. "Packaging technologies" such as solar pumps with precision soil sensors linked to the cloud will greatly enhance the effectiveness of efficient, low-cost, drip irrigation systems. These systems can be used in both rural and urban production systems. Packaging UFE technologies that are linked to value chains (markets) is critical for sustainable food production.

For Africa and much of the developing world, food security and moving out of poverty will be dependent on a second Green Revolution. This entails sustainable intensification, biodiversity, biotechnology/molecular biology, development of climate-resistant high-yielding crops, better adaption of current and future technologies that enable GAPs, uberization, and a platform-connected "internet-of-food-things"[2] (Anon, 2018e; Shaw, 2018). This will require a diverse-group of entrepreneurs along the value chain from production to servicing consumers. Providing urban and peri-urban markets with high-value niche crops and services offers great opportunities for smallholder entrepreneurs and for meeting world food security and nutritional requirements. Technology is the platform to better connect the nexus of food, water, energy, nutrition, human health, sustainability (environmental, economic, societal), and smart policy—and to do so in a way that is scalable, affordable, and sustainable.

WAY FORWARD: BUILDING TOMORROW'S INTEGRATED UFES

Technology alone will not solve the developing world's challenge of creating the next generation sustainable UFEs. The "elephant in the room" hindering progress is development and enforcement of smart policies on land use, land ownership, trade, entrepreneurship, credit and market access, cooperatives, transparency in government, rule of law, education, eradicating illiteracy—and country-wide investment in agriculture, all-weather roads, and reliable electricity (Mengoub, 2018). There also needs to be *local capacity building* and *mentorship* for scaling up technology deployment (Yeboah, 2018). Successful UFEs cannot rely on a "top-down," master-plan approach. Rather, it is critical to encourage and support development of a "bottom-up" collaboration that integrates local knowledge and ideas with technology that is linked to value-chains (markets). The interconnectivity of UFEs technologies will better enable local entrepreneurs to adapt and grow their businesses.

What is needed is a holistic, comprehensive approach that utilizes the powerful new tools and innovative business models to build UFEs that connect rural, peri-urban, and urban food production, processing, distribution, and consumption. They must be economically, environmentally, and socially sustainable, and supported by government policies and civil society. This will require a multi-discipline path linked to value-chains and dependent on sound policy and transparency (trade, land-ownership, access to finance, markets), information delivery, and GAPs (Reardon, 2016; Anon, 2018c; Yeboah, 2018). In short, a "package approach" that leads to entrepreneurship and new opportunities. UFEs will be increasingly enhanced by use of artificial intelligence, growing data streams, blockchain, Internet of Things, drones, and robotics—all of which are dramatically improving in capabilities. The cost of these and other exponential technologies is also falling, often exponentially, which will increase their availability in the developing world and overall potential for a "better, cheaper, faster, scalable" approach to development—including development of UFEs (UN-CTAD, 2018).

[2] Rajiv Shah, the former Administrator of USAID and current head of the Rockefeller Foundation, observed that some of the greatest leaps in human progress have not come from *just* new technologies—but by applying those technologies locally. There are underutilized technologies, which if digitally connected, could have a dramatic impact on the food ecosystem.

AUTHOR CONTRIBUTIONS

The authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication. FD and BG collaborated in conceptualizing how technology platforms, linked to value-chains, can revolutionize the urban food system in the developing world. FD wrote the original draft with multiple inputs from BG.

ACKNOWLEDGMENTS

The authors thank Andrea Lazenby, journal development specialist, and guest editors, R. Lawford, R. Mohtar, J. Engel-Cox, and M. Schweitzer, for the invitation and their assistance to submit a manuscript for publication in the Nutrition and Environmental Sustainability Specialty Section of the *Frontiers in Sustainable Food Systems*.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2018.00084/full#supplementary-material

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Environmental Science

ORIGINAL RESEARCH
published: 12 December 2018
doi: 10.3389/fenvs.2018.00150

Global Water Transfer Megaprojects: A Potential Solution for the Water-Food-Energy Nexus?

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OPEN ACCESS

Edited by:
Richard George Lawford,
Morgan State University, United States

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Specialty section:
This article was submitted to
Freshwater Science,
a section of the journal
Frontiers in Environmental Science

Received: 01 August 2018
Accepted: 28 November 2018
Published: 12 December 2018

Citation:
Shumilova O, Tockner K, Thieme M, Koska A and Zarfl C (2018) Global Water Transfer Megaprojects: A Potential Solution for the Water-Food-Energy Nexus? Front. Environ. Sci. 6:150. doi: 10.3389/fenvs.2018.00150

Globally, freshwater is unevenly distributed, both in space and time. Climate change, land use alteration, and increasing human exploitation will further increase the pressure on water as a resource for human welfare and on inland water ecosystems. Water transfer megaprojects (WTMP) are defined here as large-scale engineering interventions to divert water within and between river basins that meet one of the following criteria: construction costs >US$ 1 billion, distance of transfer >190 km, or volume of water transferred exceeds 0.23 km^3 per year. WTMP represent an engineered solution to cope with water scarcity. These projects are most commonly associated with large-scale agricultural and energy development schemes, and many of them serve multiple purposes. Despite numerous case studies that focus on the social, economic, and environmental impacts of individual water transfer megaprojects, a global inventory of existing, planned and proposed projects is lacking. We carried out the first comprehensive global inventory of WTMP that are planned, proposed or under construction. We collected key information (e.g., location, distance, volume, costs, purpose) on 34 existing and 76 future (planned, proposed or under construction) WTMP. If realized, the total volume of water transferred by future projects will reach 1,910 km^3 per year with a total transfer distance of more than twice the length of the Earth's equator. The largest future WTMP are located in North America, Asia, and Africa and the predicted total investment will exceed 2.7 trillion US$. Among future projects, 42 are for agricultural development, 13 for hydropower development and 10 combine both purposes. Future megaprojects are also planned to support mining, ecosystem restoration and navigation. Our results underscore the extent to which humans have and are planning to re-engineer the global hydrological network and flows through WTMP, creating a network of "artificial rivers." They emphasize the need to ensure the inclusion of these projects in global and basin hydrological models, and to develop internationally agreed criteria to assess the ecological, social and economic impacts of WTMP.

Keywords: water transfer, megaprojects, hydrology, water balance, water-food-energy nexus, biodiversity, water management

INTRODUCTION

Water is an essential resource for human well-being and the functioning of ecosystems. At the same time, increasing water scarcity is among the biggest challenges humanity is facing (Haddeland et al., 2014; Brauman et al., 2016). By 2030, the world will experience a 40% water deficit or a supply-demand gap under a business-as-usual scenario (2030 WRG, 2009). The global distribution of freshwater is uneven both in space and time (Rodell et al., 2018), and becomes further exacerbated through changes in total precipitation, seasonality, interannual variability, and the magnitude and frequency of extreme meteorological events (Rockström et al., 2014; Schewe et al., 2014). Water quality is deteriorating, too, due to industrial, agricultural and municipal pollution, further constraining water resources for humans and nature alike (Vörösmarty et al., 2010).

While the global availability of freshwater remains relatively constant, the demand is growing. This increasing demand is tightly linked to securing food and energy for a growing human population (UNESCO-WWAP, 2014; UNSD, 2018). Water and energy are necessary for all stages of food production, from irrigation to processing. Currently, irrigation accounts for 70% (or 2,710 km^3) of the water resources withdrawn by humans globally from rivers and aquifers, although the exact value significantly varies between continents and regions (FAO, 2011). Together, food production and supply chains are responsible for 30% of the total global energy consumption (UNESCO-WWAP, 2012). At the same time, water is required for power generation and cooling as well as the production of biofuels. In 2010, global water withdrawals for energy consumption accounted for 15% of the world's total withdrawals; and this withdrawal rate is expected to increase by 20% until 2035 (UNESCO-WWAP, 2014). Hence, the "water-food-energy nexus" was identified by the World Economic Forum as a key development challenge for the increasing human population (WEF, 2011). By 2050, the human population is projected to reach 9.8 billion (UN, 2017), with 66% living in urban areas (UN, 2014). In addition, food demand will increase by 50% (FAO, IFAD, UNICEF, WFP and WHO, 2017), energy demand by up to 61% (WEC, 2013), and water demand by 55% (UNESCO-WWAP, 2014). Therefore, ensuring sufficient water resources, in the required quality as well as sustainable energy and food supply are essential and interconnected goals for sustaining human well-being (UNSD, 2018; Vörösmarty et al., 2018).

High water demand increases the risk that water of the required amount and quality will not be available at the time and place it is needed (Gupta and van der Zaag, 2008; Rodell et al., 2018). This calls for large-scale engineering solutions to store, redistribute and treat water resources. Hard infrastructure and engineering solutions are often considered as a first option, not considering viable alternatives or combinations of gray and green (natural or seminatural features) infrastructure that may ensure a more sustainable use of water resources (Palmer et al., 2015; Vörösmarty et al., 2018).

Megaprojects are often high-risk projects because they require major financial investments, demand long time frames from planning to completion, and may have major socio-economic and environmental ramifications (Flyvbjerg, 2014; Sternberg, 2016). In the water sector, megaprojects include transfer projects, large dams, navigation schemes, desalination plants, treatment plants, and ecosystem restoration projects (Sternberg, 2016; Tockner et al., 2016). Megaprojects are often initiated as an expression of national and political power and expected to trigger economic and social development (Sternberg, 2016). Concurrently, the social, economic and environmental consequences of these projects do not receive adequate attention in the decision-making process (Sternberg, 2016; Zhuang, 2016).

Water transfer megaprojects (WTMP) may play an important role in sustaining the water-food-energy nexus, as they can provide water for irrigation, domestic supply, energy production, navigation, and industrial development (Sternberg, 2016). The common term is interbasin water transfer, defined as "the transfer of water from one geographically distinct river basin to another, or from one river reach to another"; hereafter called "donor" and "recipient" system, respectively (Davies et al., 1992; Gupta and van der Zaag, 2008). According to the International Commission on Irrigation and Dams (ICID, 2005), interbasin water transfer accounted for 540 km^3 a^{-1} or 14% of the global water withdrawals as for 2005, although these values should be used with caution due to major uncertainties in the underlying data. Global water withdrawal through transfer schemes is expected to increase by 25% until 2025 (Gupta and van der Zaag, 2008), primarily through an expansion of water transfer schemes. In the USA, for example, the number of interbasin water transfer schemes (primarily ordinary transfer projects of small scale) has increased by an order-of-magnitude, from 256 in 1985/1986 to 2,161 in 2017 (Dickson and Dzombak, 2017).

Concern about the environmental, societal and economic consequences of interbasin water transfers has been raised in recent periods (WWF, 2007; Zhang et al., 2015; Zhuang, 2016 and examples therein). While it has been shown that water transfer schemes can reduce the pressure on groundwater resources (Poland, 1981), improve water quality (Hu et al., 2008; Rivera-Monroy et al., 2013), and support ecosystem restoration measures (Snedden et al., 2007; Dadaser-Celik et al., 2009); there are concerns about their impacts. For example, WTMP may cause high levels of evaporative losses and rates of leakage due to poor maintenance of infrastructure (Davies et al., 1992), provoke salinization due to reduced water flow (Zhuang, 2016), increase nutrient concentrations due to inputs from nutrient-rich basins (Fornarelli and Antenucci, 2011; Jin et al., 2015), facilitate the spreading of pollutants and invasive species (Murphy and Rzeszutko, 1977; O'Keeffe and DeMoor, 1988; Snaddon and Davies, 1998; Clarkson, 2004), and change species composition (Grant et al., 2012; Lin et al., 2017).

From a social point-of-view, WTMP can alter the water balance in the affected basins, with potential beneficial or negative effects for human well-being in the donating and receiving basins. Due to increased water supply, residents in receiving basins may benefit from boosted agricultural and industry development, while environmental deterioration in donating basins may lead to a reduction in income and lead to involuntary or uncompensated resettlement of local communities (Sternberg, 2016; Yu et al., 2018).

Water transfer may also increase the probability of conflicts between countries that share water basins. For example, water transfer from non-renewable waters of the Disi aquifer by Jordan and Saudi Arabia led to concerns related to over-exploitation of commonly shared groundwater and a potential "tragedy of commons" (Müller et al., 2017). Inappropriate planning of water transfer schemes can also lead to major economic failures; for example, when high construction costs lead to increased water prices that exceed the paying ability of target groups (Sternberg, 2016).

Comprehensive data and information on the global extent of future WTMP are currently lacking (Tockner et al., 2016). Design, construction, and commencement of megaprojects require time, money and technical skills (Flyvbjerg, 2014). WTMP that are currently in the proposing, planning or construction stages may require decades until completion. Indeed, some projects may stay on the stage of a preliminary proposal, without any plan actually developed or funding assigned. However, knowing their distribution and key characteristics will help coping with the challenges humans and freshwater ecosystems are facing, and support appropriate, and alternative, strategies for managing water resources and ecosystem processes under rapidly changing conditions (Shumilova, 2018).

The aim of this study was to collate data and information about WTMP that are currently proposed, planned or under construction globally, and to be potentially completed by the year 2050.

The key research questions are:

(1) What is the global distribution of WTMP proposed, planned or under construction?
(2) Which purposes will future WTMP fulfill, particularly in meeting the water-food-energy nexus?
(3) How much water will be transferred across which distances?
(4) What are the estimated financial costs of future WTMP realization (including design and construction)?

In addition, we collected information on the distribution and key characteristics of existing WTMP, in order to put both existing and future WTMP into context. Finally, we discuss the consequences WTMP may cause in affecting humans and nature alike.

METHODS

Definition of water transfer megaprojects

Water transfer projects include any type of infrastructure that transfers water from one river catchment to another, from one river reach to another, or from any freshwater body (river, lake, groundwater source) to a place where it will be utilized by humans (Davies et al., 1992; Gupta and van der Zaag, 2008). **Megaprojects** are generally defined based on actual construction costs, with a threshold of about one billion US$ per project (Flyvbjerg, 2014). We extended that definition for **water transfer megaprojects** to include projects that meet one, or more, of the following criteria: construction costs amount to one billion US$ or more, distance of transfer is 190 km or more, or volume of water transferred exceeds 0.23 $km^3\ a^{-1}$ (Shumilova, 2018). To set these criteria we first selected a sample of 13 WTMP planned or under construction with the estimated construction cost of 1 $\pm$ 0.5 billion US$. Then, we calculated the median water transfer distance and volume of these projects (**Table S1**). These criteria were used to identify existing megaprojects, too.

Data Collection Sources and Criteria

We collected data and information on all megaprojects based on peer-reviewed publications, official web-sites of water transfer projects, environmental impact assessments, reports of non-governmental organizations, and information available in online newspapers. Data and information were collected between January and December 2017. We searched for the English terms "water transfer," "water diversion," "water megaproject," and "water redistribution schemes," using the following search engines: www.webofscience.com; https://scholar.google.com/; and www.google.com. In order to improve the data quality, we used multiple sources for each project for cross-validation (the full list of information sources for each project planned and under construction is provided in the **Supplementary Material**).

For each project, we compiled the following data and information: geographic location of the project (continent, country), project status (proposed, planned, under construction), donor and recipient system, total water transfer distance, total water transfer volume (i.e., maximum annual capacity), estimated financial construction costs (future WTMP), and main purpose(s) of the project. In case information sources provided different values on water transfer distance, volume and costs, we used the largest values found in the literature. We visualized the location of each project using QGIS software (version 2.12). Identification of the location and course of the planned WTMP was based on available project plans, terrain topography, or depicted as the shortest connection between donating and receiving water body in case no other information was available.

RESULTS

Geographic Distribution and Purposes of Existing and Future WTMP

A total of 34 existing WTMP were identified, with the majority of projects located in North America (17) and Asia (10) (**Figure 1A**, **Table S2**). A total of 76 WTMP are either under construction (25 projects) or in the planning phase (51) (**Figure 1B**; **Table S3**). The majority of future WTMP will be located in North America (33 projects) and Asia (18) (**Figure 1B**; **Table 1**). In Europe, only three WTMP are expected so far, of which two are under construction.

Two of the future projects will transfer water from aquifers (Disi Water Conveyance Project in Jordan and a pipeline from an aquifer in Eastern Nevada to Las Vegas, USA), and all others will transfer water from river systems through canals

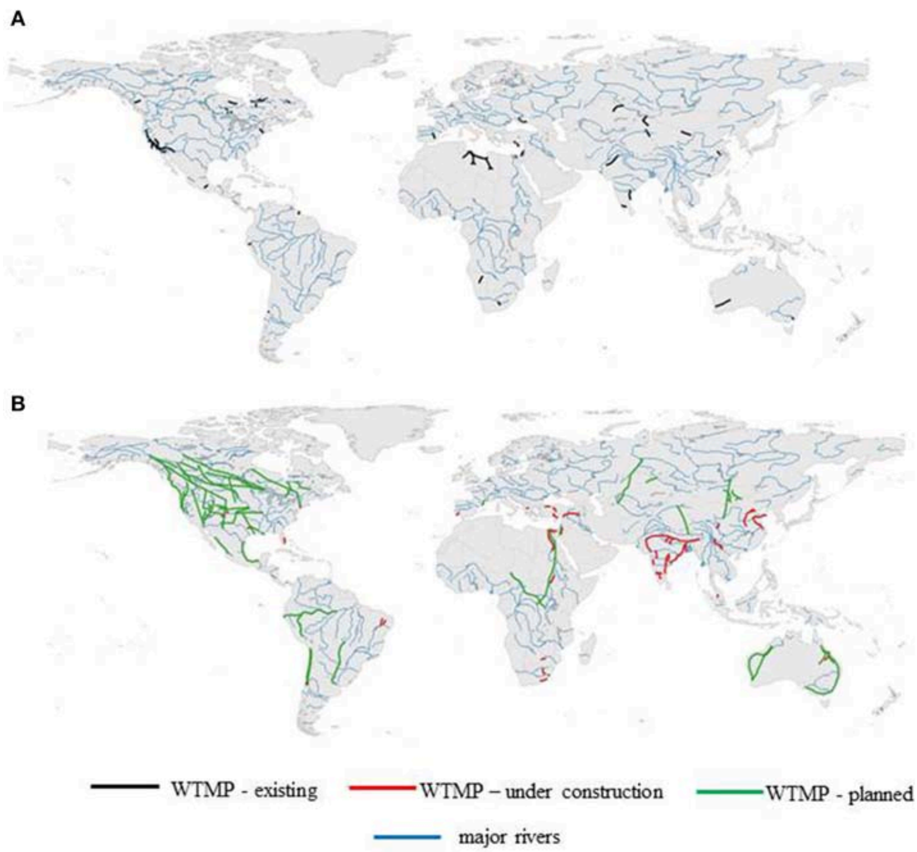

FIGURE 1 | Global distribution of **(A)** existing water transfer megaprojects (black lines) ($N = 34$) and **(B)** future water transfer megaprojects that are under construction (red lines) or in the planning phase (green lines) ($N_{total} = 76$). Blue lines show major rivers.

TABLE 1 | Summary information (per continent) on water transfer megaprojects, either proposed, planned or under construction (see text for further explanation).

Continent	Number of projects	Total water transfer distances[1] (km)	Total water transfer volume[2] ($km^3\ a^{-1}$)	Total cost of all projects combined[3] (billion US$)
North America	34	24,800	1,333	1,883
Asia	17	28,631	321	532
Africa	9	6,600	233	128
Australia	7	8,238	12.9	72
South America	6	11,780	8.2	36
Europe	3	347	2.1	1.7
Total	76	80,396	1,910	2,653

[1] *14 projects have missing information on distance (1 in Australia, 1 in Europe, 12 in North America).*
[2] *Six projects have missing information on total water transfer volume (4 in North America, 1 in Asia, 1 in South America).*
[3] *14 projects have missing information on costs (12 in North America, 1 in Europe, 1 in Africa).*

or pipelines. Among future projects we also distinguished 24 projects defined as "proposed," without further commitments at this stage (**Table S4**); although data should be treated with caution (see description of "zombie-projects" in section Global scale inventory on WTMP). Most of the proposed projects are located in North America (20), three in Australia, and one in Asia.

The inventory of WTMP purposes showed that both existing and future projects represent an important infrastructure in supporting many of the water-food-energy nexus developments. Among existing WTMP, twelve projects provide water for irrigation, seven for hydropower generation, four for both purposes, and one project serves ecosystem restoration (**Table S2**). Among future projects, 42 projects will transfer water for agriculture development (19 in North America, 8 in Asia and Africa, 3 in Australia and South America, 1 in Europe), 13 for hydropower generation (7 in North America, 3 in Africa, 2 in Asia, 1 in Europe), and ten for both purposes (**Figure 2**). Furthermore, six future WTMP will meet the needs of the mining industry, five will support ecosystem restoration, and three projects will serve as navigation canals (**Table S3**).

Water Volume and Distance of Existing and Future WTMP

For existing WTMP, the water transfer volume ranged from 0.06 to 51 $km^3\ a^{-1}$ (median: 2.4 $km^3\ a^{-1}$), with a combined

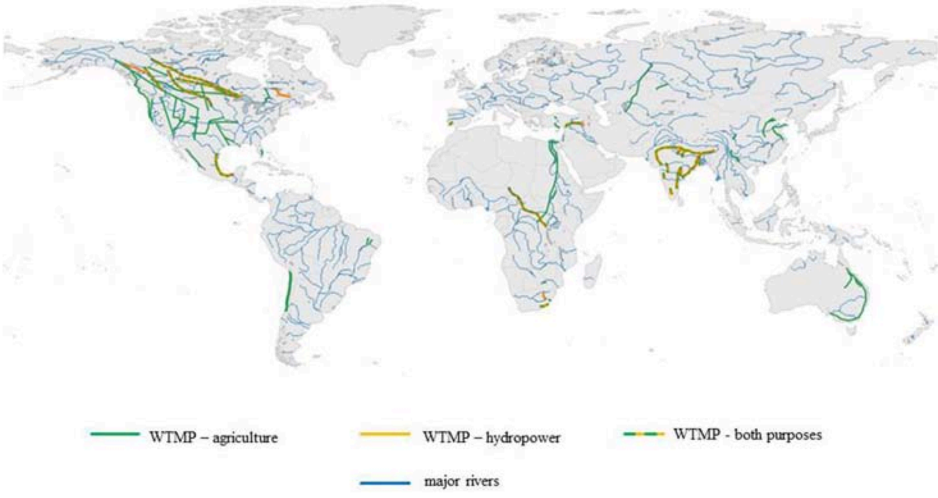

FIGURE 2 | Distribution of future WTMP according to their purposes: water supply for purposes of agriculture (green lines, $N = 43$), hydropower development (orange lines, $N = 13$) or both (orange-green stripped lines, $N = 10$). Blue lines show major rivers.

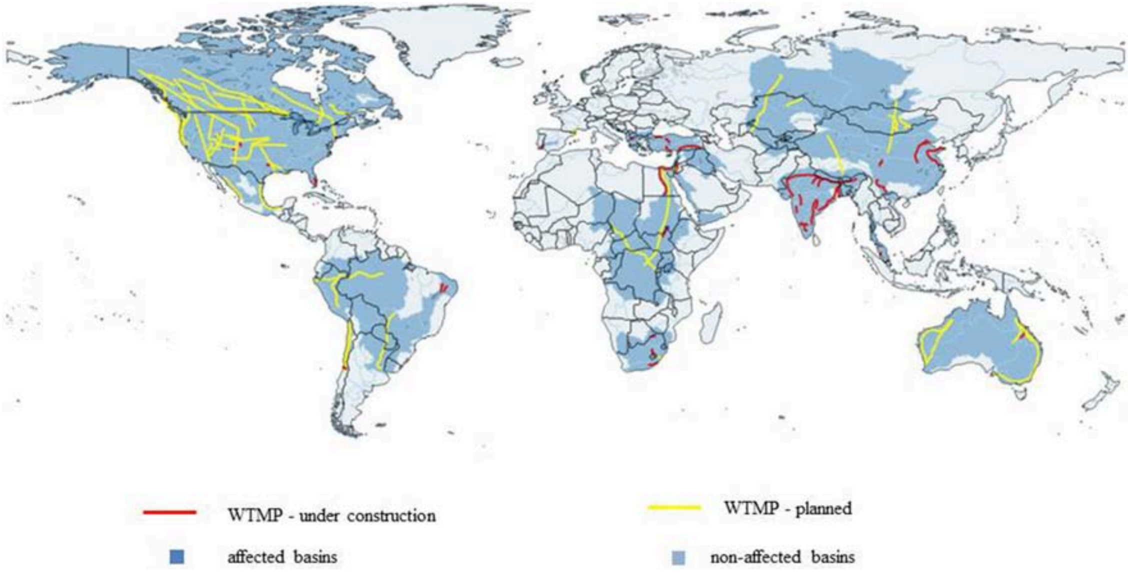

FIGURE 3 | Distribution of future WTMP under construction (red lines) or planned (yellow lines) across major river basins. Dark blue color shows major basins affected by water transfer, light blue shows non-affected basins. Black lines show countries boundaries.

volume of 204 km^3 a^{-1} (**Table S2**). The "James Bay Project" (Canada; 51 km^3 a^{-1}) and the "Goldfields Water Supply Scheme" (Australia; 33 km^3 a^{-1}) transfer the largest volumes. For future WTMP, the estimated water volume transferred per project will range from 0.05 to 317 km^3 a^{-1} (median: 2.2 km^3 a^{-1}), with a combined volume of 1,910 km^3 a^{-1} (**Table 1**). The proposed "North American Water and Power Alliance" (NAWAPA) megaproject is estimated to transfer 193 km^3 a^{-1} across the entire continent, and the proposed "Great Recycling and Northern Development (GRAND) Canal of North America" may transfer 317 km^3 a^{-1}.

The water transfer distance of existing WTMP ranged from 0.4 to 2,820 km (median: 358 km) with a combined length of 13,049 km (**Table 1**). The longest distance of water transfer amounts to 2,820 km for the "Great Manmade River" (Libya) and the California State Water Project (USA; 1,128 km). The calculated water transfer distance of future WTMP will range from 17 km to 14,900 km (median: 482 km) (**Table S3**). The combined length of all megaprojects proposed or planned (56,115 km) or under construction (24,281 km) will amount to 80,396 km. Thereof, the "National River Linking Project" (India), which is under construction, will stretch a total length of 14,900 km, and the proposed "NAWAPA" megaproject (North America) will cover 10,620 km.

Estimated Financial Construction Costs of Future WTMP

The construction costs (actual estimates) of future WTMP range from 0.095 to 1,500 billion US$ per project (median: 5.2 billion US$) (**Table 1**). The construction of all future 76 WTMP will require a combined investment of around 2.7 trillion US$. The construction of the proposed "NAWAPA" megaproject is estimated to cost 1.5 trillion US$. Regarding the projected costs per km of water transfer, the most expensive projects currently in the planning phase are the "California Water Fix and Eco Restore" project (USA; 479 million US$ per km), the Acheloos River diversion project (Greece; 339 million US$ per km) and the New Valley Project (Toshka Project) (Egypt; 290 million US$ per km). Regarding the costs of transfer in relation to the water volume transferred, i.e., costs per millions of $m^3\ a^{-1}$, the calculated costs are highest for the channel connecting Lake Baikal (Russia) with the Chinese city Lanzhou (325 million US$ per million $m^3\ a^{-1}$), the pipeline connecting the underground aquifer in eastern Nevada with Las Vegas (USA; 97 million US$ per million $m^3\ a^{-1}$), and the Kimberley-Perth canal (Australia; 73 million US$ per million $m^3\ a^{-1}$); all of which are in the planning phase.

DISCUSSION

Global Scale Inventory on WTMP

In this paper, we presented the most comprehensive global synthesis on future WTMP, which are expected to be completed by around 2050 as well as on the key characteristics of each of these projects. The inventory shows that WTMP already are and will become even more of a global phenomenon. They are planned across all continents and in countries that are both developed (e.g., USA) and developing (e.g., India, China) in terms of industrial status and *per capita* income.

By building massive water transfer infrastructures, humans are creating "artificial rivers" on Earth. If all planned projects are completed, the water transferred will encompass a total volume of up to 1,910 km^3, equivalent to over 26 times the mean annual flow of the Rhine River, and will travel a total distance of twice the length of Earth's equator. For comparison: the mean annual flow at the mouth of the Rhine River, one of the longest (total length: 1,250 km) and economically most important rivers in Western Europe, amounts to 72 $km^3\ a^{-1}$ (Uehlinger et al., 2009). While the median water transfer distance per individual project will be around one third of the Rhine River length, 17 projects will exceed the length of the river Rhine. The scale of these interventions means that they may fundamentally transform the global water cycle. The total volume of transferred water will account for up to 48 % of the global water withdrawal (based on the recent total withdrawal rate of around 4,000 km^3 $year^{-1}$ FAO, 2010), and to about 5 % of the total global continental discharge to oceans (**Table 2**). Indeed, we can expect an even greater increase because our analysis includes megaprojects only. For example, in the USA we identified nine existing megaprojects, while a recent inventory of the total number of interbasin transfer projects includes 2,161 smaller projects (Dickson and Dzombak, 2017; **Table S2**).

TABLE 2 | Water volumes transferred in future WTMP vs. volumes of continental water withdrawals and total discharge to oceans (per continent).

Continent	Water volumes transferred through future WTMP ($km^3\ a^{-1}$)	Continental water withdrawals ($km^3\ a^{-1}$)	
		Total in 2000[1]	Through IBT in 2005[2]
North America	1,333	705	300
Asia	321	2,357	146
Africa	233	235	11
Australia	12.9	32	1
South America	8.2	182	3
Europe	2.1	463	79
Sum	1,910	3,974	540

[1] *Shiklomanov (2000).*
[2] *ICID (2005).*
[3] *Fekete et al. (2002).*
IBT, interbasin transfer.

In most cases, water transfer occurs between hydrologically very different regions, i.e., from water rich to xeric areas, reconfiguring the conception and use of desert lands (e.g., Sternberg, 2016). Water is taken to serve demands of distant populations. Among such projects are the New Valley (Toshka) Project (water transfer from Lake Naser) and El Salam Project (water transfer from Nile) in Egypt for the needs of agriculture and industry in xeric areas, the Disi Water Conveyance Project (water transfer from Disi Aquifer to Amman, the capital of Jordan), and the water transfer pipeline from the aquifer in Eastern Nevada for water needs in Las Vegas. Water is also transferred to develop agricultural and economic resources, like the proposed Bradfield Scheme in Australia (water transfer from Tully, Herbert and Burdekin rivers to irrigate dry parts of Queensland and to create a lake in the middle of the continent) or the proposed Sibaral canal that aims to refill the Aral Sea. Such a redistribution of water can exacerbate disparities between water rich and water poor areas, especially in view of projected changes in freshwater availability under climate change (Rodell et al., 2018).

A significant number of future megaprojects (15 in total, **Figure 3**) are transboundary and will transfer water across longer distances compared to existing projects. The median water transfer distance of future WTMP will exceed those of existing projects by more than 100 km, although the median water transfer volume of existing and future WTMP is very similar (2.4 vs. 2.2 $km^3\ a^{-1}$, respectively). Among 76 future projects, 23 will transfer water further than 1,000 km, compared to two out of 34 existing projects. The volume and in particular the distance of future WTMP emphasize that these projects must be considered as integral parts of the global hydrosystem network, and therefore included in hydrological models.

Currently, there is no dedicated agency responsible for maintaining a database on water transfer projects, not even in countries where water transfer already is an important component of water supply, such as in the United States and China (Dickson and Dzombak, 2017; Yu et al., 2018). Furthermore, we lack internationally agreed standards to evaluate water transfer project design, performance and impacts on people and ecosystems, as have been created for large dams (World Comission on Dams, 2000; HSAP, 2010; Roman, 2017).

Our dataset contains the most comprehensive existing global collation of information on existing and future WTMP. However, we are aware that the quality and completeness of information should be treated with caution because of the heterogeneity of information on projects' characteristics. Only English search terms were applied for data acquisition, which potentially may lead to an incomplete representation of existing and future projects in certain regions, in particular in Asia and Latin America. In addition, in our database we included projects that have been proposed, but have not become a subject of further commitments, and their realization is still questionable.

Several future projects included in our inventory are so-called "zombie-projects" (Gleick et al., 2014). They were once proposed, were put on hold or set aside, but then brought back to life. According to our database, most of such projects were proposed in North America in the late 1950s and early 1960s with the aim to transfer water from northern regions of the continent (particularly in Canada) to southern parts in the United States and Mexico by building canals (Forest and Forest, 2012). For example, the NAWAPA project in North America was first proposed in 1954 and discussed again in 2010s (Nuclear NAWAPAXXI, 2013). Another example is the Sibaral Project (2,500 km long of water transfer from Siberian rivers to the Aral Sea), which was proposed during the Soviet Union era, stopped in 1986, and recently discussed again among various actors in Central Asia and Russia (Pearce, 2004). Their realization cannot be dismissed, however, as extreme droughts, natural disasters, or famines may open so-called "windows-of-opportunities" to move forward on their construction (Tockner et al., 2016). At the same time, these projects are connected with massive environmental, social, and economic interventions and therefore in most cases environmentally and economically unsustainable (Flyvbjerg, 2014; Sternberg, 2016; Zhuang, 2016).

Data on expected costs of WTMP show that these projects will require enormous and in most cases underestimated investments. The construction costs of all future WTMP (with information on costs available) will amount to more than 2.7 trillion US$ (actual estimates), which exceeds the calculated investments for constructing 3,700 large hydropower dams, either planned or under construction (Zarfl et al., 2015). The median costs of a single WTMP (5.2 billion US$) can comprise a significant proportion of the annual GDP of individual countries (for comparison, the total annual GDP of Greece is 196 billion US$ World Economic Outlook Database, 2017). In China, the estimated expenses on water transfer projects, both completed and planned as for 2015, accounted for around 1% of the country's GDP in 2014, corresponding to more than 150 billion US$ (average costs per project: 3.5 billion US$; Yu et al., 2018). High costs together with cost overruns, however, can lead to financial failures of megaprojects (Sternberg, 2016). For example, the Central Arizona Project (USA), completed in 1992, provided farmers with irrigation waters for very high fees, but investments in the project have still not been covered (Sternberg, 2016). Estimated expenses of WTMP increase while projects are under construction. The costs of the Sao Francisco irrigation project (Brazil), currently under construction, have increased from initially 4.5 to more than 10 billion US$, and may further increase until completion; while running costs are not yet included (Roman, 2017). Expenses on water transfer often compete with other societal requirements. For example, 4% of the GDP of Saudi Arabia are dedicated to sustaining water resources, compared to 8% for health and social affairs (Ministry of Finance, Saudi Arabia, 2013). Apart from financial costs related to project construction, costs related to environmental damage and social issues need to be considered too. For example, the construction of the 1,000 km long Yettinahole Diversion Project in India will lead to the deterioration of one of the world's biodiversity hot spots (Krishnadas and Jumani, 2017). Furthermore, diversion projects will also affect the water supply of downstream communities. Therefore, overall megaproject benefits should be compared to costs under different scenarios for the use of water and resources in view of multiple values dimensions (e.g., Hansjürgens et al., 2016).

WTMP Within the Context of the Water-Food-Energy Nexus

WTMP offer engineering solutions in meeting increasing water needs (Gupta and van der Zaag, 2008) and are part of national water management plans. The development of future WTMP is mainly driven by geographical or temporal limitations in water availability (e.g., large water volumes planned to be transferred from water secure areas to arid regions) as well as by existing deficits in water supply that limit further economic development (e.g., transfer schemes to provide water for mining schemes in Chile and Australia). Future WTMP are also proposed to facilitate the economic linkage of regions (e.g., navigation canals in South America and Africa). Some projects aim to provide water supply for particular cities (e.g., water transfer from the aquifer in East Nevada to Las Vegas, water transfer from Lake Baikal to the Chinese city Lanzhou). Currently, 12% of the largest cities in the world (with a population larger than 750,000 people) are dependent on interbasin water transfer, and the number of cities relying on transferred water is increasing (McDonald et al., 2014). In the next decades, further expansion of urban infrastructure is expected, particularly in developing countries (McDonald et al., 2014). The fastest growing large cities dependent on water transfer are located in China, India, and Mexico (McDonald et al., 2014).

Future WTMP will play a significant role in the water-food-energy nexus and this approach therefore could facilitate the resolution of some of the approval processes regarding realization of projects and their expected dimensions. We identified that the majority of projects is supporting the agricultural sector. The Aquatacama Project, which will transfer around 1.5 km^3

a^{-1} over a distance of 2,500 km from the south to the north of Chile, is expected to double its area of agricultural land and food production (Dourojeanni et al., 2013). Very large-scale projects proposed in North America as NAWAPA, PLHINO, and PLHIGON will jointly form a single water transfer network, boosting food production in Mexico. The area of irrigated land in Mexico will increase by 75% and grain production will be doubled (Small, 2007). Finally, the South-to-North water transfer project in China provides water for agriculture and domestic use in the densely populated areas in Northern China. A number of projects will also serve multiple purposes including providing water for agriculture, energy supply and domestic purposes. For example, Turkey, a country with the second largest hydropower potential in Europe (following Norway; Yuksel, 2015), demonstrates how water transfer schemes will support both the energy and agricultural sectors. Within the Southeastern Greater Anatolian Project (GAP), for example, 22 dams and 19 hydroelectric power plants will be constructed along the Tigris and Euphrates Rivers. After completion, the project will provide 308 MW for electricity production (45% of the total economically exploitable hydroelectric potential in Turkey) and irrigate 1.8 million ha of land, with a total length of irrigation channels of 1,032 km (Yuksel, 2015). In Egypt and Sudan, within the scope of the New Nile Project, a 2,500 km long canal will be built to provide water for agriculture and to provide a capacity of 18 GW for electricity production (Al-Naggar, 2014).

However, WTMP can cause undesirable social and economic consequences, particularly when projects with underestimated costs and overestimated benefits are approved (Flyvbjerg, 2007). Water usage can be unsustainable when water is transferred to promote agriculture in water-poor areas. For example, the Central Arizona Project (USA) supports water-intensive cotton growth in the semiarid Phoenix region. Another example is the Great Manmade River Project (Libya), which transfers groundwater from the Sahara to the Mediterranean coast, facilitating the migration of people to the desert, further increasing the pressure on already scarce water resources there (Sternberg, 2016). In addition, many of the future WTMP are transboundary and are planned in countries that are less stable politically and economically. This may lead to international disputes in water issues (Tockner et al., 2016). For example, the current conflict between the Russian Federation and the Ukraine led to the closure of the existing North-Crimean canal in 2014, which was playing a crucial role for sustaining agriculture and domestic water supply on the Crimean peninsula, supplying 85% of water needs (Vasilenko, 2017). This resulted not only in the failure of agriculture and other sectors of the local economy, but also in significant ecological damages of aquatic ecosystems in Crimea, namely the salinization of the Sivash Bay after water transfer was stopped (Shadrin et al., 2018). Another example is the Southeastern Greater Anatolian Project (GAP). Although it will support water development in Turkey, water security will be negatively affected in downstream countries such as Syria and Iraq, causing economic impacts, large-scale migration, and thus affecting the geopolitical situation in the region, especially in combination with climate change (Feitelson and Tubi, 2017; Rodell et al., 2018).

Impacts on Freshwater Ecosystems

Environmental impacts of individual interbasin transfer projects have been analyzed in multiple studies (Zhuang, 2016 and references therein), and the impacts of megaprojects in general are likely to be similar, albeit at a grander scale given their size. Most of the projects have already raised various discussions among stakeholders, pointing out that benefits of water transfer projects are overestimated, while costs are underestimated (WWF, 2007). An example of a future project that has caused concern about potential impacts is the "Acheloos Diversion" project (Greece; under construction) that was dubbed a "Modern Greek Drama" (Tyralis et al., 2017) and which may cause irreversible damage to ecosystems containing internationally protected species (WWF, 2007). Another example is the Sao Francisco irrigation project (Brazil), which is expected to increase desertification and cause salinization of irrigated soils due to increased evapotranspiration, lead to biodiversity loss, fragmentation of native vegetation, and disrupt fishing due to more dams (Stolf et al., 2012). Although the National Integration Ministry claimed that environmental impacts of the Sao Francisco project will be minimal, opponents of the project included state government institutions of the proposed donor basins, technical councils, and churches. On the other hand, some of the future WTMP have the objective of restoring ecosystems. For example the "Transaqua" project is expected to refill Lake Chad and the "Comprehensive Everglades Restoration Plan" is expected to restore the hydrology of one of the most important wetlands globally (Ifabiyi, 2013; CERP, 2015).

Globally, WTMP will redistribute large volumes of water between distantly located catchments, in particular in Asia and North America (**Figure 3**), thereby changing the hydrological balance. Large water withdrawals can lead to a flow reduction in donating basins. For example, the annual flow of the Yellow River in China was reduced by 10% in 2013, compared to the average flows within the last 60 years due to average withdrawal of 3.3 $km^3\ a^{-1}$ (Yu et al., 2018). In many cases, however, extraction of streamflow from the donating basins is not significant. For example, half of the interbasin transfer schemes that existed in the US in 1973–1982 extracted 0.04%, and 78% of the projects $<1\%$ of annual streamflow from the donating basins (Emanuel et al., 2015). However, under drought condition the percentage of withdrawal can be significantly higher. Overall, water transfer between wet and dry catchments will lead to a flow homogenization at regional and continental scales, but solid data to underpin this observation are still missing (McDonald et al., 2014).

Overall, the effects on freshwater ecosystems need to be estimated individually for each project. In general, the extent of the effects will depend on the physical and biological characteristics of the donating and recipient systems, the types of connecting and storage structures (pipelines or open canals, dams or natural infrastructure), the volume of water transferred and the frequency of transfers (Soulsby et al., 1999; Gibbins et al., 2001; Fornarelli and Antenucci, 2011). The current inventory of future WTMP (see **Table S3**) can serve to identify potential impacts on freshwaters by overlapping the WTMP data with other datasets (e.g., with hot-spots of biodiversity, water quality in donating, and receiving basins).

CONCLUSIONS

Within the next decades, we may expect up to a 9-fold increase in the volume of water transferred by WTMP if all planned projects are completed. As water scarcity becomes a global phenomenon, WTMP are currently considered to be an engineering solution to meet increasing water demands in both developed and developing countries. While these projects may play a fundamental role in food and energy production, there are concerns about their social, environmental and economic costs. Even projects which seem to be both environmentally and economically unsustainable could be implemented if the facilitating economic and political conditions prevail.

Presently, the lack of reliable data does not allow a full evaluation of the environmental, social, and economic potential impacts of future WTMP. Projects costs need to be integrated into the context of estimated benefits. The size of these WTMP suggests, however, that their impacts will cover regional and continental scales and will be irreversible. Thus, it is recommended that natural or green infrastructure solutions be seriously considered as alternatives or part of a gray-green infrastructure combined solution (e.g., Palmer et al., 2015). For example measures such as using recycled water, improving piping, and distribution in existing systems, using natural wetlands or groundwater systems as storage systems and increasing the efficiency of irrigation for agricultural purposes should come first in addressing the challenges of water shortage, although they may not eliminate the problem completely considering its scale.

Overall, the results of the inventory of WTMP emphasize the need to include these projects in global hydrological models and to develop internationally agreed criteria for their multiple assessments. Otherwise, we are facing an engineered water future, which may constrain alternative solutions to cope with an increasingly uneven distribution, both in space and time, of the global water resources. We need to manage our hydrological systems as hybrid systems–as regional water resources for human use as well as highly valuable ecosystems, for the benefit of people and nature alike.

AUTHOR CONTRIBUTIONS

OS, KT, and CZ designed the study. OS, AK, and CZ collected information. OS compiled the manuscript and all co-authors contributed to the text.

ACKNOWLEDGMENTS

This work had been carried out within the SMART Joint Doctorate Programme Science for the Management of Rivers and their Tidal systems, funded by the Erasmus Mundus programme of the European Union (http://www.riverscience.it). OS is thankful for a partial support from IGB equal opportunity fund for young female scientists and DFG (SU 405/10-1). We also acknowledge support by the German Research Foundation (DFG) and the Open Access Publishing Fund of the University of Tübingen. The authors thank Dominik Reiner for his support in cross-checking the compiled data on future WTMP, and three reviewers for their very helpful comments. The content of this manuscript is also part of the doctoral thesis of OS as listed in the reference list. The submitted manuscript is published as a preprint version on the EarthArXiv preprint server (Shumilova, O., Tockner, K., Thieme, M., Koska, A., Zarfl, C. (2018). Global water transfer megaprojects: A solution for the water-food-energy nexus? EarthArXiv [Preprint]. doi: 10.31223/osf.io/ymc87).

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2018.00150/full#supplementary-material

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Environmental Science

ORIGINAL RESEARCH
published: 18 December 2018
doi: 10.3389/fenvs.2018.00153

Governing the Water-Energy-Food Nexus Related to Hydropower on Shared Rivers—The Role of Regional Organizations

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OPEN ACCESS

Edited by:
Rabi Mohtar,
Texas A & M University, United States

Reviewed by:
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World Wide Fund for Nature, India
Marcos Callisto,
Universidade Federal de Minas Gerais, Brazil

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Specialty section:
This article was submitted to Freshwater Science, a section of the journal Frontiers in Environmental Science

Received: *06 July 2018*
Accepted: *03 December 2018*
Published: *18 December 2018*

Citation:
Dombrowsky I and Hensengerth O (2018) Governing the Water-Energy-Food Nexus Related to Hydropower on Shared Rivers—The Role of Regional Organizations. Front. Environ. Sci. 6:153. doi: 10.3389/fenvs.2018.00153

An evolving literature on the Water-Energy-Food (WEF) nexus argues that there is a need to better understand the conditions under which nexus coordination may occur. A case in point are hydropower investments on shared rivers which might impact the provision of energy, water and food security across borders. In international basins, governing the WEF nexus impacts of hydropower relies on voluntary negotiations between the respective countries involved. It has been argued that such negotiations may be facilitated by regional organizations, such as international river basin organizations (IRBOs), but this claim has hardly been investigated systematically. Drawing on regime theory in international relations and the literature on benefit sharing, this paper asks what role regional organizations may play in governing hydropower-related WEF nexus impacts. It compares three cases of hydropower planning on shared rivers. The Rusumo Falls and the Ruzizi III hydropower projects (HPPs) are joint investments in Africa's Great Lakes region facilitated by an IRBO and a regional energy organization, respectively. On the Mekong, Laos is constructing the Xayaburi dam despite reservations by the Mekong River Commission and downstream riparians. The paper finds IRBOs and regional energy organizations may play a role in facilitating cross-border nexus governance by supporting benefit-sharing arrangements and by fostering the application of environmental and social safeguards and international law principles. However, it also shows that the influence of regional organizations varies, and how successfully they support nexus governance also depends on whether the HPP is planned unilaterally or jointly; the availability and consensus on data on nexus impacts; and the presence or absence of donors and private sector capital and investors.

Keywords: water-energy-food nexus, governance, hydropower, transboundary river, river basin organization, Rusumo Falls, Ruzizi III, Xayaburi

INTRODUCTION

In international river basins, hydropower projects (HPPs) generate multiple cross-border, cross-sector interdependencies related to water, energy and food security. Many African and Asian countries have been investing strongly in hydropower to supply their rapidly growing economies (IHA, 2017). Many of these investments take place along international rivers. While the main purpose of hydropower is to contribute to energy security, dams often negatively affect water and food security and ecosystems services by blocking fish migration routes, destroying fertile agricultural lands and leading to the eviction of project-affected communities. Hence, investments in HPPs may raise several issues in relation to the water–energy–food (WEF) nexus by one-sidedly focusing on energy production, but neglecting the impact on water and food security.

The WEF nexus debate acknowledges the increasing interconnectedness of water, energy and land resources [sometimes referred to as the WEL nexus, e.g., ODI et al. (2012)] in providing water, energy and food security [WEF nexus, e.g., Hoff (2011), WEF-WI (2011)] for a rising world population under conditions of economic growth and climate change. For instance, Müller et al. (2015) point out how four output dimensions, namely the provision of water, energy and food security and a world of less than two degrees warming increase pressures on inputs such as soil, water and biodiversity and the ecosystem services they provide. Hence, pursuing one security may go along with synergies and trade-offs related to the other securities. Nexus thinking therefore argues for mobilizing synergies and managing critical trade-offs (Hoff, 2011; WEF-WI, 2011; ICSU, 2017). Still, the term WEF nexus has no globally agreed definition. Lebel and Lebel (2018) identify politicized and de-politicized notions of the term. Some of these notions carry positive connotations, while others are negative, depending on the actors involved and their attitudes toward a particular development project [for other conceptualizations of nexus see Keskinen et al. (2016)].

Despite a wide-ranging WEF literature investigating synergies and trade-offs in the provision of water, energy and food securities, Weitz et al. (2017) point out that our understanding of what governing the WEF nexus means and under which conditions it works or not remains very limited and more empirical work on the matter is warranted (see also Villamayor-Tomas et al., 2015). This paper therefore seeks to contribute to the evolving literature on governing the WEF nexus by providing a more in-depth analysis of the case of hydropower investments on shared rivers and the role that regional organizations may have in governing nexus impacts.

Some authors argue that in a transboundary context, regional basin organizations may be particularly well-positioned to govern nexus impacts due to their access to key actors in relevant sectors and across geographical scales (e.g., UNEP, 2014; Scheumann and Tigrek, 2015). We investigate these arguments by drawing on the literature on regime theory and the literature on benefit sharing in order to investigate the role of regional organizations in the transboundary governance of the water–energy–food nexus (hereinafter "nexus governance") related to hydropower investments along international rivers. Empirically, we focus on three recent investments into hydropower on shared rivers: the Ruzizi III, Rusumo Falls, and Xayaburi dam projects. Drawing upon Paavola (2007) and Müller et al. (2015), the paper understands nexus governance as a dynamic and recursive process involving state and non-state actors who establish, reaffirm or change institutions to resolve conflicts and negotiate political decisions in a way that takes into account interdependencies between soil, water and biodiversity systems in the provision of water, energy and food security.

The section on WEF Nexus, HPPs and the Potential Role of Regional Organizations further conceptualizes the WEF nexus related to hydropower investments on shared rivers and the potential role of regional organizations in governing this nexus situation. The paper then introduces the cases studies and the methodologies used. The section on Results presents key findings, following by a discussion of these findings. The Conclusion presents the wider implications for nexus governance.

WEF NEXUS, HPPs AND THE POTENTIAL ROLE OF REGIONAL ORGANIZATIONS

In order to conceptualize the potential role of regional organizations in governing the WEF nexus related to hydropower investments on shared rivers, this section draws upon and brings together three strands of literatures, namely (1) on governing the WEF nexus, (2) on regime theory/neo-institutionalism in international relations, and (3) on benefit-sharing related to HPPs on shared rivers. The section on Governing the WEF Nexus Related to Hydropower on Shared Rivers discusses implications of the emerging literature on governing the WEF nexus for the case of hydropower on shared rivers. Drawing on regime theory and literature on benefit sharing, section Potential Benefits From Coordination and Nexus Governance Related to HPP on Shared Rivers asks for potential benefits from—or incentives for—coordinating WEF-nexus implications of hydropower projects across countries. Further elaborating on regime theory/neo-institutionalism, section Regional Organizations as Coordinating Agencies? then focuses on the role of regional organizations in fostering the governance of WEF-nexus implications of hydropower projects on shared rivers.

Governing the WEF Nexus Related to Hydropower on Shared Rivers

The WEF nexus literature often bemoans a lack of coordination between relevant policy sectors and argues that there is a need to "overcome" siloed decision-making and to work across sectoral boundaries (Hoff, 2011; Leck et al., 2015; Rasul and Sharma, 2016). Many authors stress the need for cross-sector coordination and adequate multi-level governance, taking the geographical scale of the respective nexus problem into account (Leck et al., 2015; Müller et al., 2015; Weitz et al., 2017; Pahl-Wostl, in press). Others argue for flexible, adaptive and polycentric governance mechanisms for nexus governance (Gallagher et al., 2016). Hence, managing the WEF nexus is not only a matter of understanding interconnections (e.g., through modeling) of technology and infrastructure, but also a matter of governance (Bazilian et al., 2011; Kurian, 2017).

However, as Stein et al. (2014) argue, governance can as much be part of the solution, as it can be part of the problem. Weitz et al. (2017) thus argue that there is a need to better understand the conditions under which coordination related to the WEF nexus might come about, including the benefits that self-interested actors might derive from coordination as well as the emergence and role of coordinating agencies, but also the challenges that are likely to hinder coordination across WEF sectors and levels of governance. Based on their comprehensive evaluation of the literature on Integrative Environmental Governance they put forward that coordination may be supported by communicative (e.g., Sustainable Development strategies), organizational (e.g., working groups, coordinating agencies), and procedural (e.g., Strategic Environmental Assessments, SEA) instruments, smart policy mixes as well as the presence of meta-governance principles (e.g., transparency, accountability) and information. However, they also note that (1) negotiations usually take place among actors with unequal power, (2) cross-sector coordination may be inhibited by the transaction costs of involving all affected actors, and (3) solutions may simply lie outside the concerned nexus sectors. Recent case studies on governing the WEF nexus in developing countries also hint at these obstacles, but highlight low state capacities as well as lack of data related to natural resource use as additional barriers (Never and Stepping, forthcoming; Rodriguez-de-Francisco et al., in preparation).

When hydropower investments are made along international rivers, it is not only necessary to ensure coordination between the energy, water, environment and, possibly, agricultural sectors within the investing country, but often also with respective sectoral institutions in riparian countries and possibly with further non-state actors, if conflicts among states are to be prevented. In the international system, such cross-border, cross-sector coordination relies on voluntary negotiations of the actors involved. However, it has been argued that such negotiations may be supported by interstate organizations at regional level (hereinafter "regional organizations"), such as international river basin organizations (IRBOs). For instance UNECE (2015: 5) argues that given that IRBOs "…have experience in bringing together different stakeholder[s] across a basin, they lend themselves naturally to the implementation of nexus-based management approaches in shared basins." Similarly, a draft UNEP report points out that IRBOs can be catalysts to help govern the WEF nexus as they usually work with the agricultural sector on irrigation, the energy sector on hydropower or the environment sector on wetlands (UNEP, 2014). However, the report also warns that the institutional set-up, mandate and capacity of IRBOs may vary considerably across basins, which may influence the ability of IRBOs for nexus governance. Furthermore, Scheumann and Tigrek (2015) put forward that in transboundary settings it may sometimes be easier for energy rather than for water sector institutions to resolve issues around hydropower. Hence, regional economic communities, regional energy organizations or possibly regional power pools may also play a role in nexus governance.

In the following, we argue that nexus governance related to hydropower on shared rivers takes place, if riparian countries coordinate in the design of HPPs so that interdependencies between energy, water and food security are taken into account. We assume that coordination can be expected, if it is in the (perceived) self-interest of the respective investing countries (section Potential Benefits From Coordination and Nexus Governance Related to HPP on Shared Rivers). We furthermore explore in what ways regional organizations might influence whether such coordination occurs (section Regional Organizations as Coordinating Agencies?).

Potential Benefits From Coordination and Nexus Governance Related to HPP on Shared Rivers

Regime theory in international relations theory argues that in the international system coordination and cooperation can be expected when it is in the interest of the actors involved and, in particular, when the actors involved may realize benefits from cooperation (e.g., Keohane, 1984). However, often, even where potential benefits of cooperation exist, cooperation may be inhibited by collective action dilemmas in which individual rationality leads to collectively sub-optimal outcomes (Stein, 1982). In this case, regime theory assumes that institutions—or international regimes—may play a critical role in promoting cooperation. International regimes can be understood as "implicit and explicit principles, norms, rules, and decision-making procedures around which actors' expectations converge in a given area of international relations" (Krasner, 1983). Complementary to regime theory, the literature on benefit sharing explores in greater depth opportunities for the generation of benefits of cooperation on shared rivers as well as institutional prerequisites for their realization (Sadoff and Grey, 2002; Klaphake, 2006; Dombrowsky, 2009; Scheumann et al., 2014). We use this literature to explore potential benefits from cooperation and hence a country's potential self-interest in coordination and nexus governance related to HPPs on shared rivers.

While the main purpose of HPPs is to contribute to energy security, they may negatively affect water resources, ecosystems and livelihoods, including water and food security, at the reservoir site or downstream of it. However, HPPs may also themselves be negatively impacted by upstream land and water use.

In many cases, hydropower projects on international rivers are pursued unilaterally by one riparian state. However, the literature on benefit sharing has established that it can be in the self-interest of states to engage in multilateral coordination and cooperation in order to avoid negative impacts or to generate positive-sum outcomes. If self-interest is understood in a narrow sense, e.g., ignoring reputational effects, an investing state may not be concerned about negative impacts on downstream countries. However, the situation may change if the investing state is interested in maintaining general good relations with its co-riparian states or if an international water treaty commits signatories to avoid significant harm (LeMarquand, 1977).

Hence, whether negative impacts of HPPs on downstream countries and related nexus effects are taken into account also depends on how self-interest is defined. The situation is more obvious, if the HPP itself is negatively impacted by upstream countries' land and water uses. For instance, it could be conceivable that hydropower investors offer Payments for Ecosystem Services (PES) to land and water users upstream in order to reduce negative impacts on the operation of the plant (Rodriguez-de-Francisco et al., in preparation).

The literature on benefit sharing has argued that under certain conditions benefits from joint dam construction offer incentives to pursue HPPs as joint rather than unilateral investments. Such incentives to cooperate exist if: (i) cooperation will enable states to overcome economic or financial limitations to unilateral action (e.g., in the case of the Manantali dam on the Senegal River); (ii) altering the design of a dam upstream will increase aggregate net benefits (e.g., dams on the Columbia River); (iii) locating a dam upstream will increase aggregate net benefits (e.g., Lesotho-Highlands Project on the Orange-Senqu River); or (iv) if a joint dam on a border river will produce mutual benefits (e.g., Kariba Dam on the Zambezi River) (Hensengerth et al., 2012; Scheumann et al., 2014). In the case of joint investments, it is often easier than in the case of unilateral investments to take multiple benefit and cost streams for the various actors involved into account and to compensate those who lose. In fact, taking the various cost and benefit streams into account may even be necessary in order to come to an agreement. Hence, it can be assumed that joint investments are conducive toward nexus governance. However, the literature also indicates that in past projects, the effects of these joint dams on the provision of ecosystem services were not necessarily considered (Hensengerth et al., 2012). Indeed, coordination over dam projects in the above cases has occurred in the interest of maximizing electricity output, rather than in the interest of generating positive trade-offs for water and food security. Hence, while nexus governance may be easier and more likely in the case of joint rather than unilateral investments, even joint investments do not provide a guarantee for adequate nexus governance. This raises the question to what extent nexus governance related to HPPs on shared rivers may be further fostered by regional organizations as potential coordinating agencies.

Regional Organizations as Coordinating Agencies?

When international regimes are institutionalized in a way that they take on actor quality, understood as the ability to act independently, we may speak of international organizations (Schmeier et al., 2016 with reference to Keohane, 1988). More specifically, IRBOs have been defined as "institutionalized forms of cooperation that are based on binding international agreements covering the geographically defined area of international river or lake basins characterized by principles, norms, rules and governance mechanisms" (Schmeier et al., 2016). Out of 124 potential cases, Schmeier et al. (2016) identified a total 81 IRBOs worldwide that satisfied their definition.

As argued by neo-institutionalism, a key function of international organizations is to support member states' interaction (Abbott and Snidal, 1998), and as such reduce transaction costs. Overall, the literature on international and regional organizations identifies various functions that these organizations may fulfill. It has been argued that they provide a stable negotiation forum, which may be used for (1) building trust, (2) establishing rules of engagement (e.g., supporting principles of international law and social and environmental safeguards), (3) analyzing cooperative strategies, (4) pooling or attracting financial resources, (5) sharing the benefits and costs of cooperation, (6) monitoring the implementation of agreements—and hence enforcement—and (7) managing conflicts (e.g., Schiff and Winters, 2002; Hensel et al., 2006; Linn and Pidufala, 2008; Gerlak and Schmeier, 2016).

In terms of nexus governance, in the following we argue that there may be three main avenues by which regional organization may encourage member states to take the cross-border, cross-sector effects of hydropower investments into account: first, by supporting benefit-sharing arrangements, second by ensuring the application of safeguards, and third by fostering the application of principles of international water law. First, regional organizations may support the negotiation of benefit-sharing arrangements by two or more riparian states. This will mostly relate to cases in which co-riparians opt for joint investments, but could theoretically also apply to unilateral investments [e.g., such as currently discussed for the Grand Ethiopian Renaissance Dam (Tawfik and Dombrowsky, 2018)]. In this context, regional organizations may also support the self-interested coordination with upstream water and land users [as occurred during the negotiations for the Columbia River Treaty (LeMarquand, 1993)].

Second, regional organizations may support the application of international social and environmental safeguards (Abbott and Snidal, 1998). This will be easier if investments are planned jointly, but may even apply to unilateral investments. This could include a comprehensive options assessment before a decision on a particular energy generation option is taken, as recommended by the World Commission on Dams (WCD, 2000). A Strategic Environmental Assessment (SEA) "helps define key aspects related to the effects of the energy installations; evaluates a wide range of likely environmental and health impacts; compares alternatives and pros and cons; determines adaptation and mitigation measures and actions; and helps move toward increased efficiency of resources" (UNECE, 2015). Possibly, the regional organization could also carry out a "transboundary nexus assessment," as developed by UNECE (UNECE, 2015; Strasser et al., 2016). Furthermore, a regional organization may develop its own guidelines for sustainable hydropower, as did the International Commission for the Protection of the Danube River (ICPDR, 2013) and the Mekong River Commission (MRC, 2009). Once a decision on a hydropower investment is taken regional organizations may coordinate the preparation of transboundary Environmental and Social Impact Assessments (ESIAs) (UNECE, 1991; Bastmeijer and Koivurova, 2008) and Resettlement Action Plans in order to minimize and mitigate negative impacts.

Third, IRBOs, in particular, may support the application of principles of international water law. IRBOs are usually based on basic customary principles of international water law, such as "equitable and reasonable utilization," "avoidance of significant harm," and "prior notification" (McCaffrey, 2003; Schmeier, 2013). While "significant harm" is to be avoided, according to the 1997 UN Watercourse Convention, the less severe "significant adverse effects" are to be dealt with through procedures of prior notification (see Articles 13–19). So far, 36 states have ratified the convention, and are bound by these principles (Gupta, 2016). Even if riparian countries have not ratified the Convention, we may expect that many IRBOs encourage notification processes as a customary principle of international water law (McCaffrey, 2003). However, in many cases such as the Mekong, the issue has been as to what international water law principles such as "significant harm" mean, and different basin states have applied different views, leading to differences in perception that are hard to unite (Conca et al., 2006).

Empirical research on IRBOs shows that the design, the functions and the effectiveness of IRBOs vary significantly. IRBOs differ greatly in terms of their membership, mandate and functional scope, organizational and financing structure and capacities (Dombrowsky, 2007; Schmeier, 2013; Gerlak and Schmeier, 2016). Next to contextual factors, IRBO design has been identified as an important determinant of IRBO effectiveness (Schmeier, 2013; Gerlak and Schmeier, 2016), and it is also likely to influence nexus governance. For instance, it can be assumed that it is more likely that transboundary effects are considered if all affected countries are members of the regional organization. Furthermore, it may be easier to involve various sectors if the organization has a sufficiently broad mandate and functional scope to do so. Where in place, secretariats may provide information and hence reduce uncertainty, increase transparency and lower transaction costs (Linn and Pidufala, 2008; Saruchera and Lautze, 2016), and may even serve as agenda setters by exploring technically feasible and mutually acceptable solutions (Bauer, 2006; Dombrowsky, 2007; Jinnah, 2014). Hence, in the case studies we will further explore what role the respective regional organizations played in terms of supporting benefit-sharing arrangements, ensuring the application of safeguards, and fostering the application of principles of international water law, and how these potential roles were influenced by their institutional designs (membership, functional scope und secretariat).

THE CASES AND METHODOLOGY

Our research is based on a case study approach, as the total universe of possible cases to be studied for our object of analysis is rather limited, and as it is not straightforward to establish causal relationships in the respective complex settings. Still, case studies are one approach to test whether certain theoretical assumptions are applicable in the real world (Yin, 1994). According to Gerring (2007), the case study approach is defined as an intensive study of a single unit or a small number of units (the cases). It allows some degree of inference about a larger class of similar units, although the unit under consideration is not representative and homogeneity across the sample is not possible. It also enables theoretical development based on empirical insights obtained from the field work conducted. We have selected three cases that illustrate variations of failure and success by regional organizations to manage nexus impacts of HPPs. (1) The Rusumo Falls project on the Kagera River, a tributary of the Nile, is pursued by Burundi, Rwanda, and Tanzania (**Figure 1**). The Nile Equatorial Lakes Subsidiary Action Program (NELSAP), a sub-organization of the Nile Basin Initiative (NBI), coordinates, and the World Bank finances, the project. (2) Planned by Burundi, the Democratic Republic of Congo (DRC), and Rwanda, the Ruzizi III HPP on the Ruzizi River is being coordinated by Energie des Grands Lacs (EGL), a regional energy organization (**Figure 1**). There are plans to involve a private investor as part of a public–private partnership (PPP) supported by several development banks. (3) Laos is constructing the Xayaburi dam on the Mekong with the support of Thai investors; the investment decision was taken outside of the MRC, although Xayaburi falls under the remit of the MRC's mandate (**Figure 2**). These cases differ in the following aspects: first, whether hydropower is planned jointly (Ruzizi, Rusumo) or unilaterally (Xayaburi); second, whether the process is supported by an IRBO (Rusumo, Xayaburi) or a regional energy organization (Ruzizi); and, third, whether private investors are present (Ruzizi, Xayaburi) or not (Rusumo). As such, they allow for a deeper understanding of the role of IRBOs in managing WEF nexus.

All cases build on extensive field research involving qualitative semi-structured expert interviews [on expert interviews see Bogner et al. (2005)]. We found qualitative semi-structured interviews to be useful in highly politicized contexts such as presented here as they allowed to "elicit [...] tacit knowledge and subjective understandings and interpretations" (Marshall and Rossman, 2006: 53). This method further allowed for a prior elaboration of a flexible interview guideline (adaptable for different actor groups) which facilitated good comparability between interviews (Bryman, 2008). Interviewees were selected following a snowball sampling technique. Snowball sampling is a non-probability sampling technique that starts with the identification of an initial interviewee, who then provides further contacts. The procedure was repeated with additional interviewees until saturation was reached [see Kirchherr and Charles (2018) for a description and a critical review of this method in a hydropower context]. In all cases, counterpart institutions acted as important gatekeepers: they were connected to all relevant stakeholders involved in the projects and facilitated access to important interviewees.

Field work for Rusumo Falls and Ruzizi III was carried out between December 2012 and April 2013 and included a review of pertinent planning documents and 95 stakeholder interviews with representatives of regional organizations, donor representatives, members of the national negotiation teams, representatives of the government ministries or agencies involved, environmental and social experts, representatives of sub-national and local administrations, as well as representatives of the affected communities, civil society and non-governmental organizations (NGOs) in all four countries. Interviewees were

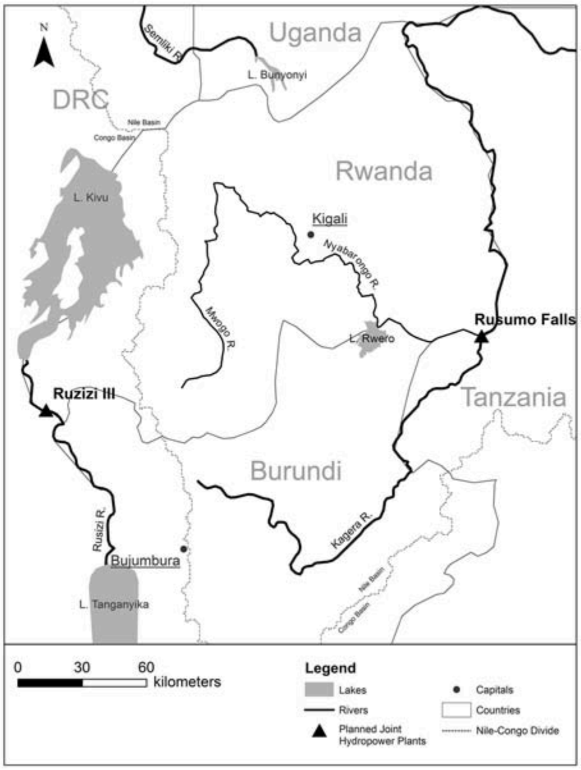

FIGURE 1 | Location of the Rusumo Falls and Ruzizi III projects, Source: Own preparation.

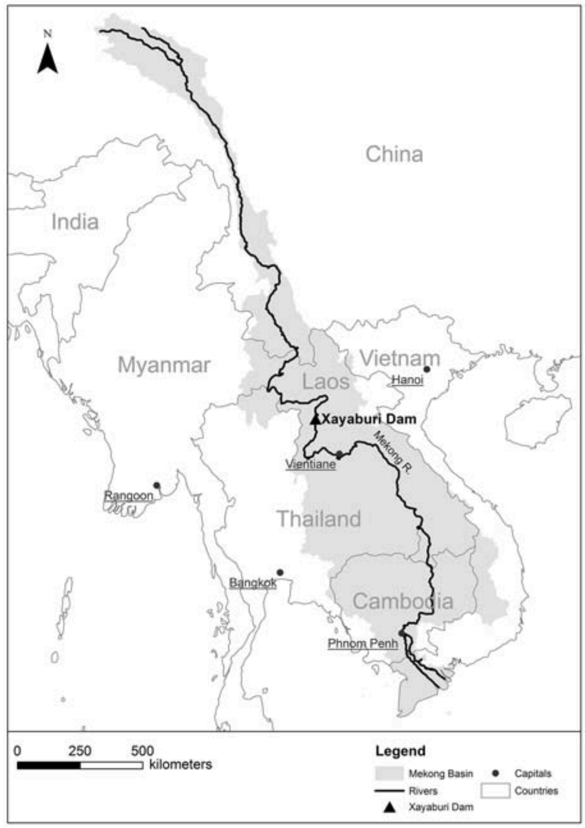

FIGURE 2 | Location of the Xayaburi dam, Source: Own preparation.

selected based on their involvement in the negotiation of both hydropower projects, their energy and environment sector expertise or their connection to local project-affected populations. Initial access to interviewees was provided by NELSAP for Rusumo Falls and EGL for Ruzizi III. Information was updated in 2016 and 2018 based on internet updates provided by the relevant regional and donor agencies. The interviews were transcribed, coded and analyzed using atlas.ti content analysis software.

Field work for the Xayaburi case was carried out during a four-week stay at the MRC in Laos in September 2011 and includes a review of relevant planning documents, the MRC's planning history for all Mekong mainstream dams including Xayaburi, and a total of 21 interviews with MRC personnel and NGOs. The information was updated through personal email communication with a former advisor to the MRC in August 2014, and during interviews with NGOs in Cambodia involved in Mekong basin planning in July 2015. In line with the snowball method, interviewees were selected in collaboration with international donor organizations, who provided the initial access to the MRC Secretariat and to NGOs in Vientiane. Interviewees were selected on the basis of their involvement in basin-wide planning processes, their knowledge and involvement in hydropower planning processes, the drafting of relevant policies (including EIA and resettlement), their knowledge of benefit-sharing processes, and their connection to local project-affected communities.

All of our interviewees were therefore considered experts, as they possessed specific technical, process, or interpretative knowledge in fields related to hydropower planning processes. Their knowledge constitutes not only specialized expertise, but it is in large parts also practical and action-oriented knowledge which intermingles with subjective interpretations (Bogner et al., 2005). This in turns lends itself to a qualitative analysis as advanced here.

The data gathered in the semi-structured interviews was analyzed with the help of qualitative content analysis. Qualitative content analysis is an empirical, methodologically controlled approach of analyzing large amounts of data linked to fixed/recorded communication (Mayring, 2000). In this case it refers to the transcribed interviews. The method rests upon a rule-based approach and is based on the assumption that the content of the interview situation, e.g., the perceptions of the interviewed experts, has to be revealed by interpretation (Mayring, 2000).

The coding of the transcribed interviews was the essential part of our qualitative content analysis. As we pursued a theory-based research design for our empirical data gathering, we were necessarily following the path of deductive category/code development. Thus, based on our understanding of the theoretical framework, we formulated definitions of relevant concepts and attributed coding rules and examples which were summarized in a coding manual (Mayring, 2000). Although a pure *ex ante* formulation of codes might be theoretically possible, we allowed for the development of predefined categories as well as inductive code definition based on the transcribed interviews themselves. The interpretation of data was thus an iterative process in which feedback loops allowed our research to be sufficiently open and at the same time adaptable to new, unexpected findings (Gläser and Laudel, 2009). In the Ruzizi and Rusumo cases, transcription and coding was done digitally and supported by f4 and atlas.ti content analysis software. In the Xayaburi case, coding proceeded as above but was done manually, following the recommendations by Bazeley (2007) for small-scale studies [for a debate on manual vs. electronic coding of qualitative interviews see Basit (2003)].

The African cases were analyzed by Ines Dombrowsky at the German Development Institute/Deutsches Institut für Entwicklungspolitik (DIE). The research design and methodology were peer reviewed by an expert group and presented and discussed in a two-hour public meeting at DIE to ensure compliance with the Guidelines on Safeguarding Good Scientific Practice and Preventing Scientific Misconduct of DIE, and the Proposals for Safeguarding Good Scientific Practice by the Deutsche Forschungsgemeinschaft/German Research Foundation (DFG). According to these institutional and national guidelines and regulations, an approval by an Ethics Committee was not required. In addition, for research in Rwanda an exposé was presented to the Rwandan Ministry of Science upon which the Rwandan government granted the research permit.

The case study on the Xayaburi dam was carried out by Oliver Hensengerth, who was employed at the University of Southampton during the time of field research. The project underwent the standard approval procedures of the University of Southampton following the funding decision by the British Academy, and the project was approved as part of this process, which is designed to ensure compliance of all research projects with the Ethics Policy of the University of Southampton.

In all three cases, given the political sensitivity of the research and the (partly) authoritarian political context in which the research took place, interviewees were not asked to sign consent forms. Instead, all subjects gave verbal informed consent to the use of anonymized statements from the interviews for scientific purposes.

RESULTS

The following sub-sections scrutinize transboundary nexus governance in each case by analyzing the roles the respective regional organizations played in terms of supporting benefit-sharing arrangements, ensuring the application of safeguards, and fostering the application of principles of international water law, and how these potential roles were influenced by their institutional designs, in particular their membership, functional scope and the presence of a secretariat.

Rusumo Falls HPP

The Rusumo Falls HPP will be an 80 MW run-of-river plant on the Kagera River at the border between Rwanda and Tanzania (see **Figure 1**). While planning goes back to the 1980s in the context of the then existing Kagera Basin Organization (Rangeley et al., 1994), Burundi, Rwanda and Tanzania resumed preparation in 2006 in the context of the Nile Equatorial Lakes Subsidiary Action Program (NELSAP). NELSAP is an investment program of the Nile Basin Initiative (NBI) which includes all Nile riparian countries in the Equatorial Lakes region plus Sudan and Egypt as downstream riparians. The NBI de facto performs the functions of an IRBO and is recognized as such (Schmeier et al., 2016), even if a ratified international legal agreement is outstanding. The functional scope of NBI and NELSAP is broad and includes water, energy, and environmental issues. The planning of Rusumo Falls was taken forward by representatives of the energy administrations of the three participating countries, supported by the NELSAP Coordination Unit (CU) in Kigali as a secretariat.

Rusumo Falls is a trilateral joint investment based on a benefit-sharing arrangement (Dombrowsky et al., 2014). Given that the HPP will be located at the border between Rwanda and Tanzania, the two countries had to cooperate to build a HPP. However, interestingly upstream Burundi participates in the project as an equal partner. According to our interviews, Burundi was included for at least two reasons. First, it had already been part of the planning for Rusumo Falls in the context of the Kagera Basin Organization (Int. 5, 8, 87). Second, as a reservoir project the reservoir would have inundated Burundian territory (Int. 5, 7, 19, 41). The power generated is envisioned to be equally shared among the three countries. The HPP will be publicly owned, but privately managed. The Rusumo Power Company Limited, co-owned by the three governments involved, was registered in March 2013. Financial closure with the World Bank was reached in August 2013.[1] The World Bank's International Development Association provided USD 113.3 million as loans or grants to each country for its equity in the Rusumo Power Company. The compensation of project-affected populations took place in 2015. The contract with the construction firm was signed in November 2016 and construction started in March 2017.[2] Rusumo Falls will be connected to the East African Power Pool.

In 2002, energy experts from the Nile Equatorial Lakes countries decided to carry out an SEA of energy options, given that it was a requirement of the World Bank before selecting specific projects. The SEA presented in 2005 identified Rusumo Falls HPP (as well as Ruzizi III) as one of the five most realistic medium-term power options (NBI, 2005). The SEA acknowledged that Rusumo Falls was comparatively advanced in terms of technical preparation, but identified potential social and environmental impacts as drawbacks and recommended further assessments. Overall, the SEA signaled a preference for hydropower options due to the expected high cost and small size of solar energy,

[1] http://nelsap.nilebasin.org/attachments/article/34/Rusumo%20Factsheet_-_ENGLISH.pdf, retrieved 19 July 2016.

[2] http://www.nilebasin.org/index.php/new-and-events/133-construction-of-rusumo-falls-hydroelectric-project-to-start-30-march-2017, retrieved 2 July 2018.

or lack of identified resources for wind or geothermal energy.

In 2006, Rwanda, Burundi and Tanzania signed a Joint Project Development Agreement for Rusumo Falls. A consultant was selected to carry out a feasibility study, including an ESIA in 2007 and 2008 (SNC Lavalin International, 2008). However, it turned out that for an in-depth ESIA, procedures had to be harmonized, and a new topographical mapping, a land use study and a household survey had to be carried out (SNC Lavalin International, 2012). The countries requested the consultant to do so for the so-called "full development scheme" in order to maximize hydropower production (SNC Lavalin International, 2012). In May 2011, the consultant indicated that 17,450 households would be affected. The countries therefore decided to pursue a smaller reservoir, the "intermediate development scheme." This still resulted in 7,330 affected households. Hence, in 2012, the countries decided to go for a run-of-river scheme [Interview (Int.) 57]. Since the World Bank required a change of consultant due to corruption charges, the final results were presented in March 2013. For the run-of-river scheme, the capacity of the plant had to be reduced from 90 to 80 MW, while the number of affected households was reduced from 17,450 to 669 (ARTELIA, 2013). Of these, a total of 178 households and business units had to be resettled. The project's environmental impacts were considered moderate. The project would mainly affect biological diversity in the Rusumo Falls spray zone and interrupt the river's ecological flow on a stretch of 500 meters. Therefore, the ESIA recommended that the spray zone be equipped with an artificial spray system and a minimum environmental flow of 10% (ARTELIA, 2013; Int. 56). In terms of negative effects on the HPP, it is expected that the reservoir will be moderately affected by sediment inflows (ARTELIA, 2013). Hence, the ESIA recommended a sediment transport study to be performed before start of construction and to potentially adapt the design to minimize risk (ARTELIA, 2013). The ESIA was carried out according to the World Bank safeguard policies and national laws. In order to ensure that the ESIA also fulfills the respective countries' national laws, upon a World Bank request, the environmental agencies of three countries also provided clearance certificates for the HPP.[3] In order to comply with international water law principles, NELSAP sent a riparian notification to the Nile riparian countries downstream in November 2012 and all necessary "no objection" notifications were received (Int. 57).

Hence, while the energy ministers had initially insisted on maximizing energy generation, in the end the inclusive inter-state approach and the ESIA-induced change of scheme minimized negative impacts on the water and food security of affected communities in the three participating countries. However, the planning process could have been accelerated, had the countries decided to pursue a run-of-river HPP from the beginning. As one country representative stated: "Of course it has taken time because we wanted this project really to be a big project, to be implemented at full capacity, but because of the environmental and social impact, we really had to reduce our ambitions" (Int. 95).

[3]http://nelsap.nilebasin.org/attachments/article/34/Rusumo%20Factsheet_ _ENGLISH.pdf,retrieved19July2016.

Ruzizi III HPP

The 147 Megawatt Ruzizi III run-of-river HPP to be located on the Ruzizi River on the border between Rwanda and DRC (see **Figure 1**), is jointly planned by Burundi, the DRC and Rwanda in the context of Energie des Grands Lacs (EGL), a regional energy sub-organization of the Communauté Économique des Pays des Grands Lacs (CEPGL). EGL consists of a General Assembly of the Ministers of Energy of the three countries, an Institutional Meeting of Experts, a board of Account Auditors and the Managing Committee.[4] EGL holds an office (the secretariat) in Bujumbura directed by the Managing Committee and with staff drawn from the three countries in roughly equal proportion. The purpose of EGL is regional energy planning.[5] According to Rangeley et al. (1994: 11): "EGL may be seen as an RBO only in that, through its parent organization CEPGL, it is responsible, among other things, for hydro-electric power development on the Ruzizi river linking Lake Kivu to Lake Tanganyika. Beyond that, it is a regional energy planning organization." For the negotiation of the Ruzizi III project, each country established a negotiation team. The planning process is coordinated by the EGL office. According to our interviews, downstream Burundi is included, as it is an equal partner in EGL and as the three countries already cooperated in the development and construction of the Ruzizi II HPP under the auspices of EGL (Int. 1, 2, 5, 6, 8, 47, 87, 89, 96). It is also included as it could potentially be affected by the project (Int. 5, 7, 19, 41).

Ruzizi III is conceived as a public–private joint venture, in which the investor will have the majority and the countries equal minority shares supported by donor soft loans. Each country is supposed to have access to one third of the energy produced, and hence, similar to Rusumo Falls, the HPP is based on a regional benefit-sharing arrangement (Dombrowsky et al., 2014). A pre-feasibility study was prepared in 1991 (CEPGL, 2012). In-depth planning started in 2007 after conflicts in the region had calmed down. Project preparation is supported by the European Investment Bank, the German KfW Development Bank, the African Development Bank, the Agence française de développement, the European Union and the World Bank.[6] Negotiations between the then preferred investor, Sithe Global and Industrial Power Services (IPS, Kenya), and the three countries started in October 2012. Total costs were estimated at USD 625 million, and the African Development Bank was first to commit a total of USD 138 million of loans and grants for

[4]http://www.egl-grandslacs.org/index.php/en/about-egl/egl-bodies, retrieved 2 July 2018.

[5]http://www.egl-grandslacs.org/index.php/en/about-egl/mission-and-objectives, retrieved 2 July 2018.

[6]http://www.afdb.org/en/news-and-events/article/afdb-approves-regional-hydropower-ppp-to-increase-electricity-supply-and-integration-in-burundi-drc-rwanda-15255/, retrieved 20 July 2016.

the construction of Ruzizi III in December 2015.[7] Signature of the Project Agreements between the three countries and a new investor consortium consisting of IPS and SN Power (Norway) had last been envisioned for May 2018. However, the signature could not be realized as no final consensus could be reached on three outstanding issues, including on avoiding that potential surplus construction would be reflected in the tariff.[8] Instead the three countries signed a Declaration reinforcing their intention to proceed with the project. Like Rusumo Falls, Ruzizi III is supposed be connected to the East African Power Pool.

In terms of social and environmental safeguards, as mentioned above, Ruzizi III was identified as a medium-term priority energy investment in NELSAP's SEA of 2005. In the SEA, this option had the best rank in the economic, financial and environmental categories, as no resettlement was expected (NBI, 2005). The EGL office coordinated the preparation of the ESIA, which was financed by the European Investment Bank. In 2012, a pre-final ESIA was presented (SOFRECO et al., 2012). For the ESIA, SOFRECO conducted a household survey and various stakeholder consultation workshops. The ESIA found that 648 households would be affected, and eight to nine would have to be resettled. Due to its potential affectedness, Burundi is supposed to participate equally in the Local Community Development Plan. Interviewees also argued that given that all three countries will benefit from the electricity produced, communities in the project areas of all three respective countries should benefit too (Int. 34, 37, 38, 44, 54, 55, 66, 71, 78). The environmental impacts of the HPP were considered moderate: next to the existing Ruzizi I and II HPPs, Ruzizi III would be a further obstacle for the Ripon barbell fish. Furthermore, Ruzizi III would interrupt the ecological flow on a stretch of 4.3 km. Therefore, the migration of fish shall be secured by the installation of fish passes and a minimum ecological flow of 8% is to be maintained (SOFRECO et al., 2012). The European Investment Bank required the countries to carry out the ESIA according to World Bank safeguards as well as respective national laws. In case of divergence between national laws and World Bank policies, the higher standard was applied (SOFRECO et al., 2012). In March 2016 the Social and Environmental procedure manual was validated.[9] Hence, in this case, donor safeguards also played a role, and their application was facilitated by the regional organization EGL. However, the pre-final ESIA needs to be validated by the private investor.

Given that EGL is a regional energy organization, international law principles are not anchored in its statutes. However, prior notification was also not required as all affected riparian states are involved in project preparation.

Quite significantly, given that the functional scope of EGL does not include land and water uses, EGL as a secretariat even facilitated the set-up of an IRBO to promote the sustainable management of the Lake Kivu and Ruzizi River Basin, the Basin Authority of the Lake Kivu and the Ruzizi River (Autorité du Bassin du Lac Kivu et de la Rivière de Rusizi, ABAKIR). This was done given that the Ruzizi valley is very steep, and human-induced and natural erosion (as well as litter) may provide significant threats to the project (SOFRECO et al., 2012). The International Convention on the Integrated Management of Water Resources of the Lake Kivu and Ruzizi River Basin (ABAKIR, 2011) was signed by the Water Ministers of the three states in July 2011. Pending ratification through the heads of state, an interim institutional arrangement was set up at the premises of CEPGL in January 2013, financed by the European Development Fund (Int. 17, 62). ABAKIR is supposed to provide a basis for a better use of shared waters in the basin and therefore mitigate the risk of lower energy output due to detrimental upstream water usage. In addition to ABAKIR, a coordination center will be put in place by the three countries to coordinate the use of the Ruzizi River across the Ruzizi I, Ruzizi II and Ruzizi III HPPs (Int. 2). Furthermore, the ESIA proposed to set up a 5 years anti-erosion program in the order of USD 1.7 million (SOFRECO et al., 2012). In this context, the consultants also suggest that the project developer considers setting up a PES scheme in the Ruzizi Valley.

Xayaburi HPP

The Xayaburi HPP is a 1285 Megawatt HPP built by Laos on the mainstream of the Mekong, financed by private Thai banks and constructed by the Thai construction company Ch. Karnchang. Laos plans to export 95% of the electricity produced to Thailand (Middleton and Dore, 2015). Laos along with Thailand, Cambodia and Vietnam is a member of the MRC. Upstream China and Myanmar are not members and have observer status. China has been collaborating with the MRC during dry season flow, but has refused to share further data.

The MRC has a wide-ranging functional scope. Article 1 of the 1995 Agreement on the Cooperation for the Sustainable Development of the Mekong River Basin (henceforth: 1995 Agreement) commits members to "cooperate in all fields of sustainable development, utilization, management and conservation" including hydropower, fisheries, navigation, and flood control. The principal tool for this is the Basin Development Plan (MRC, 2016a) which develops a joint planning approach, including an equitable distribution of risks and benefits between all member states. This joint planning function is carried out by the MRC's Secretariat on behalf of member states, who are represented in the Council (heads of government) and the Joint Committee (sector ministries) and who determine the Secretariat's work plan (1995 Agreement, Chapter IV). The Basin Development Plan is mutually agreed by member states. To implement it, the MRC has set out a number of guidelines and procedures. With relevance to mainstream hydropower dams, this includes a 5-volume Knowledge Base on Benefit Sharing (MRC, 2011), the Procedures for Prior Notification, Consultation and Agreement (PNPCA) (1995 Agreement, Article 5; (MRC, 2016b), and the Preliminary Design Guidance for Proposed Mainstream Dams in the Lower

[7] http://www.afdb.org/en/news-and-events/article/afdb-approves-ruzizi-iii-hydropower-plant-project-bringing-green-energy-to-burundi-drc-and-rwanda-15275/, retrieved 20 July 2016.
[8] http://www.egl-grandslacs.org/index.php/fr/publications/actualites/89-declaration-de-kinshasa-sur-le-projet-ruzizi-iii, retrieved 2 July 2018.
[9] http://www.afdb.org/en/news-and-events/article/afdb-approves-regional-hydropower-ppp-to-increase-electricity-supply-and-integration-in-burundi-drc-rwanda-15255/, retrieved 20 July 2016.

Mekong Basin (MRC, 2009). The MRC also applies principles of international water law, notably the principles of reasonable and equitable utilization, and no harm (1995 Mekong Agreements, Articles 5 and 7) and has operationalized the principle of prior notification in the PNPCA. The focus on hydropower is important as Laos and Cambodia are planning a total of eleven dams on the Mekong mainstream, of which nine are to be located in Laos and two in Cambodia. This is in addition to the upstream dams built or planned by China. The first of the eleven dams in the Lower Mekong is the Xayaburi dam.

Although as a mainstream dam Xayaburi is subject to MRC procedures and guidelines, Laos initiated the project unilaterally. In 2007, Laos concluded a Memorandum of Understanding (MoU) with Ch. Karnchang to study the feasibility of the project; in 2008 the two parties signed a Project Development Agreement. In 2010 Thai engineering consulting company TEAM completed the feasibility study and the ESIA. However, the ESIA assessed impacts only ten kilometers downstream from the dam site. Hence, transboundary effects with respect to sediment transport and fisheries, and implications for food security downstream were not studied.

Still in 2010, Laos and the Electricity Generating Authority of Thailand (EGAT) signed a MoU for a Power Purchase Agreement despite ambiguity over the status of the dam (Matthews, 2012); and Laos and Ch. Karnchang signed the Engineering, Procurement and Construction contract (Hensengerth, 2015). Following the completion of these processes, Laos submitted the project documents to the MRC, which started the MRC's first ever PNCPA process. In these processes, the politics of the Thai electricity sector played an important role. In particular, the monopoly position and profit structure of the Thai state-owned electricity utility EGAT, private sector profit interests, and civil society opposition against domestic HPPs are strong drivers for the Thai government and private actors to support hydropower development in Laos, with an eye to importing the produced energy (Matthews, 2012).

The PNPCA process lasted for six months, from October 2010 to April 2011 and was held at Joint Committee level. It ended without agreement, with downstream Vietnam and Cambodia citing a threat to their food security, a claim that Laos rejected. The issue was moved up to Council level, but still members were unable to find a compromise. During the Council meeting in December 2011, Council members decided to commission a study to further explore potential transboundary impacts of mainstream hydropower dams (the so-called Council Study). Meanwhile, Cambodia and Vietnam found support for their concerns in a transboundary SEA study for all planned Mekong mainstream dams, commissioned by the MRC in 2009, funded by MRC donors, and conducted by Australian environmental consulting firm ICEM. The SEA suggested a severe lack of data on transboundary impacts and therefore a moratorium on dam-building for ten years to allow the generation of reliable data (ICEM, 2010). In contrast to the TEAM ESIA study, the SEA considered cumulative impacts of the eleven mainstream dams (Suhardiman et al., 2015). Again, Laos rejected that Xayaburi would produce any downstream impacts. Yet, facing a public backlash from downstream countries, international donors as well as regional and international NGOs and media outlets, Laos commissioned Swiss-Finnish consultancy Pöyry to conduct a study on whether Laos complied with the 1995 Agreement, the PNPCA, and the Preliminary Design Guidance for Proposed Mainstream Dams in the Lower Mekong Basin. This so-called Compliance Study, published in 2011, found Laos in compliance but suggested alterations to the dam design to allow fish passage and sediment flush (Pöyry, 2011). While Laos subsequently altered the dam design accordingly, it did not alleviate concerns by Vietnam, Cambodia and NGOs who insisted on implementing the moratorium proposed by the SEA. Citing its compliance with MRC guidelines and procedures, and insulated from international pressure by private Thai finance, Laos continued planning for the dam and held the ground breaking ceremony in November 2012.

The Council Study was published in 2017. It concludes that if mainstream dams are not realized, the Lower Mekong Basin would lose almost 60% of economic benefits in the power generation sector. At the same time, however, "nearly 25% of the hydropower gains would be lost in the fisheries sectors" (MRC, 2017b: 6, 52). In the absence of benefit-sharing mechanisms and coordination with China and Myanmar, positive and negative impacts will be unevenly distributed between upstream and downstream countries, but also between poor and richer population groups, with significant impacts on food security to be felt particularly in Laos and Cambodia (MRC, 2017a: 2–4, 6–7). The Council Study therefore confirmed previous studies suggesting a strong impact on food security due to the impact on fisheries (Smajgl et al., 2015; Pittock et al., 2016). Yet, regardless of the 2011 Council decision to conduct a multi-year study, Laos continued with dam-planning: in 2014 it notified the MRC of its decision to start construction of the Don Sahong dam. Indeed, Fawthrop[10] argued that "[w]ork is moving forward faster than the completion of scientific studies needed to provide the evidence of 'significant harm.' " And in November 2016, Laos notified the MRC of its intention to start construction of the Pak Beng HPP.[11]

DISCUSSION

This paper asked how regional organizations may influence nexus governance related to hydropower projects on international rivers. We posited that countries investing in hydropower can be expected to coordinate regarding the HPP's energy, food and water security impacts if coordination is in their perceived self-interest. Regional organizations may furthermore foster transboundary nexus governance by supporting benefit-sharing arrangements, ensuring the application of safeguards, and fostering the application of principles of international water law. We assumed that these potential roles were influenced by the organization's institutional designs, including an inclusive membership structure, a sufficiently broad functional scope

[10] https://thediplomat.com/2014/04/mekong-summit-struggles-to-halt-devastating-dams/, retrieved 5 July 2018.

[11] Further details on the Don Sahong and Pak Beng PNPCA can be found on the MRC's PNPCA pages at http://www.mrcmekong.org/topics/pnpca-prior-consultation/, retrieved 5 July 2018.

und the presence of a secretariat. Overall, the cases show that there can be fundamental differences in the way cross-border, cross-sector coordination related to hydropower investments does or does not take place and the role regional organizations do or do not play in this.

With respect to the investing state's self-interest to coordinate across countries and sectors, fundamental differences exist between the African and the Mekong cases. The two African HPPs are investments on border rivers, and hence required coordination at least among the two border states. Still, quite significantly in both cases, Burundi as potentially affected third country was included as an equal partner which fully participates in the benefit-sharing scheme. In the Rusumo Falls case, WEF nexus governance furthermore took place in so far as the dam design was changed from a reservoir to a run-of-river project. In the Ruzizi III case, the set up of ABAKIR as IRBO can be considered as an additional element of nexus governance. In contrast, Xayaburi is a quasi-unilateral investment by Laos (albeit with Thai support) on a transboundary river. In this case Laos (and Thailand) decided to go ahead with the project despite potential negative effects on downstream Cambodia and Vietnam, even if in the end some modifications in dam design, and hence arguably some limited nexus governance, took place. However, the unilateral investment happened even despite Lao and Thai membership in the MRC and elaborate MRC provisions on joint planning and benefit sharing related to mainstream Mekong dams. Hence, in line with literature on benefit sharing, the cases show that nexus governance may be easier in the case of joint rather than unilateral investments. Furthermore, in the two African cases, arguably not least due to donor requirements, more attention was given to social and environmental impacts that in some earlier joint dam projects studied by Hensengerth et al. (2012).

In terms of the HPP itself being negatively impacted by upstream countries' land and water uses, the Ruzizi case is illustrative. The set-up of an IRBO for Lake Kivu and the Ruzizi River (ABAKIR) and the proposed PES schemes demonstrate that it can be in the self-interest of those who plan HPPs to coordinate with—and even to set up—an IRBO in order to reduce negative effects of upstream water and land uses on the HPP.

With respect to the role of the regional organizations in supporting benefit-sharing arrangements, in the African joint investments NELSAP and EGL provide the platforms for joint project preparation and the respective secretariats are supporting the planning process in several ways, even if both processes are taking much more time than originally envisioned and even if it is still uncertain whether a final agreement will be reached for Ruzizi III. In contrast, while the MRC Secretariat sought to influence the decision-making process related to the Xayaburi dam, it was in a fundamentally different position, having no implementation mechanism to force countries to provide mutually beneficial solutions. Hence, Xayaburi points to the limits of IRBOs to coordinate HPP investments, if member states are unwilling to pursue respective investments in the framework of the regional organization. It also shows that the scale at which HPP investment decisions are taken may not correspond to the basin level (Matthews, 2012; Hensengerth, 2015), which may limit the influence of IRBOs.

In terms of the role of the regional organizations in ensuring the application of safeguards, in all three cases regional organizations initiated SEAs with the support of donors. The two African HPPs were identified in an SEA of power options coordinated by an IRBO (NELSAP). However, the preparation of this SEA was driven by World Bank policies, so it is unclear whether this would have taken place in the absence of donors. In the Xayaburi case, the MRC Secretariat initiated a donor-supported SEA after Laos had signed a MoU with Ch. Karnchang. While the SEA recommended a ten-year moratorium on construction, and further studies, Laos did not take up this recommendation, illustrating the limits of the MRC and of the SEA as a procedural instrument vis-à-vis private-sector-supported investments. Suhardiman et al. (2015: 199) point out that the MRC Secretariat still used the SEA "as a way of providing political space and opening the discussions on dams to a wider public" and of informing the PNPCA process. Hence, the MRC Secretariat used the SEA to influence the discourse and Laos's dam design to a certain extent in a situation where the limits of its agenda-setting power became obvious.

With respect to the role of regional organizations in the preparation of ESIAs, the juxtaposition of the two African and the Mekong cases also illustrate stark differences, depending on whether the investments are undertaken jointly or unilaterally. The African joint investments coordinated through regional organizations made an ESIA covering all states involved obvious. However, similar to the SEA, in both cases the ESIAs needed to satisfy World Bank requirements. In contrast, in the Xayaburi case, Laos did not prepare a transboundary ESIA and resisted doing so even after repeated requests from Vietnam, Cambodia, the MRC Secretariat and donors. Hence, regional organizations are more likely to be in a position to coordinate ESIAs in the case of joint rather than unilateral investments.

In terms of the role of regional organizations supporting the application of international water law in general and prior notification in particular, the cases show that the two IRBOs, NELSAP and MRC, promoted notification procedures, albeit with differing success. In the Rusumo case, the downstream countries beyond Lake Victoria provided no objections without further complications. It is worthwhile noting that impacts can be expected to be minimal since HPP-induced flow variations of the Kagera River would be buffered by Lake Victoria. Furthermore, as a run-of-river project, no consumptive uses and low evaporation losses are expected. Still, Egypt's no objection reflected a shift of attitude, as Egypt used to observe Rwandan water uses carefully before the NBI was established (Int. 57). In the Xayaburi case, the application of prior notification through the PNPCA process did not lead to constructive consultations. While downstream countries, donors and NGOs used the MRC as a focal point for their protest (Hensengerth, 2015), the PNPCA process certainly remains unsatisfactory. The case also shows that the international legal principles of reasonable and equitable utilization and avoidance of significant harm were understood differently by member states, leading to a rejection or to different interpretations of underlying data. Donors subsequently proposed a review of the implementation of the PNPCA provisions (Hensengerth, 2015). In contrast to the IRBOs, EGL as regional energy organization did not apply notification procedures. However, they were unnecessary in this case as all potentially affected riparian countries were part of the investment, suggesting that membership matters in this regard. Hence, while an advantage of IRBOs may be the application of principles of international water law, the Xayaburi case also shows that this may shift the conflict to one around the interpretation of the respective principles.

Therefore, while regional organization may support benefit-sharing arrangements and the application of environmental and social safeguards and international law principles, their influence also depends on the willingness of the member states and investors to abide by the organization's rules. This, however, is not only the case for nexus governance but a general challenge in international relations and therefore also for regional organizations.

We furthermore assumed that the design of regional organizations, including a broad functional scope, an inclusive membership and the existence of a coordinating secretariat matter in promoting nexus governance. With respect to membership, the inclusive institutional arrangements in the cases of Rusumo Falls and Ruzizi III ensured that potential negative impacts on third countries (in both cases Burundi) were considered and that Burundi would even equally benefit from the respective HPPs. In the Mekong case, the fact that China and Myanmar only have observer status in the MRC limits MRC members' coordination with upstream water users. However, it should also be noted that Laos and Thailand went ahead with Xayaburi despite their respective membership in the MRC. This implies that while joint membership may promote coordination, it cannot be considered a sufficient condition for nexus governance.

In terms of functional scope, in the case of NELSAP, coordination of energy, water and land issues is within the mandate of NELSAP. Still, this did not prevent the energy experts for a long time from pursuing a reservoir project in order to maximize hydropower generation, although they finally changed the scheme once the resettlement figures were provided. In the case of Ruzizi III, EGL's functional scope was considered too narrow to deal with land and water uses upstream. Therefore, given the significant threats to the HPP by erosion, EGL even supported the set-up of ABAKIR as IRBO for Lake Kivu and the Ruzizi Basin, which however, still has to demonstrate its effectiveness. In that sense, a narrow functional scope did not prevent nexus governance. In the Mekong case, the MRC has an encompassing coordinating role for the sustainable development of the Mekong basin. The MRC has formulated rules for basin development, to which member states are bound. The MRC would therefore be ideally placed to consider WEF nexus and has even initiated WEF nexus dialogues (Middleton et al., 2015; Lebel and Lebel, 2018). However, as discussed above, the MRC could not prevent Laos from generating financial resources outside of the MRC and the organization's donor framework to become financially independent of any multilateral financing arrangements and from any pressure emerging from such arrangements—in sharp contrast to the African case studies. Hence, our assumption that it may be easier to involve various sectors if the organization has a sufficiently broad mandate and functional scope to do so, is not directly supported by the cases studied.

In the Rusumo Falls and Ruzizi cases, the respective secretariats played an important role in coordinating the planning and the negotiation processes. In the case of Rusumo Falls, the ESIA coordinated by NELSAP eventually led to the change of the HPP design. In the case of Ruzizi III, EGL facilitated the set up of ABAKIR as IRBO. In contrast, while in the Xayaburi case the MRC Secretariat became a focal point of the protests of downstream countries, donors and NGOs, it was not in a position to enforce its comprehensive planning procedures for mainstream dams, showing that the influence of the secretariat to set the agenda may be limited and hinges upon the willingness and compliance by its member states.

Beyond our analytical framework, the analysis shows that the effectiveness of regional organizations in fostering nexus governance is also influenced by the availability of data as well as the presence of donors and private investors. All cases show that the assessment of impacts and nexus governance is data intensive and that the lack of good data or a refusal to generate the respective data may be a hindering factor. In the Mekong case, gaining a joint understanding of impacts turned out to be difficult and Laos did not accept the ten-year moratorium suggested in the SEA to improve the scientific basis for dam planning. In the Rusumo Falls case, it took three additional years of study until an ESIA that satisfied donor demands was presented. The fact that the scientific basis for environmental impact assessments in Africa's Great Lakes region was limited was also supported by the interviews. While one group of interview respondents reiterated findings from the ESIAs that the environmental impacts of Ruzizi III and Rusumo Falls HPPs would be limited (e.g., Int. 1, 24, 56), one independent local environmental expert believed that the scope and quality of the environmental impact assessments for Rusumo Falls and Ruzizi III were inadequate (Int. 23). Doubt in the quality of the ESIA was also supported by negative experiences with other development projects (Int. 23, 64). Furthermore, several interlocutors stated that they were insufficiently informed about environmental impacts and lacked knowledge (e.g., Int. 68).

The cases also illustrate that besides regional organizations, the presence or absence of other actors, including donors and the private sector, plays a crucial role—and maybe a more important role than the regional organizations themselves. The Xayaburi case illustrates that access to private sector capital may change the power position by and enable unilateral action of countries which, due to lack of access to financial and technical resources, were previously in a weak negotiating position (Hensengerth, 2015). But also the Thai utility EGAT and the Thai government played important roles in moving forward with the Xayaburi dam by concluding the power purchase agreement and by allowing Thai private banks to provide the loans despite the ambiguities in the PNPCA process. In the Ruzizi case, due to the relative economic weakness of the countries, donors are still involved next to the private investor. In this case it is still open whether a final deal will be reached, also given that the private investor is in a strong negotiation position vis-à-vis the countries involved. If the public-private joint venture comes about, the application of environmental and social safeguards will also depend on their uptake by the private investor. In contrast, Rusumo Falls is entirely donor funded. According to one interviewee, the World Bank wanted Rusumo Falls to be a "pilot" for sustainable hydropower after its reengagement with the sector (Int. 3). Still, even the World Bank could not prevent the countries from pursuing the reservoir project in the first place.

Last but not least, the Ruzizi case shows that besides IRBOs, as usually argued in the literature, also regional energy organizations may play a role in nexus governance [see also Scheumann and Tigrek (2015) for the Coruh River shared by Georgia and Turkey]. While this paper has provided first insights into potential strengths and weaknesses of both types of organizations in nexus governance, this could still be studied more systematically.

CONCLUDING REMARKS

This paper sought to contribute to the evolving literature on governing the WEF nexus by analyzing the case of hydropower investments on shared rivers and the role that regional organizations may play in governing nexus impacts. In line with Weitz et al. (2017), the article showed that under certain conditions self-interested actors might derive benefits from coordination and from governing WEF nexus impacts and that this might be promoted by coordinating agencies and procedural instruments, such as SEAs and ESIAs. This pertains in particular to the African cases studied, where hydropower investments on border rivers required coordination among the border states, where the existence of regional organizations facilitated the inclusion of Burundi as a further affected country, and where donors requested the application of World Bank environmental and social safeguards. In these cases, regional organizations supported benefit-sharing arrangements, the application of safeguards and, where applicable, international law principles, even if it is still open whether a final agreement on Ruzizi III can be reached. In contrast, the Xayaburi case illustrates that the picture may be different in the case of hydropower investments on transboundary rivers, if the investing state believes that it is in its self-interest to proceed with the respective hydropower investment outside the frame of regional organizations. In fact, as the Xayaburi case illustrates, new private investors from middle income countries may fundamentally change the power dynamics on international rivers despite the existence of an IRBO, and the latter's influence on investment projects by member states may be very limited: while Laos eventually adjusted the design of the Xayaburi dam to some extent, a moratorium on dam construction could not be imposed. This also points to the limits of regime theory in explaining power dynamics in international basins (e.g., Furlong, 2006; Zeitoun, 2007), and supports Weitz et al.'s contention that nexus governance may be limited by power dynamics. Beyond the factors highlighted by Weitz et al. (2017), the article also found that the assessment of impacts and nexus governance may be complicated by poor or disputed data.

The question is what recommendations can be drawn from the analysis. While regional organizations may play a role in WEF nexus governance, the Xayaburi case also points to their limits. At the same time, had the MRC not been in place, it is questionable whether adjustments would have been made to the design of the Xayaburi dam at all. Therefore, particularly in view of the increase in private sector investments in hydropower on international rivers, consideration should nevertheless be given to further setting up and strengthening regional organizations in order to support nexus governance (Dombrowsky and Scheumann, 2016). At the same time, the cases also show that environmental and social safeguards are important irrespective of the existence of regional organizations, even if the latter may support their application. Hence, also private sector initiatives, such as the Hydropower Sustainability Assessment Protocol of the International Hydropower Association, may be worth supporting to ensure nexus governance (IHA, 2010). This said, the cases also illustrate that the basin scale is rarely the scale of decision-making for energy investments, which points to the limits of influence of IRBOs. Hence, while nexus impact of hydropower investments should be studied at the basin scale, it would be inadequate to limit the analysis of nexus governance related to hydropower to the basin scale.

AUTHOR CONTRIBUTIONS

ID had the idea for this article. She drafted a first version of the introduction, the conceptual framework and the discussion section, and revised these based on substantial feedback and intellectual input by OH. Field work for the African HPPs was carried out by ID, who also wrote the respective sections. Field work for the Xayaburi HPP was conducted by OH, who wrote the respective sections.

ACKNOWLEDGMENTS

This paper was prepared in the context of the project 'Implementing the Water–Energy–Food Nexus: Incentive structures and policy instruments' funded by the German Federal Ministry for Economic Cooperation and Development (BMZ) (grant no. 2015.95.834). Field research in Africa was carried out within the Post-graduate Training Programme on Development Cooperation of the German Development Institute, and the contributions by Julia Bastian, Daniel Däschle, Simon Heisig, Johannes Peters and Christian Vosseler to the field research are greatly acknowledged. Field research for the Xayaburi dam was funded by a British Academy Small Research Grant 'Institutionalizing Environmental Norms for Large Dams: The Case of the Mekong River Commission' (grant number SG111140). The open access fee was covered by the 'BMZ project Implemeting the 2030 Agenda: Integrating Growth, Environment, Equality and Governance' (grant no. 2016.9595.6). The authors are indebted to EGL, MRC and NELSAP for hosting them and for their invaluable support in carrying out the interviews, and to all interview partners for their valuable time and inputs. Earlier versions of the paper benefited from discussions with Waltina Scheumann and helpful comments by Claudia Pahl-Wostl as well as two reviewers.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Environmental Science

ORIGINAL RESEARCH
published: 22 January 2019
doi: 10.3389/fenvs.2019.00001

Changing Patterns of Tree Cover in a Tropical Highland Region and Implications for Food, Energy, and Water Resources

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OPEN ACCESS

Edited by:
Richard George Lawford,
Morgan State University, United States

Reviewed by:
Elzbieta Antczak,
University of Łódz, Poland
Angelina Sanderson Bellamy,
Cardiff University, United Kingdom

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Specialty section:
This article was submitted to
Land Use Dynamics,
a section of the journal
Frontiers in Environmental Science

Received: 24 September 2018
Accepted: 03 January 2019
Published: 22 January 2019

Citation:
Alemneh T, Zaitchik BF, Simane B and Ambelu A (2019) Changing Patterns of Tree Cover in a Tropical Highland Region and Implications for Food, Energy, and Water Resources. Front. Environ. Sci. 7:1. doi: 10.3389/fenvs.2019.00001

The Blue Nile Highlands of Ethiopia are a densely populated, predominantly rural region dominated by smallholder crop-livestock mixed farming systems. Population growth, coupled with low productivity, have long posed a threat to natural forest ecosystems in the region, as trees have been removed for fuelwood and to clear area for grazing or crop production. In recent years, however, there has been a trend to replace cropland with eucalyptus plantations. This change has major implications for the hydrology, soils, and agricultural economy of the region. This study examines changes in tree cover for a highland area at the center of the Blue Nile Highlands. Landsat imagery from 1986 to 2017 is applied to characterize changing tree cover patterns over space and time. We find that total tree cover in this highland region has shifted dramatically over the past 30 years. Between 1987 and 1999 there was dramatic loss of tree cover, particularly in areas of natural vegetation at high and low elevation. This period coincided with the fall of the *Derg* government and the transition to the current political system. In the period since 1999 there has been an increase in tree cover, with rapid gains in recent years. This increase has taken two distinct forms: regrowth in previously forested areas, due in part to active conservation measures, and the establishment of eucalyptus plantations in mid-elevation zones. The ecological and economic implications of these two types of tree cover—protected forest vs. woodlot plantations—are quite distinct, with plantation forestry providing biomass energy at a cost to food production and water resources. Mapping cropland conversion to eucalyptus in recent years makes it possible to quantify the net impacts that this trend has had on local production of energy and food, and to estimate implications for water consumption. Effective monitoring of these changes is important for the ongoing development and implementation of effective land use policy in the region.

Keywords: tropical highlands, eucalyptus globulus, agroecological zones, Blue Nile basin, tree cover changes

INTRODUCTION

Under natural conditions, the Highlands of Ethiopia are a forest-dominated region. The relatively cool and mostly wet conditions support mixed forests of Choke mountain such as Asta (*Erica arborea), Hypericum revolutum*, giant lobiloa (*Lobelia synchopetala*), lady's mantle (*Alchemilla humania*), and Guassa grass (*Festuca* spp.) (Teferi et al., 2010). Indeed, although the highlands have been home to farming and grazing activities for many centuries, it has been estimated that at the turn of the Twentieth century the highland zone was still highly forested, with a cover of ∼40% (Britenbach, 1961). Today that coverage is greatly reduced, as population growth coupled with low productivity agriculture have driven rapid deforestation for fuel wood, creation of new grazing lands, and expanded croplands. Loss of forest cover has had significant implications for biodiversity, has accelerated land degradation, and has fundamentally altered watershed hydrology (Zeleke and Hurni, 2001). This is a significant concern for local livelihoods and for national resource management. In the Western Highlands, which form the headwaters of the Blue Nile River, the impact that forest cover change has on hydrology and erosion takes on international significance. Historically, erosion from the Ethiopian Highlands has been credited with delivering fertile sediment to Sudan and Egypt, but it has also been to blame for filling reservoirs and clogging irrigation channels in Sudan (Eggen et al., 2016). In coming years, as Ethiopia completes the Grand Ethiopian Renaissance Dam (GERD) on the Blue Nile, sediment from the highlands will no longer reach downstream countries in large volumes, but it may affect operations and project lifespan of the GERD or of complementary dams planned further upstream.

Interestingly, the loss of tree cover in the Western Highlands that characterized much of the Twentieth century is believed to have reversed in recent years (Strategic Environmental and Social Assessment, 2017). This has occurred for two reasons. First, increased awareness of ecosystem services and the dangers of land degradation have led to conservation efforts in some recently deforested areas (Zeleke and Hurni, 2001). Second, there has been a rapid expansion of plantation forestry in favor of field crop agriculture in the past decade. These plantation forests are dominated by eucalyptus—specifically, *Eucalyptus globules* and *Eucalyptus camaldulensis*—with *Acacia diccurence* also common in some areas. Ecologically and hydrologically, these single species plantations are entirely different from natural forest cover, and the loss of active cropland and possible contribution of eucalyptus plantations to loss of soil fertility has been met with alarm in some government reports and scientific studies (Kidanu et al., 2005; Amhara National Regional State Bureau of Agriculture, 2017; Jaleta et al., 2017; Strategic Environmental and Social Assessment, 2017). At the same time, plantation forests, and particularly eucalyptus plantations, offer substantial economic benefit in local communities. The trees are fast growing, easy to cultivate (Christina et al., 2011; Qiao et al., 2016), provide land tenure security, are at low risk of failing, and provide higher direct economic returns than most traditionally cultivated field crops (Bekele, 2015; Jaleta et al., 2017). They also provide some wood for local use. Though the primary markets for eucalyptus charcoal and scaffolding are urban and international—the trade between western Ethiopia and Sudan is significant—a fraction of woody material is used locally for fuel and other applications (Strategic Environmental and Social Assessment, 2017).

While government officials and some researchers have begun to investigate this eucalyptus dynamic (Mengist, 2011; Bekele, 2015; Jaleta et al., 2016, 2017; Strategic Environmental and Social Assessment, 2017), there is a general lack of information on the extent of the process and conservation efforts in natural forest zones have been described but their impacts have not been quantified. Analyses of the social dynamics and environmental impacts associated with these changes require consistent information on tree cover change at landscape scale, and on the implications that these changes have for interconnected energy, water, and food resources in the region. Here we apply satellite imagery to investigate change in tree cover over the period 1986–2017. The analysis is stratified by agroecological zone in order to isolate changes in historically forested regions from change in areas where tree plantations are replacing cropland. This analysis provides a quantitative estimate of changing tree cover pattern in the Blue Nile Highlands that we can associate with policy and economic trends over the past three decades. We then apply estimates of plantation biomass production, eucalyptus water consumption, and average crop yields in the region to convert maps of tree cover change to first order estimates of policy-relevant impacts on energy, water and food resources. These data can provide a foundation for analysis and modeling efforts to understand the economic, hydrological, and ecological impacts of tree cover change in the region.

MATERIALS AND METHODS

Study Area

The Blue Nile Highlands are located in western Ethiopia, centered around 10°N, and 36°E (**Figure 1**). The region is characterized by hilly and sometimes steeply dissected terrain. We performed our study in the East Gojjam Zone, a region that is representative of Blue Nile Highland conditions and that includes a large elevation gradient: 800–4,200 meter above sea level (m.a.s.l.), from the gorge of Blue Nile River to the top of Choke Mountain. The rainy season coincides with the northern shift of inter-tropical convergence zone (ITCZ) in boreal summer, with most rainfall falling between May and September (Taye et al., 2011; Zaitchik et al., 2012). The distribution of rainfall across the Blue Nile Highlands shows variability associated with topographic gradients. The western slopes tends to be wetter than the eastern slopes, and in our study region the strongest precipitation gradients follow elevation: wettest conditions are at high elevation and the driest conditions are in the Blue Nile gorge (Simane et al., 2013). These precipitation contrasts combined with the elevation temperature gradient produce a sequence of distinct agroecological zones (**Figure 1**; **Table 1**). These zones are characterized by different ecologies and crop mixes, with implications for livelihood strategies and climate vulnerabilities (Simane et al., 2013).

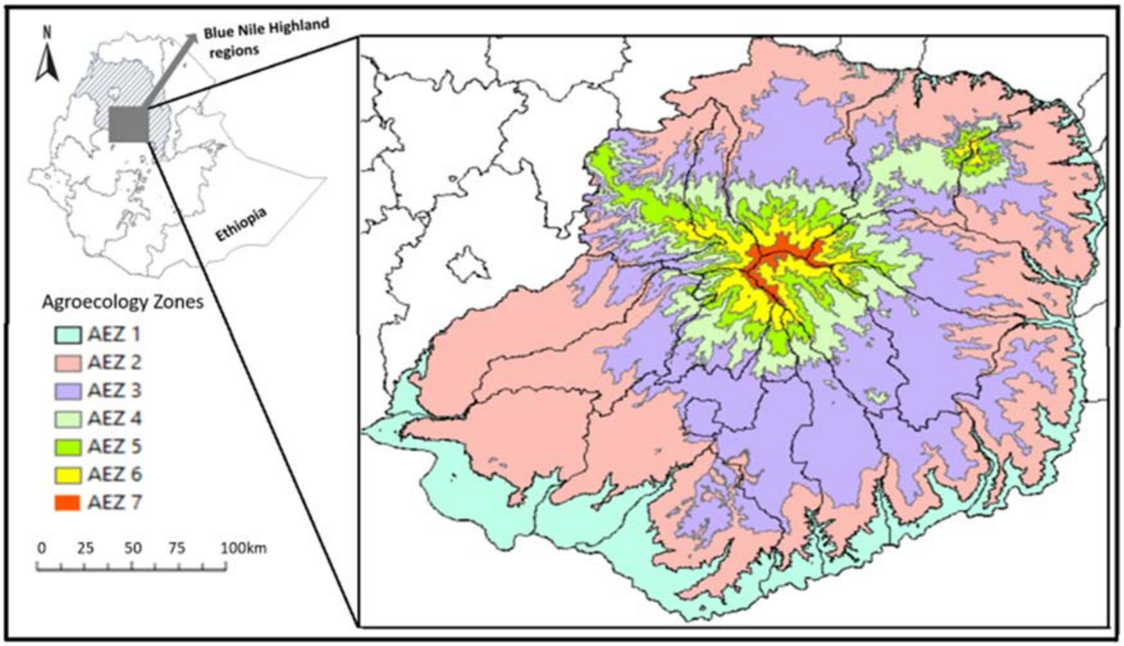

FIGURE 1 | Agroecologial zones of Choke Mountain, in the Blue Nile Highlands. Zones are shown for East Gojjam zone, which defines the spatial extent of this study. Black lines are woreda boundaries.

TABLE 1 | Traditional classification of agroecological zone in the Choke Mountain wahtershed (modified from Simane et al., 2013), (AEZ, agroecology zones).

Agroecology zones	Traditional climatic zone	Altitude (m)
AEZ1 Lowland (Blue Nile river valley)	Berha (hot arid)	<800
AEZ2 Midland plain (Black soil area)	Kola (warm semiarid)	800–1,800
AEZ 3 Midland plain (Brown soil)	Woinadega (cool, sub-humid)	1,800–2,400
AEZ 4 Sloping area	Dega (cold, humid)	2,400–3,200
AEZ 5 Hilly and mountainous area	Dega (cold, humid)	3,200–3,800
AEZ 6 Protected and forested area	Wurch (afro alpine, cold, moist)	>3,800
AEZ 7 Protected natural grassland area	Wurch (afro alpine, cold, moist)	>3,800

Agriculturally, East Gojjam is dominated by smallholder crop-livestock mixed farming systems (Zaitchik et al., 2012; Eggen et al., 2016). The types of crops cultivated in the region differ as a function of agroecological zone and the soil type. For example, teff, wheat, barley, sorghum, maize and potato are among the most widely cultivated crops for home consumption and for market purposes, with sorghum and maize dominant at low elevations, teff and wheat found predominantly in midland agroecosystems, and barley and potato found in high elevation agroecozones. Importantly, the highest elevation zones—agroecological zones 6 and 7—were relatively undisturbed forest and grasslands until recent decades (Simane et al., 2013). Only in the 1980s did land and population pressure lead to significant encroachment on these zones for grazing, collection of fuel wood, and in some cases production of barley or potato (**Figures 2A,B**) (Simane et al., 2013). Similarly, in the lowest elevation zone (agroecozone 1) there was, until recent decades, reasonable scrub and tree cover in the steep and dissected terrain of the gorge. As population pressure increased in the last decades of the Twentieth century, these wooded areas were encroached upon in an effort to create new, albeit extremely marginal, cropland.

In the midland agroecozones 2–5, slopes are reasonably gentle, soils are more fertile, and there is neither the crop-limiting cold of the highlands nor the frequent droughts found in the gorge. In these areas subsistence agriculture is reasonably productive, and it has long been the favored land use. However, due to a combination of factors that will be discussed later in the paper, recent years have seen a dramatic increase in eucalyptus plantations (**Figures 3**, **4**). Rapid changes in tree cover in these zones, then, is almost exclusively due to plantation forestry, while changes in agroecozones 1, 6, and 7 are more closely related to the removal or reestablishment of natural tree stands.

Data

The objectives of this study are to quantify and characterize changes in tree cover over the past several decades and evaluate the observed land cover changes in terms of food, energy and water resources. Since a long time record is required, and since forest plantations in Ethiopia can be less than a hectare in size, we used Landsat images which are 30 m resolution continuously from 1986 to the present (Landsat-4 through Landsat-8). The

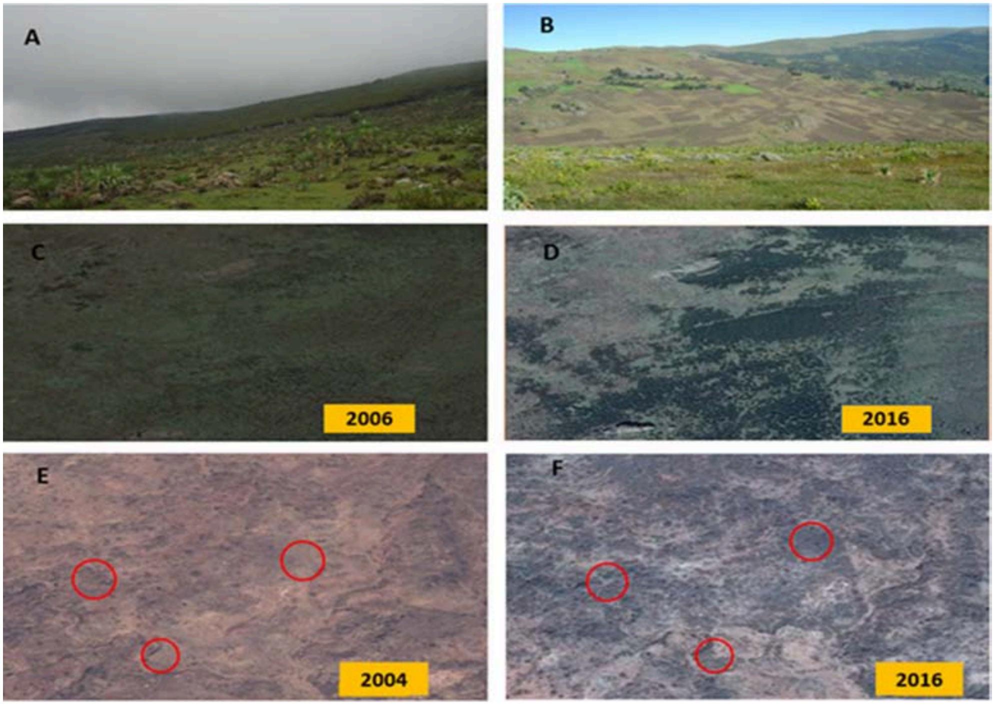

FIGURE 2 | (A,B) example pictures by (Temesgen Alemneh) showing tree cover clearance in agreoco zones 6 and 7 for grazing **(A)** and cropping **(B)**; **(C,D)** satellite images of agroeco zone 7, showing some reestablishment of natural tree cover in the last decade; **(E,F)** satellite images of agroeco zone 1, showing return of natural tree cover. Satellite images are from Google Earth/Digital Globe **(C,E)** and Google Earth/CNES/Airbus **(D,F)**. (Red circles indicated in E and F are used to draw out areas of tree cover returns between 2004 and 2016).

spatial resolution and multispectral character of Landsat imagery is well suited for agriculture and other environmental monitoring studies (Cohen and Goward, 2004).

For this study, images from Landsat-5 Thematic Mapper (TM) and Landsat-8 Operational Land Imager (OLI) provided the best seasonally matched images of the study region over the broadest possible time period (**Table 2**). We selected dry season images from the period after field crops are harvested (late January and February), in order to maximize the availability of cloud free images and to minimize confusion between young trees and active field crops. At this time of year, trees are some of the only live and actively growing vegetation in the study area, making them relatively easy to detect.

A limitation of our method is that we do not directly distinguish plantation forest from natural forest. At Landsat spectral and spatial resolution there were no distinguishing characteristics that made it possible to do this reliably across the entire landscape. Instead, we classify all tree cover as a single class and interpret the results on the basis of landscape context; i.e., natural forest is found in steep or protected lands at low and high elevation, while there is essentially no natural forest in the midland agricultural region beyond a few protected areas around churches that have not changed over time. For this reason, we were able to interpret midland tree cover change (agroecozones 2-5) as a function of plantations, where tree cover change on steep slopes of the gorge (agroecozone 1) and in the protected area on top of the mountain (agroecozones 6–7) was understood to be natural tree cover change. Further, we do not attempt to distinguish between tree species in plantation forestry. It is known that the majority of plantations in the study region are monocrop eucalyptus, but other orchard and woodlot species are present and are included in our tree cover results.

Image Processing

Supervised classification was performed on each selected Landsat image using the Maximum Likelihood classifier in ESRI ArcMap 10.5. All reflective bands were used as input to the classification. Training regions were manually digitized, with classes identified through visual inspection of the landsat images, cross-checked with Google Earth for recent images, and the authors' extensive experience living and working in the region. The following classes were defined as input to the maximum likelihood classifier: (1) tree cover; (2) cropland; (3) grazing land; (4) other vegetation (such as bush and shrubs); (5) water body; and (6) settlement and towns. Training regions, and the subsequent classification results, were limited to East Gojjam Zone, which offers a convenient boundary for the analysis. The accuracy of the classification approach was evaluated for the 2017 image using 265 points and comparing the classification result to the land cover class as determined from high resolution Google Earth imagery from the same time period. As our focus is on comparing tree covered to non-tree areas, we selected approximately 50% of points from tree covered areas (as identified in Google Earth) and 50% from non-tree areas. User's accuracy (error of commission),

FIGURE 3 | Pictures by Temesgen Alemneh: **(A–D)** examples of first rotation cultivation of eucalyptus on croplands, and **(E,F)** the second rotation growing eucalyptus after harvesting.

Producer's Accuracy (error of omission), Overall Accuracy, and the Kappa Coefficient were calculated using standard methods (Jensen, 1996). Kappa Coefficient is a measure of the difference between the observed agreement between two maps and the agreement that might be attained by chance (Campbell, 2007), and is calculated as:

$$K = \frac{\text{Observed} - \text{Expected}}{1 - \text{Expected}}$$

It was not possible to evaluate the classification of the earlier images due to lack of availability of high resolution imagery, so we adopt our 2017 accuracy assessment as indicative of the performance of our classification approach.

Subsequent to classification, all classes were collapsed into one "tree" class and one "non-tree" class. These classes were applied in order to map and quantify changes in tree cover over the period of study. We did not attempt to distinguish between natural forest and plantation forest in the classification stage, owing to the optical diversity of both types of forest as a function of age, siting, and species. Instead, we distinguish between plantation and natural forest by landscape context and land use history, as described in results and discussion. All analyses were performed for East Gojjam as a whole and also stratified by agroecological zone.

RESULTS AND DISCUSSION

Accuracy of Land Cover Classification

We categorized the land uses of the Blue Nile Highland regions into trees, croplands, grasslands, other vegetation, water bodies and settlement and towns. These categories capture the major land covers of the study region, and they were applied consistently across all images to allow for analysis of land use dynamics over time (Fagan et al., 2015) in different agroecological zones of the region.

Accuracy assessment of the 2017 classification demonstrates adequate performance. In an evaluation of the classification for 265 points with known land cover identified in high resolution Google Earth images from within 1 year of the Landsat acquisition date, we found overall accuracy of 92.5% for tree vs. non-tree (91.3% for all classes) and Kappa coefficient of 0.85 for tree vs. non-tree—i.e., 85% improvement over chance agreement.

FIGURE 4 | High resolution images highlight rapid expansion of eucalyptus plantations in agroecology zone 5 **(A–E)** (between 2004 and 2014, and 2004, 2014, and 2016) and in agroecology zone 4 **(F–G)** at the expense of croplands. All satellite images are from Google Earth/Digital Globe **(A,C)**, and Google Earth/CNES/Airbus **(B,D–G)**.

With respect to tree vs. non-tree classes, the User's Accuracy for trees was 88.0% and the Producer's Accuracy was 97.7%. The slightly lower User's Accuracy is a result of terrain shadows being incorrectly classified as forest. Full results are presented in **Table 3**.

Tree Cover Change Between 1987 and 2017

Our analysis of tree cover change through time begins in 1986. This date represents the oldest seasonally appropriate image we could obtain from the Landsat 4–8 mission series, and it is also a historically appropriate time to establish a baseline for recent land cover change dynamics. In 1986 the *derg* dictatorship had been in power for 12 years but was beginning to weaken, with government reorganization occurring in 1987 and the regime ultimately falling in 1991, after an extended civil war. The *derg* had overseen a large tree plantation program throughout the country, including the use of both exotic species (e.g., eucalyptus) and indigenous plants (e.g., *Hagenia abyssinica*). The program was implemented at the household level in each homestead area, in stream buffer zones—i.e., along river banks to prevent erosion—and in open areas selected by the community for common use. This activity significantly contributed to the expansion of tree cover in the region. In this sense, 1986 represents a potential high tree stand period within recent Ethiopian history.

Indeed, our classification of Landsat imagery from 1986 and 1987 indicate that East Gojjam Zone was 6–8% covered by trees—including both natural forest and plantation—at this high stand

TABLE 2 | Cloud free Landsat satellite images acquired over the Blue Nile highlands; East Gojjam, Ethiopia.

Year	Path/row	Image acquisition date	Satellite and sensor
1986	169/053	28 January 1986	Landsat-5 TM
1987	169/053	31 January 1987	Landsat-5 TM
1999	169/053	17 February 1999	Landsat-5 TM
2014	169/053	25 January 2014	Landsat-8 OLI
2017	169/053	17 January 2017	Landsat-8 OLI

TM, thematic mapper; OLI, operational land imager.

TABLE 3 | Error matrices of classification map of landsat imagery from Blue Nile highland regions.

Classification	Tree cover	Grass	Crops	Town/village	Water	Row total
Tree cover	125	10	6	1	0	142
Grazing	2	29	2	0	0	33
Cropland	0	1	85	0	0	86
Town/village	1	0	0	2	0	3
Water	0	0	0	0	1	1
Column total	128	40	93	3	1	265

TABLE 4 | The total area coverage of each agroecology zones and percentage of the tree cover in each year.

Agroecology zones	Total area coverage (km^2)	Percentage of tree cover in each year				
		1986	1987	1999	2014	2017
1	2136.21	11.1	5.8	0.9	0.05	1.7
2	6124.37	7.7	4.8	1.3	1.5	4.8
3	4755.58	4.8	4.1	1.3	2.7	4.6
4	1438.09	6.3	7.4	3.5	7.3	13.7
5	685.37	8.6	9.5	3.8	10.1	17.6
6	461.13	24.6	26.8	6.7	15.6	20.8
7	115.86	57.4	56.7	13.4	14.2	18.9

period. Tree cover was greatest in AEZ 7 (56–57%; **Table 4**), the natural forest and grassland area at the top of the mountain, but was also relatively high in the steep, erosion-prone slopes of the Blue Nile gorge (AEZ 1; 6–11%) and in the high elevation, low productivity AEZ 6 (25–27%), located just downslope of the AEZ 7 mountain top (**Figure 5**). Classification results are relatively stable between 1986 and 1987 for most AEZ, as would be expected, but there is a significant difference in AES 1 between the 2 years that is likely an artifact of illumination rather than an actual large-scale change.

Subsequent to the fall of the *derg* in 1991 there was an extended transition period as the new government consolidated power and put land policies in place. This period, represented in our analysis by the difference between the 1987 and 1999 images, was associated with land grabbing for crops and grazing, encroachment of agriculture to higher elevation, and a weakening of communal land management arrangements. These dynamics are dramatically evident in our classification of tree covered areas, as the 1999 image is the low point in our analysis for tree cover across all AEZ. Overall tree cover dropped to 2%, with major losses in the ecologically sensitive and/or erosion prone portions of AEZ 1, 6, and 7. The loss of natural forest cover in high elevation zones is particularly apparent (**Figure 6**), as natural tree cover was lost to fuelwood harvesting, conversion for grazing land, and in some cases low productivity cropping. Tree cover was also reduced in midland AEZ, primarily due to the loss of plantation and buffer strip tree planting enforced by the *derg*. We do note that a lack of appropriate Landsat imagery in this period limits our confidence in the quantitative details of our classification result. Only one cloud free dry season image could be obtained for this historic period, and it is possible that illumination effects or other image-specific conditions could introduce error. Nevertheless, site-specific examinations like **Figure 6** confirm that the general patterns of tree loss are realistic.

The period between 1999 and 2014 saw relatively small rates of change in tree cover. Some gain was observed in AEZ 6, as government watershed protection policies were established and enforced. Tree cover also increased somewhat in AEZ 4 and AEZ 5, as the trend toward plantation forestry, primarily eucalyptus, began to take shape in the 2000's (Bewket, 2005). With these exceptions, however, total tree cover was mostly static over this 15 year period, particularly relative to the rapid changes seen before and after. Overall, tree cover in 2014 was 3%.

In contrast to the relative stasis between 1999 and 2014, changes in tree cover between 2014 and 2017 are dramatic. Overall tree cover increased by 3% from 2014 to 2017, but what is most notable is the location of this increase. The change is in some part attributable to forest recovery at the top of the mountain, and there is a small amount of regrowth in AEZ 1 that could be attributed to new conservation efforts or to transient differences in climate (or image quality) between the 2 years. But in the mid-elevation AEZ there is a significant increase in tree cover, most evident in AEZ 4 and AEZ 5. In 2017, tree cover in these two AEZ is higher than it was at any other period in our analysis, including the 1986 and 1987 baseline images. The reason for this change is almost entirely attributable to a shift from mixed crop and livestock agriculture to plantation forestry, dominated by eucalyptus (e.g., **Figure 7**).

Implications for Food, Energy, and Water Resources

The quantitative tree cover area estimates presented above are subject to uncertainties related to classification method, Landsat resolution, and the limited availability of cloud-free imagery in the middle period of analysis. Nevertheless, the general trends of deforestation at high and low elevations in the first period of analysis (1986 to 1999) followed by stabilization (1999 to 2014) and a combination of forest recovery due to conservation and a rapid expansion in plantations in recent years (2014 to 2017) appears to be consistent across the analysis, supported by image evaluation with Google Earth, and in line with known land cover change patterns in the study region.

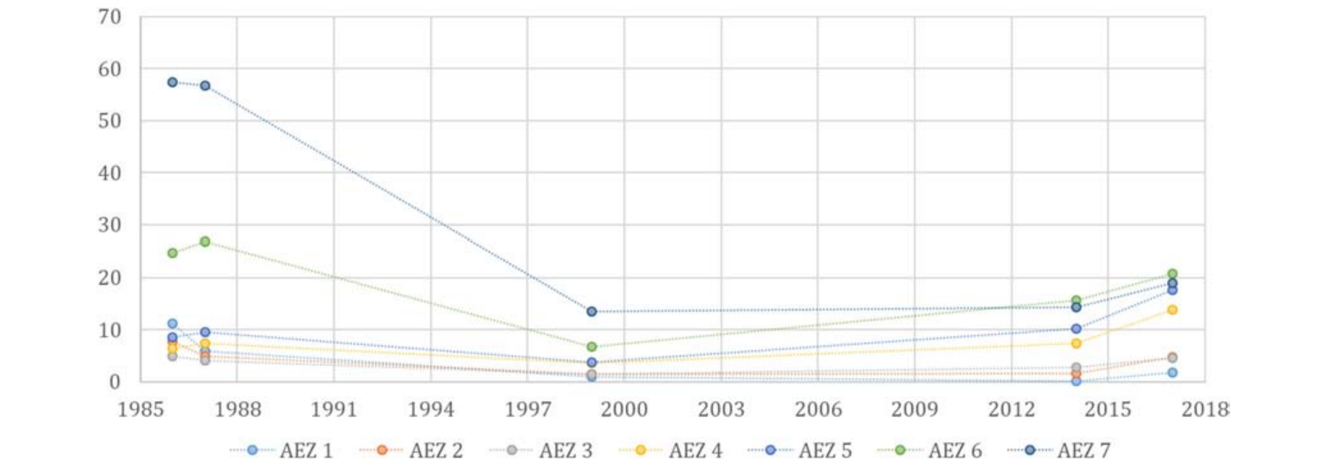

FIGURE 5 | Percent tree cover in each AEZ in the 1986, 1987, 1999, 2014, and 2017 Landsat classifications.

FIGURE 6 | True color Landsat composites for the summit of Choke Mountain in **(A)** 1987 and **(B)** 1999. **(C)** Shows classified change in tree covered area between the two images: red is tree cover lost between 1987 and 1999, green is tree cover gained, and yellow is persistent tree cover. Gray shading in **(C)** is hill shade.

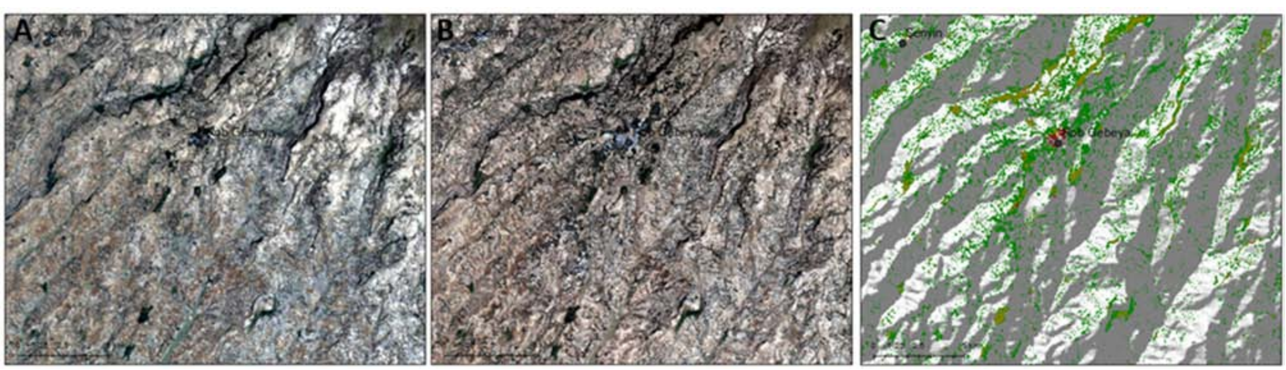

FIGURE 7 | True color Landsat composites for a region centered on AEZ 4 and 5 in **(A)** 1999 and **(B)** 2017. **(C)** Shows classified change in tree covered area between the two images: red is tree cover lost between 1999 and 2017, green is tree cover gained, and yellow is persistent tree cover. Gray shading in **(C)** is hill shade.

Recovery of forest cover at the mountain top (AEZ 7, AEZ 6) (**Figures 2 C,D**) and in the steep Blue Nile gorge (AEZ 1) (**Figures 2E,F**) provides multiple benefits: reduced erosion, higher river flow in the dry season, and enhanced biodiversity, among others (Yitebitu et al., 2010). Expansion of tree plantations, however, has been controversial. While tree crops—and in particular rapid-growing eucalyptus species—offer significant economic and land security benefits to the farmer, they come at the cost of lost food production, increased water consumption, and, for eucalyptus, allelopathy that can prevent returning a plot to field crops and that acts to reduce yields on neighboring plots (Kidanu et al., 2005; Mesfin and Wubalem, 2014). Here we consider the total impact that conversion of crop and pasture land to tree plantation has on energy, food and water in the study region. The numbers are not intended to be exact, but rather to provide general order of magnitude considerations to put the current eucalyptus boom in context. We assume that all plantations are eucalyptus. This is not entirely true, but it is true for the large majority of plots. The energy implications of eucalyptus production are significant. Rural households in Ethiopia depend heavily on biomass energy in the form of fuelwood, charcoal, cow dung and crop residues. These traditional biomass energy sources account for about 90% of total primary energy use in Ethiopia (Mekonnen and Köhlin, 2008), and about 99% of rural areas rely on biomass as their primary cooking fuel. Biomass is mainly used for cooking and to a minor extent for heating and lighting, and demand for biomass energy has increased over recent decades as population has increased (Chanie et al., 2013; Bekele, 2015). This demand is, in part, responsible for loss of natural forests and for declining soil fertility. Plantation forestry has the potential to address this demand. While eucalyptus plantations in the study region currently serve multiple markets, including domestic timber needs and charcoal trade to Sudan, the presence of plantation forests does address local energy need to some extent. Studies of eucalyptus growing regions in Ethiopia have indicated that on the order of half of the harvested eucalyptus biomass is used locally for energy and other uses (e.g., Barreiro and Tomé, 2012; Berhanu et al., 2017).

The productivity of eucalyptus plantations varies widely as a function of environment, species, management, and stand age. In Ethiopia, rotations of eucalyptus are usually between 5 and 25 years (Selamyihun, 2004). The average annual rate of biomass production increases with time in this age range (Pohjonen and Pukkala, 1990). Realized biomass yields differ dramatically by site and management approach, and a wide range of estimates can be found in the literature. Here we use the estimates of Pohjonen and Pukkala (1990), which indicate that for an average site and a coppicing cycle of 5–10 years, eucalyptus stands yielded an average of approximately 30 m^3 ha^{-1} yr^{-1}, averaged across the harvesting cycle. For a Eucalyptus globulus wood density of 545 kg m^{-3} (Barotto et al., 2017), this means a wet wood yield of $\sim$16,000 kg ha^{-1} yr^{-1}. Using a rough conversion of 10 MJ kg^{-1} for freshly harvested wood, this is equivalent to 160 GJ ha^{-1} yr^{-1}.

Our estimates of tree cover change indicate that between 2014 and 2017 14,280 ha of tree cover was added to AEZ 4 and 5. Assuming that this change was entirely associated with forest plantation, and recognizing that almost all forest plantations in these elevation zones are eucalyptus (Bewket, 2005), we calculate a total energy production of $2.3 \cdot 10^6$ GJ yr^{-1}. Rural households in the study area use a combination of fuelwood, dung, and crop residues for biomass energy, but fuelwood is the most common and represents about two-thirds of total biomass energy use (Bewket, 2005; Federal Democratic Republic of Ethiopa, 2012)-. Average annual household wood consumption is estimated to be about 511.3 kg (5,113 MJ) (Bewket, 2005), such that the increase in forest plantation area observed between 2014 and 2017 could meet the fuelwood needs of nearly 225,000 households if 50% of the material was used locally for energy. As a point of comparison, the Ethiopian Central Statistics Agency (2007) census recorded a total of 506,520 households in East Gojjam. The population is estimated to have increased substantially in the decade since this census, but the first order conclusion is that expansion of forestry plantation on this scale can have a transformative impact on the biomass energy economy of the region.

This gain in energy production comes at a direct cost of land lost for food production. There is the direct loss of land converted to eucalyptus plus additional loss due to allelopathy and shading affecting neighboring fields (Dessie and Erkossa, 2011). Considering only the direct effect, the average yields of grain crops in AEZ 4 and AEZ 5 are on the order of 3,200 and 3,100 kg ha^{-1} for wheat, respectively, and 2,100 and 2,300 kg ha^{-1} for barley (Eggen et al., submitted). These are two of the major staple grains in these AEZ (Simane et al., 2013). Engido (Avena spp.) and potato are also important, but we do not have consistent yield estimates for those crops. Maize and tef are planted to lesser extent (Simane et al., 2013, Eggen et al., submitted). To make a simplified assumption, if all of the land converted to plantation forestry between 2014 and 2017 came from productive crop lands previously planted in wheat or barley, then these AEZ lost a total of $4.5 \cdot 10^7$ kg of wheat production or $3.1 \cdot 10^7$ kg of barley production. The average rural household consumes 447 kg of staple grain per year (Worku et al., 2017), so this total loss translates to the grain needs of on the order of 70,000 to 100,000 households. This clearly indicates that the trend in eucalyptus production has a potentially significant impact on future food security of the region (Amhara National Regional State Bureau of Agriculture, 2017).

Eucalyptus also draws scrutiny because of its high transpiration rate, which leads to significant water consumption. Eucalyptus roots are capable of reaching shallow ground water, meaning that mature stands can impact water reserves that are typically untapped by crops and grasses. One estimate from Ethiopia holds that eucalyptus plantations use 785 liters of water to produce 1 kg of biomass (Davidson, 1989). Using our biomass production estimate of $\sim$16,000 kg ha^{-1} yr^{-1}, this translates into a consumption of 12,560 m^3 water per hectare per year, or 1,256 mm m^{-2} yr^{-1}. This rate of water consumption is on the same order as the total annual rainfall in these AEZ, and is substantially higher than estimated evapotranspiration from crops and grasslands in the area (Zaitchik et al., 2012). This raises a concern for the viability of local streams and, considering the study region's location in the headwaters of the Blue Nile basin, potentially has broader implications for water resources in a contentious transboundary basin. The impact would not appear to be overwhelming relative to the total water balance of the basin: the Blue Nile has an average annual flow on the order of 50 billion cubic meters per year. Even if eucalyptus doubles the rate of evapotranspiration relative to other land uses, the conversion 14,280 ha to eucalyptus in AEZ 4 and 5 would only result in an evapotranspiration increase of 90 million cubic meters per year. Extrapolated over the entire Blue Nile basin this could become meaningful, but it will not drastically change total downstream water availability. The impact on local streams and the character of the hydrological regime is likely to be more relevant when considering impacts on locally-available water (Christina et al., 2011). Potential benefits of increased water consumption include reduction in local waterlogging and possible reduction of certain types of saturation-induced flooding (Jaleta et al., 2017).

CONCLUSION

The Blue Nile highlands of Ethiopia are a region of subsistence, low input agriculture and high population growth. These characteristics make for significant land pressures, including the conversion of marginal lands and natural forest and grasslands into cropped agriculture. This trend has been noted by numerous sources and in many parts of the Ethiopian highlands (e.g., FAO, 2010). Our analysis of tree cover in Landsat imagery captures this trend for the first portion of our analysis period: between 1987 and 1999 there was substantial loss of forest cover in steep lands and high elevation areas in East Gojjam. However, in recent years deforestation has slowed due to enforcement of watershed protection policies (Federal Democratic Republic of Ethiopa, 2018). At the same time, tree cover in the form of plantation forestry—particularly of eucalyptus—has increased rapidly on land that was previously used for crops or communal pasture. Combined, these trends have led to an increase in total tree cover in both high or marginal areas (AEZ 1, 6, and 7) and in fertile agricultural areas (especially AEZ 4 and 5). The analysis presented here relies on a relatively small number of Landsat images, and is therefore subject to some uncertainty in the quantitative estimates of tree cover change. The general patterns, however, are robust across images early in the period (1986 and 1987) and at the end of the period (2014 and 2017), and they align with general understanding of tree cover trend in the region (e.g., Amhara National Regional State Bureau of Agriculture, 2017).

The expansion of eucalyptus plantations has been controversial. While these plantations currently offer significant economic benefit to farmers (Matthies and Karimov, 2014; Bekele, 2015) and help to meet timber and fuel wood demand, the practice removes land from food crop production, consumes large amounts of water, and, due to allelopathy and shading, reduces crop yield for neighboring farms. Studies and reports on the phenomenon come to divergent conclusions about the long-term desirability of the trend (Demel, 2000; Mesfin and Wubalem, 2014). We do not attempt a socioeconomic analysis of the eucalyptus boom, nor do we make any conclusions about the net benefit or cost of eucalyptus conversions in this region. Instead, we attempt to provide some context for the observed land cover change in terms of basic resources of energy, food, and water. Using area change estimates from our own analysis together with published estimates (Kidanu et al., 2005; Mesfin and Wubalem, 2014; Jaleta et al., 2017) of eucalyptus wood yield, water use, and energy content, we find that eucalyptus plantations on the scale observed in the study region have the potential to offset on the order of 99% of rural household energy use, averaged across East Gojjam. While we do not know whether eucalyptus is actually being used in this way, it is helpful to consider how the practice might contribute to energy needs, simply to assess its value in terms of basic human needs. We also find that the total water consumption is significant relative to the local water balance, in that eucalyptus in the Ethiopian highlands have been estimated to have annual water consumption on the same order as annual precipitation in the study area. The impact on main stem Blue Nile flows might also be detectable, but we estimate that it is small relative to the total flow of the river, or relative to the volume of evaporation observed at downstream open water reservoirs along the Nile. Finally, using observed yield data from the AEZ most affected by the eucalyptus boom, we estimate that grain production directly lost to land conversion into forest plantation is on the order of $3.1{\cdot}10^7$ kg of barley production or $4.5{\cdot}10^7$ kg of wheat production, which is enough to meet the grain needs of 70,000 to 100,000 households under current consumption patterns. These diverse impacts on food, energy, and water are relevant to any policy intended to discourage or encourage further eucalyptus conversions in the Ethiopian highlands.

AUTHOR CONTRIBUTIONS

TA and BZ conceived of the study. TA implemented all analyses, performed literature review, and wrote the manuscript. BZ supported the analysis and edited the manuscript. BS provided expertise in agricultural systems of the region and policy implications of plantation forestry. AA provided manuscript review and environmental health perspectives.

FUNDING

This research project was supported by the Belmont Forum NILE-NEXUS project through NSF grant ICER-1624335.

ACKNOWLEDGMENTS

We acknowledge Johns Hopkins University, department of Earth and Planetary Science for giving visiting scholarship including financial support to the Ph.D. candidate TA. Furthermore, we would like to forward our in-depth thanks to the Carnegie Landsat Analysis System lite (CLASlite) software package course support team for providing continuous support and giving guidelines to use the package efficiently.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Environmental Science

ORIGINAL RESEARCH
published: 30 January 2019
doi: 10.3389/fenvs.2019.00005

Water-Energy-Food Nexus Sustainability in the Upper Blue Nile (UBN) Basin

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The Nile basin ecosystem is under stress due to rapid population growth, inefficient utilization of resources, climate change, and persistent conflicts among riparian countries. The Blue Nile is a major tributary of the Nile River and contributes about 60% of the total annual flow. This paper presents a framework for optimal allocation of land and water resources in the upper Blue Nile (UBN) basin. This framework consists of two optimization models that aim to: (a) allocate land and water resources optimally to rain-fed and irrigated agriculture, and (b) allocate water to agriculture and hydropower production while maximizing the total net benefits. The optimal agricultural expansion is expected to reduce the UBN flow by about 7.6 cubic kilometers, impacting the downstream countries Egypt and Sudan. Optimal operation rules for the Grand Ethiopian Renaissance dam (GERD) are identified to maximize annual hydropower generation from the dam while achieving a relatively uniform monthly production rate. Trade-offs between agricultural expansion and hydropower generation are analyzed in an attempt to define scenarios for cooperation that would achieve win-win outcomes for the three riparian countries sharing the basin waters.

Keywords: UBN basin, optimal resource allocation, irrigation, hydropower, water-food-energy nexus, the Nile conflict, GERD, rainfed agriculture

OPEN ACCESS

Edited by:
Jill A. Engel-Cox,
National Renewable Energy Laboratory (DOE), United States

Reviewed by:
Richard Meissner,
Council for Scientific and Industrial Research (CSIR), South Africa
Claudia Ringler,
International Food Policy Research Institute, United States

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Specialty section:
This article was submitted to Freshwater Science, a section of the journal Frontiers in Environmental Science

Received: *26 June 2018*
Accepted: *09 January 2019*
Published: *30 January 2019*

Citation:
Allam MM and Eltahir EAB (2019) Water-Energy-Food Nexus Sustainability in the Upper Blue Nile (UBN) Basin. Front. Environ. Sci. 7:5. doi: 10.3389/fenvs.2019.00005

INTRODUCTION

Water, food, and energy are basic human needs with many interactions between them. These interactions define the water-food-energy nexus. In order to produce food, water, and energy are primary inputs (Khan and Hanjra, 2009; Mushtaq et al., 2009; UN-DESA, 2011). Similarly, in order to produce energy, water is mostly either a direct input for hydropower generation or an indirect one through bio-fuels and oil excavation, and last but not least in order to use water, energy is needed. This highlights the complexity of the interactions between the three elements and the importance of considering them together in decision-making while considering the trade-offs and synergies that result from different basin-wide management scenarios of the three resources. This study looks into the water-food-energy nexus in the Upper Blue Nile (UBN) basin within the Ethiopian borders. The UBN basin covers more than half of the Blue Nile basin's area. The Blue Nile basin is a transboundary system shared by three countries facing water-scarcity problems which escalated the Nile water conflict.

The Blue Nile contributes about 60% of the total Nile River flow at Aswan and is shared by the three countries: Egypt, Ethiopia, and Sudan. In 2011, Ethiopia announced the construction of the Grand Ethiopian Renaissance dam (GERD) at the outlet of the UBN basin, right at the border between Ethiopia and Sudan. The GERD construction was announced suddenly and without prior consultation with neighboring countries (Hammond, 2013; Sanyanga, 2014; Salman, 2016). The dam, currently under construction, is relatively large compared to the border dam and the millennium dam which were previously proposed and designed at the same location (USBR, 1964; IPOE, 2013). The GERD has been a source of controversy between Ethiopia and Egypt. On one hand, Egypt fears the risks of reducing its Nile water flows and the potential loss of its fertile lands and hydropower production from the High Aswan Dam. On the other hand, the Ethiopian government is expecting the GERD to help meet its increasing domestic electricity demands, export electricity to neighboring countries, and fishery development (Pottinger, 2013). However, uniform flows downstream the GERD will provide some benefits for Sudan which include: protection from high floods, providing an opportunity for agricultural expansion, reducing reservoirs' siltation, and enhancing hydropower output from the existing hydropower plants (Whittington et al., 2014).

The Upper Blue Nile basin (UBN) extends from Lake Tana in the Ethiopian highlands to the Sudanese border at Diem and has a drainage area of 176,000 square kilometers. The UBN's climatology varies from humid to semiarid. The annual precipitation increases from northeast to southwest and ranges from 1,200 to 1,600 mm (Conway, 1997, 2000; Tafesse, 2001; UNESCO, 2004; Kim et al., 2008). The mean annual temperature is about 18.5°C (Kim et al., 2008), and the annual potential evapotranspiration is estimated to be about 1,100 mm (Gamachu, 1977; Kim et al., 2008).

There are several optimization studies that evaluate the impacts of the basin's agricultural and hydropower potential development on downstream countries, based on the recommendations of the 1964 United States Bureau of Reclamation (USBR) study. Guariso and Whittington (1987) applied a linear programming model to maximize hydropower production in Ethiopia and agricultural expansion in Egypt and Sudan. They concluded that the irrigation development of the UBN basin would reduce the downstream flows and the High Aswan Dam (HAD) storage. Whittington et al. (2005) have developed the Nile Economic Optimization Model (NEOM), a deterministic non-linear model that optimizes the entire Nile basin water resources development. This study finds that the total direct economic benefits are relatively evenly distributed among Ethiopia, Egypt, and Sudan. However, they found that irrigation benefits would be mainly reaped in the downstream countries Sudan and Egypt from a system-wide perspective to capture the hydroelectric power generation along the Blue Nile gorge upstream. They conclude that abstracting irrigation water upstream results in significant losses in hydro-electric power generation which is the main source of economic benefits for the upstream countries Ethiopia and Uganda. Several network flow optimization models have been used for optimal basin-wide water allocation (McBride, 1985; Kuczera and Diment, 1988; Hsu and Cheng, 2002). However, since these modeling efforts were in network form, they were not capable of capturing the spatial variability in the basin land use, slope, soil, and climatology.

There are several studies on the optimal spatial allocation of water resources (McKinney and Tsai, 1996; Watkins et al., 1996; McKinney and Cai, 2002; Whiteaker et al., 2007). These studies have only analyzed agriculture using the data for the proposed irrigation projects in Ethiopia's masterplan and the outputs of the USBR study without revisiting the agricultural potential of the UBN basin lands and how to optimally allocate the lands between rain-fed and irrigated agriculture. Alemayehu et al. (2010) used the WEAP model to simulate irrigation water demand, hydropower and environmental flows under four scenarios: baseline, ongoing development, likely future development, and full potential development. They showed that if all the planned development occurs, on average 2,198 GWh/year power could be generated, 677 Mm^3/year of water supplied to irrigation schemes, and the mean annual water level of Lake Tana May be lowered by 0.44 m.

Simulation-based optimization models have also been used to solve large-scale river basin problems (Loucks, 1979; Wurbs, 1993; Loucks et al., 2005; Rani and Moreira, 2010). This combined approach utilizes an optimization model for screening purposes and a simulation model to evaluate the optimum alternatives. Extensive research has been done on the optimal allocation of water in agricultural lands using different procedures including: stochastic-dynamic programming (Ghahraman and Sepaskhah, 2002), simulated annealing (Georgiou and Papamichail, 2008), real-time modeling (Delavar et al., 2011; Ramezani Etedali et al., 2013), fuzzy programming (Safavi and Alijanian, 2010), genetic algorithm (Haq and Anwar, 2010), and particle swarm optimization (Nagesh Kumar and Janga Reddy, 2007; Khashei and Bijari, 2011). Evolutionary algorithms and multi-objective programming have been applied as well-related classes of problems, such as deficit irrigation (Ganji et al., 2006), cropping patterns (Nagesh Kumar et al., 2006; Sarker and Ray, 2009; Zeng et al., 2010; Bergez, 2013), water resource systems (Nagesh Kumar and Janga Reddy, 2007; Sulis and Sechi, 2013), irrigation planning (Haq and Anwar, 2010; Gurav and Regulwar, 2012; Anwar and Haq, 2013), and economic optimization (Alvarez et al., 2004; Groot et al., 2012; Singh and Panda, 2012).

Several studies have investigated the impacts of the initial filling of the GERD on the downstream Nile River flows (King and Block, 2014; Zhang et al., 2016). Different conclusions were reported on the method and years of filling, for different scenarios of the Blue Nile flow ranging from dry, up to wet years. Wheeler et al. (2016) concluded that with effective communication and coordination between the three countries and an agreed annual release from the GERD, increased benefits and reduced downstream risks can be achieved. Similarly, Jeuland et al. (2017) investigated the long-term impacts of the GERD on Ethiopia, Sudan, and Egypt and found that through maximizing the overall economic benefit of the three countries, the annual economic benefit to Ethiopia would increase from 253 to 1,465 million US$ from hydropower generation, but the annual economic benefit to Sudan would decrease from 1,691 to 1,595 million US$ as a result of maximizing hydropower from all Nile dams and promoting downstream agricultural production in Egypt.

The objective of this paper is to provide an integrated approach to optimally allocate water and land resources between rain-fed and irrigated agriculture and hydropower to address the water-food-energy nexus in the UBN basin and find win-win opportunities to resolve the ongoing Nile water conflict. However, we would like to acknowledge that although this modeling exercise provides great insight to aid political decision makers, cooperation among riparian countries sharing an international river basin is usually very rare. This study will show how cooperation among the riparian countries can yield higher benefits for the river basin system as a whole which is often hindered by domestic politics, uncertainty of future supply and demand and the corresponding transaction costs.

APPROACH

Our approach to analyze the food-water-energy nexus in the UBN basin consists of three main stages. The first stage is identifying the agricultural potential in the UBN basin through delineating the lands suitable for rain-fed and irrigated agriculture. After identifying the basin's agricultural potential, we delineate them into different suitability classes and calculate the quantity required of soil treatment inputs to improve the UBN soils from one suitability class to a class with higher agricultural productivity and corresponding costs. The arability maps and the assimilated basin hydrology obtained in our previous research (Allam et al., 2016) are then used as input data to a land-water allocation model that optimally allocates the water and land resources between rain-fed and irrigated agriculture. Finally, a hydropower operation model is constructed to maximize the hydropower production from the GERD.

Delineation of Potential Arable Lands

A land evaluation analysis is conducted by applying the FAO Framework for land evaluation (FAO, 1976) through a GIS Multi-Criteria Decision Making (MCDM) platform to delineate the potential arable lands in the UBN basin. After screening several topography and soil properties datasets, it was found that the 90 m resolution SRTM DEM (Farr et al., 2007) and the African Soil Information Service (AFSIS) (Leenaars et al., 2014) are the most representative datasets for the UBN basin. The UBN basin lands are classified according to their degree of suitability; namely highly suitable (S1), moderately suitable (S2), marginally suitable (S3), and physically unsuitable for agriculture (N) based on the crop soil properties requirements according to Sys et al. (1985, 1993). Furthermore, a temperature suitability analysis is conducted using the 0.5- degree resolution globally available CRU temperature dataset (CRU TS 2.0) (Harris et al., 2014). This analysis is done for five crop groups: (a) Cereals: including teff, sorghum, millet, wheat, and barley, (b) Legumes: including peas, beans, lentils, and pulses, (c) Oilseeds: including sesame, sunflower, safflower, and cotton, (d) Coffee and (e) Sugarcane. These crop groups were chosen based on the atlas of agriculture in Ethiopia prepared by both the Cental Statistical Agency (CSA) and the International Food Policy Research Institute (IFPRI) for the period 2006/07 to 2010/11.

Land-Water Allocation to Rain-Fed and Irrigated Agriculture

The optimal water and land allocation in the UBN is investigated using an optimization model that maximizes the agricultural net-benefits from rain-fed and irrigated agriculture in the upper Blue Nile basin. The inputs to the model are the long-term average basin hydrology for the duration of 2002-2013, assimilated using a monthly data assimilation model (Allam et al., 2016) and the delineated arable lands. The model is constrained with mass and energy balance equations, crop production functions and relevant hydrologic thresholds. Data on production costs such as soil treatments, fertilizers, transportation costs, and the crop market prices and crop production were collected from several global data sources such as Faostat (2016) and USDA (2016) and local data sources obtained from a collaborator from local studies that were done within the basin or in nearby areas (Ibrahim, personal communication). Soil treatments such as limestone and sulfur application rates are obtained from several studies on the soil acidity and alkalinity (Spies and Harms, 1988; Everhart, 1994; Mitchell and Huluka, 2008; Anderson et al., 2013). The decision variables are the size of cropped and natural vegetation areas, flow routing through the basin, and crop yields. The model allocates land to different crop groups and allows for improving the land from one suitability class to another in order to achieve higher yields at an incurred cost for soil enhancement inputs. Eleven potential irrigation reservoirs are identified from Ethiopia's master plan—all of them are considered here as an input for the optimization model. The model decides on the ones that are best to invest in and their optimal capacity. **Table 1** summarizes the 11 proposed projects and their costs.

The objective function of the optimization model is:

$$\begin{aligned} Max\ NB = & \sum\nolimits_{crop} \left(p_{crop} - c_{crop}\right) Y_{crop} \\ & - d\left[\sum\nolimits_{Res} \left(FC_{RES} y_{RES} + VC_{RES} V_{RES}\right)\right. \\ & \left. + \sum\nolimits_{Res} \left(FC_{IRR} y_{RES} + VC_{IRR} A_{IRR}\right)\right] \end{aligned}$$

Where:

p_{crop}: crop market price in ($ per ton) for a production of a crop,
c_{crop}: crop inputs costs in ($ per ton) for a unit production of a crop,
Y_{crop} : crop production in Tons,
FC_{RES}, VC_{RES}, FC_{IRR}, *and* VC_{IRR}: The Fixed and Variable costs for the reservoir and irrigation infrastructure, respectively.
y_{RES}: binary variable to decide whether or not to build an irrigation reservoir and the corresponding irrigated areas.
V_{RES} : Model decision on a reservoir volume.
A_{IRR}: Model decision on the irrigated area.
d: discounting factor calculated as: $\frac{r}{1-(1+r)^{-T}}$: where r = 5% and T = 40 years.

The model is formulated on a regular grid of quarter degree (∼25 km) pixels (**Figure 1**) and describes temporal changes over

TABLE 1 | A summary of the proposed irrigation reservoirs, their proposed capacity, and their costs.

Reservoir	Fixed cost ($)	Variable cost (M$/Mm^3)	Capacity (MCM)
Gumera A	35.7	0.28	333
Megech	47.1	0.28	260
Ribb	37	0.25	173
Gilgel Abay	103.2	0.23	419
Negeso	71.2	0.39	177
Anger	73.9	0.07	3,583
Upper Guder	53.4	0.25	244
Nekemete	90.7	0.06	3,340
Dabana	139.3	0.18	1,923
Upper Didessa	0.4	0.06	2,490
Neshe	21	0.06	464

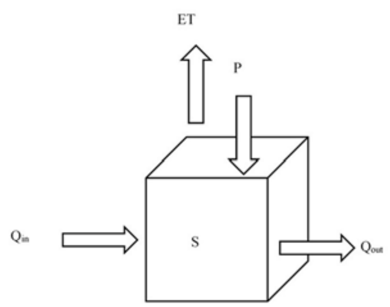

FIGURE 1 | A schematic diagram of a typical grid cell with hydrologic variables used in the data assimilation procedure.

a typical year, using a monthly time step along with the following constraints.

The water budget (or mass balance) constraint for each pixel:

$$\Delta S_{n,m} = S_{n,m+1} - S_{n,m} = Q_{in\,n,m} + P_{n,m} - ET_{n,m} - Q_{out\,n,m}$$

Where;

$\Delta S_{n,m}$: The change in the monthly storage of pixel n (km^3/month), time step m,
Q_{in}: The flow into the pixel from tributary pixels contributing into it,
Q_{out} : The outflow from the pixel as shown in **Figure 1**,
$P_{n,m}$: The pixel long-term average monthly precipitation for the period 2002-2013 (km^3/month) and
$ET_{n,m}$: The pixel monthly evapotranspiration (km^3/month).

The inflow to pixel n is the sum of all contributions from upstream pixels:

$$Q_{in_{n,m}} \sum\nolimits_{trib} \left(\Delta t(P_{n,m} - ET_{n,m} - \Delta S_{n,m})\right)$$

The storage in each pixel is limited by the soil water holding capacity with a root zone of depth 1.5 m which depends on the soil type in each pixel. If storage exceeds the capacity, the excess water contributes to runoff toward a downstream pixel:

$$S_{n,m} \le S_{threshold\,n}$$

The change in storage in each pixel is constrained by the soil infiltration and exfiltration capacities as follows:

$$\Delta S_{min} \le \Delta S_{n,m} \le \Delta S_{max}$$

Where:

$S_{threshold}$: The storage water holding capacity in pixel (km^3) using the HWSD dataset (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2012)
$\Delta S_{\min}\&\Delta S_{max}$: The infiltration and exfiltration capacity rates of the basin's soil which vary from pixel to pixel based on the soil type based on HWSD dataset (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2012).

The monthly pixel actual evapotranspiration is divided into three components; evaporation from water bodies $ET_{lake_{n,m}}$, crop evapotranspiration $ET_{crop_{n,m}}$ and evaporation from natural vegetation and soils $ET_{natveg_{n,m}}$ as follows:

$$\boldsymbol{ET_{n,m} = ET_{crop_{n,m}} + ET_{natveg_{n,m}} + ET_{lake_{n,m}}}$$
$$ET_{crop_{n,m}} = K_{crop_{n,m}}\ PET_{n,m}\ \left(A_{crop_n}/A_n\right)$$
$$ET_{lake_{n,m}} = PET_{n,m}$$
$$\boldsymbol{ET_{non-crop_{n,m}} = K_{natveg_{n,m}} PET_{n,m}\ \left(A_{natveg_n}/A_n\right)}$$

Where;

$K_{crop_{n,m}}$: The crop factor, FAO I&D No. 33 (Doorenbos and Kassam, 1979).
$PET_{n,m}$: The pixel monthly long-term average potential evaporation for the period 2002-2013 cubic kilometers.
$\frac{A_{crop\,n}}{A_n}$: The crop area fraction of pixel n.
$K_{natveg_{n,m}}$: The implicit natural vegetation crop factor (Allam et al., 2016).
$\frac{A_{natveg\,n}}{A_n}$: The natural vegetation area fraction of pixel n.

Evapotranspiration is constrained by the energy balance as follows:

$$ET_{n,m} \le \frac{R_{net\,n,m}}{\lambda CF} + C\Delta T_{n,m}$$

Where;

$R_{net\,n,m}$: The monthly available net radiation for pixel n (W/m^2),
λ: The latent heat of vaporization (kJ/kg),
CF: Unit conversion factor,
C: A constant parameter to account for the sensible and ground heat fluxes
$\Delta T_{n,m}$: The monthly change in temperature at pixel n.

The land constraints ensure that the pixel area is solely divided between cropland and natural vegetation, the crop area is less than the delineated arable area to that crop and that the crop area is left fallow after the season ends as follows:

$$\sum_{crop} A_{crop_n} + A_{natveg_n} = A_n$$
$$A_{crop_n} \leq y_{rain\,n,crop} Arablearea_{n,crop}\ \forall\ K_{crop_{n,m}} > 0$$
$$A_{crop\,n,m+1} = A_{crop\,n,m}\ \forall\ K_{crop_{n,m}} > 0\ \&\ m \neq Endmonth_{crop}$$
$$A_{crop_n} = 0\ \forall\ K_{crop_{n,m}} = 0$$

The last two equations ensure that if an area is allocated as cropland it is seen through from plant date to harvest without changing the crop during the season. They prevent the optimization program from gaining an unrealistic advantage by switching crops when a crop demands less water or from changing the size of the plot devoted to cropland.

A crop can be allocated to a cropland if and only if the available water depth in the root zone is greater than the crop water requirement:

$$AW_{n,m} = S_{root\,n,m}/A_n$$
$$AW_{n,m} \geq\ y_{rain\,n,crop} K_{crop\,m} PET_{n,m}$$

Where;

$S_{root\,n,m}$: The soil moisture in the root zone.
$AW_{n,m}$: The monthly available water depth in the root zone in pixel n.
$y_{rain\,n,crop}$ & $y_{rains\,n,crop}$: The binary variables that take the value of one when the available water is greater than the crop water requirement and zero if otherwise.

A constraint to allow for some water-stressed crop production from rain-fed agriculture with a crop yield reduction corresponding to the water stress according to the FAO Irrigation and Drainage Paper No. 33 (Doorenbos and Kassam, 1979).

$$AW_{n,m} \geq\ y_{rains\,n,crop} \left[0.8\ K_{crop\,m} PET_{n,m}\right]$$
$$A_{crops_n} \leq y_{rains\,n,crop} Arablearea_{n,crop}\ \forall\ K_{crop_{n,m}} > 0$$

Where:

The crop production constraint for non-water-stressed and water-stressed crops is formulated as follows:

$$Y_{crop} = \sum_{m,n} \left(A_{crop\,n,m}/LGP_{crop}\right) y_{rain_{n,crop}} + \sum_{m,n} \left(A_{crops\,n,m}/LGP_{crop}\right) y_{rains_{n,crop}}$$

Where;

LGP_{crop} : The length of growing period for the corresponding crop group.

Production constraints for staple crops such as teff, legumes, and cereals were included in the model to account for the national use of crops for food security purposes. This constraint was calculated as follows:

$$Y_{crop} \geq P_{Eth}\ cons\ PShare_{basin}$$

Such that:

P_{Eth} : Population in Ethiopia
$cons$: Per capita consumption if crop
$PShare_{basin}$: The share of the country's total production grown in the UBN basin.

Population data was extracted from landscan database (Bright et al., 2017), per capita consumption and shares grown in the basin data were obtained from the IFPRI report "The structural transformation in Ethiopia: Evidence from cereal markets".

The equations below describe the model constraints for the irrigation reservoirs capacity, water balance, and the irrigation water requirements:

$$\begin{aligned} S_{Res,m} &\leq V_{Res} \\ V_{Res} &\leq Cap_{Res} y_{Res} \\ \Delta S_{Res,m} &= Q_{in_{Res,m}} - Q_{out_{Res,m}} - ET_{Res,m} + P_{Res,m} \\ \Delta S_{Res,m} &= S_{Res,m+1} - S_{Res,m} \\ Q_{out_{Res,m}} &\geq IrrDiv_{Irr,m} \\ IrrDiv_{Irr,m} &= (1+\varepsilon) \sum_{crop} k_{crop} PET_{Irr,m} A_{crop_{Irr}} \end{aligned}$$

Where;

$S_{Res,m}$: is the reservoir water storage for month m and reservoir Res.
$Q_{in_{Res,m}}$: is the monthly inflow into Reservoir Res.
$Q_{out_{Res,m}}$: is the monthly outflow from Reservoir Res.
$IrrDiv_{Irr,m}$: is the irrigation diversion for the irrigation area corresponding to Reservoir Res.

The GERD Operation Model

A non-linear optimization model is formulated to identify the optimal operations for the GERD through minimizing the deviation between the GERD monthly hydropower production and the maximum installed turbines capacity. The objective function is formulated as follows:

$$Min\ \sum_m \left(\frac{HP_m - HP_{Max}}{HP_{Max}}\right)^2$$

Such that:

HP_{Max}: GERD max hydropower capacity calculated as: $N_{days\,m} N_{hours\,d} P_{CAP} PF$
$N_{days\,m}$: The Number of operating days in month m
$N_{hours\,d}$: The Number of operating hours per day
P_{CAP}: The total installed power plant capacity (6,000 MW)
PF: Plant factor (0.62).

The GERD operation model is based on a set of constraints that describe the reservoir capacity, the turbines capacity, the spillway capacity, the storage depth relationship, water balance, and hydropower production. The Reservoir, turbine, and spillway capacity equations are described as:

$$S_{GERD_m} \leq 74\ \&\ d_{GERD_m} \leq 154$$
$$S_{GERD_m} \geq 10\ \&\ d_{GERD_m} \geq 100$$
$$Q_{spillway_m} \leq 38.88$$

$$Q_{Turbines_m} \leq 11.16$$

The Mass balance equations for the GERD are represented as:

$$\Delta S_{GERD\,n,m} = S_{GERD\,n,m+1} - S_{GERD\,n,m} = Q_{in\,n,m} + P_{n,m} - ET_{n,m} - Q_{out\,n,m}$$

$$Q_{out\,n,m} = Q_{spillway_m} + Q_{Turbines_m}$$

The hydropower production is formulated as:

$$HP_m = \gamma \epsilon Q_{Turbines_m} d_{GERD_m}$$

Such that:

S_{GERD_m}: Reservoir Storage for month m (km^3)
d_{GERD_m}: Reservoir depth for month m (m)
$Q_{spillway_m}$: Spillway discharge during month m (km^3/month)
$Q_{Turbines_m}$: Flow through the GERD turbines during month m (km^3/month)
γ: Specific weight of water (KN/m^3).

RESULTS AND DISCUSSION

Evaluation of L and Arability

The main factors constraining the UBN basin lands suitability for agriculture are steep slopes and soil pH. The analysis shows that soil pH and, specifically, the soil acidity in the central areas of the UBN basin greatly limits the basin arability to cereals, legumes, and oilseeds. Coffee, however, is more tolerant to the acidic soils in the central areas of the basin unlike the other crops but more sensitive to the soil limestone content (alkalinity) which limits about 5% of the basin's arability to coffee. **Table 2** shows the fractions of the UBN basin lands that are excluded from the different suitability classes and constrained only by slope, or by both slope and/or soil pH. **Figure 2** shows the spatial distribution of the UBN basin's suitable lands for growing cereals. In general, temperature is not a limiting factor for agriculture in the basin except for growing arabica coffee, which requires lower temperatures. Hence, 28% of the basin area in the lower western lands is not suitable for growing coffee especially during the dry season (March through May).

Land-Water Allocation Model

The land-water allocation model finds that 50 percent of the basin area could be converted from the current land-use, which consists mainly of savanna and shrublands, to rain-fed agriculture; maximizing the revenues of rain-fed grown crops adding up to 5,000 Million USD for the average flow year. It should be mentioned that the current population density in these areas is less than 20 people for each square kilometer of area (Bright et al., 2017) due to the spread of the tsetse fly in these areas, which leads to death of young cattle and the abortion of cows which drove away the grazing communities from this region. **Figure 3** shows a comparison between the basin areas defined as cropped lands according to the 2009 MODIS land use dataset and the optimal cropland allocation model. Most of the croplands are allocated to grow teff, with an area of about eight and a half

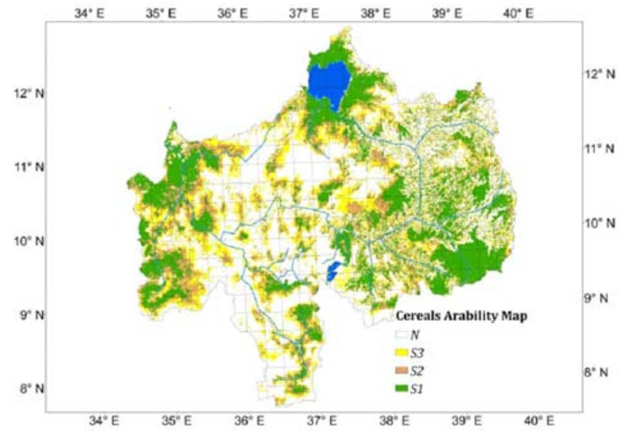

FIGURE 2 | Delineated suitable lands for agriculture at different land suitability levels for cereals.

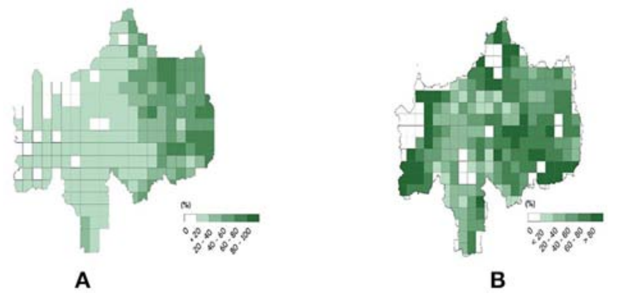

FIGURE 3 | A comparison between **(A)** the existing cropland using 2009 MODIS land use dataset and **(B)** the model optimal cropland that maximizes the rain-fed agriculture Net Benefits.

TABLE 2 | A summary of the fraction of the UBN basin lands limited by slope (%), soil pH, and both slope and/or pH for different land suitability classes and for different crop groups.

		Cereals		Legumes		Oilseeds		Sugarcane		Coffee	
	Sl	pH	Sl ∪ pH	pH	Sl ∪ pH	pH	Sl ∪ pH	pH	Sl ∪ pH	pH	Sl ∪ pH
S1	36	58	75	43	66	50	68	12	48	36	74
S2	24	42	57	34	52	27	45	4	29	19	51
S3	16	28	41	28	42	12	28	1	20	10	36

The suitability classes are: highly suitable (S1), moderately suitable (S2), and marginally suitable (S3).

million hectares, and a corresponding yield of nine million tons. Teff is an important food grain and an economically superior staple crop that accounts for about quarter the cereal production in Ethiopia and is used to make injera (Gabre-Madhin, 2001). Teff is priced twice as high as Sorghum, the cheapest cereal in the country (**Figure 4**). The UBN basin currently supplies Ethiopia with 70 percent of its total consumption of teff (Minten et al., 2012). The rest of the allocated croplands grow legumes and oilseeds with areas of 160 thousand and two thousand hectares, respectively. The reduction in the basin run-off corresponding to the optimal land-water allocation is expected to be about 7.55 cubic kilometers. **Figure 5** shows a comparison between the current monthly run-off and the run-off with the rain-fed agricultural expansion that maximizes net-benefits.

The model is also run for the minimum and the maximum precipitation years within the available remotely sensed precipitation data from 1998 to 2015 to test for the sensitivity of the optimal allocation to rainfall variability. The annual precipitation depth averaged over the basin varies from 1,100 mm for the driest year to 1,310 mm for the wettest year. **Table 3** summarizes the net benefits from rain-fed agriculture for the dry, average and wet years, the incurred costs for agriculture inputs and the total revenue. The maximum net benefits from agriculture vary between 1,280 and 2,300 Million USD for the dry and wet years. The cropland area varies between 31 percent of the total basin area for the dry year scenario to 51 percent for the wettest year scenario, and the annual production of teff varies between 5.1 and 9.4 M tons.

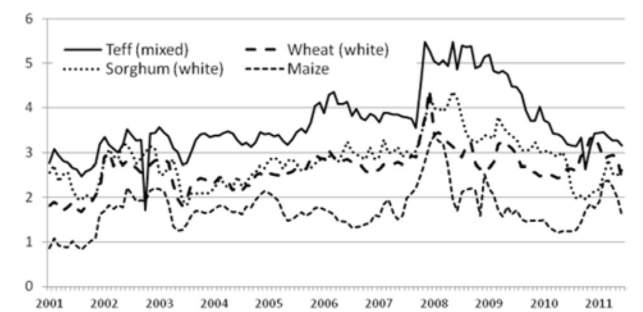

FIGURE 4 | A comparison of cereal prices in Addis, 2001-2011 compiled based on Ethiopian Grain Trade Enterprise (EGTE) wholesale prices (in ETB per kg) (Minten et al., 2012).

The annual production of legumes does not vary significantly between the driest and the wettest years, but a drop occurs in the average flow year. This drop is due to the conversion of lands that were dedicated to grow legumes in the driest year to grow teff instead since teff is more water consumptive which limits its growth in the dry-year scenario yet it is more profitable which makes it more desirable economic-wise as more water becomes available in the average flow year. Similarly, the oilseeds production decreases with the increase in rainfall.

For irrigated agriculture, the model finds that only three out of the 11 proposed irrigation reservoirs are economically attractive. The three reservoirs are Ribb, Gilgel Abay, and Dabana. The model builds both Ribb and Gilgel Abay up to their design capacities proposed in the master plan, while Dabana is built to about half of the proposed design capacity, as shown in **Figure 6**. The model allocates most of the irrigated lands to sugarcane due to its high productivity and revenues. For the three irrigation projects the sugarcane yield is about four million tons, with a production value of about 500 Million USD. The coffee yield, however, varies between 18,000 tons in the dry year and 26,000 tons in the wet year with a corresponding production value that varies from 75 to 104 Million USD.

The GERD Operation Model

The optimal GERD reservoir operation can be achieved by maintaining a monthly flow through the turbines of about three to four cubic kilometers. The corresponding hydropower production is mostly uniform with higher hydropower generation during the summer where the electricity demands usually peak. **Figure 7** shows the monthly hydropower production for the dry, average, and wet year scenarios. The

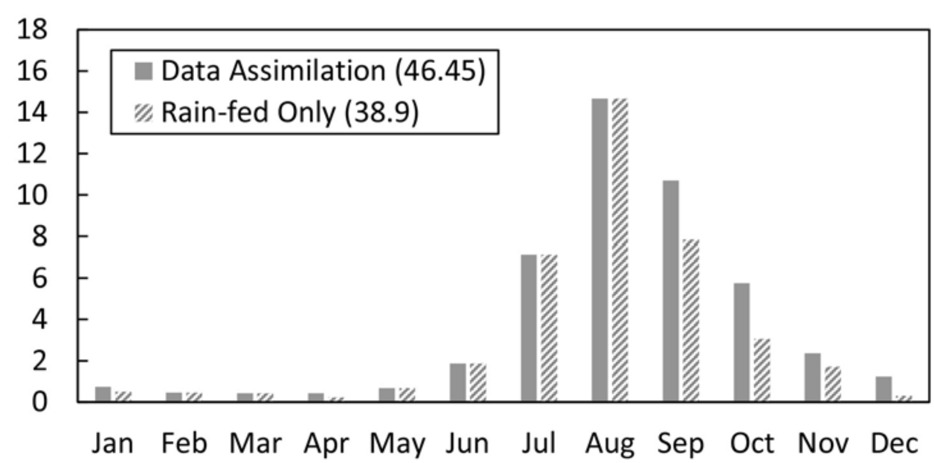

FIGURE 5 | A comparison between the long-term average basin runoff and the resulting runoff after allocating water and land resources to rain-fed agriculture.

TABLE 3 | The maximized net benefits from rain-fed agriculture, the crops revenues, and the input costs for the dry, average, and wet years.

(M$)	Dry year	Avg. year	Wet year
Net benefits	1283.3	2169.2	2298.4
Rain-fed Agriculture Revenues	2939.6	5000.2	5284.5
Input costs	1656.3	2831	2986.1

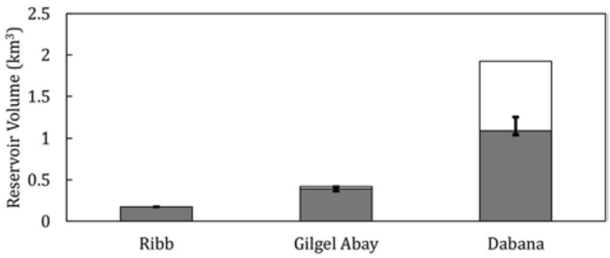

FIGURE 6 | The model reservoir capacity compared to the master plan (the red error bar shows the model built reservoir capacities for the dry and wet years).

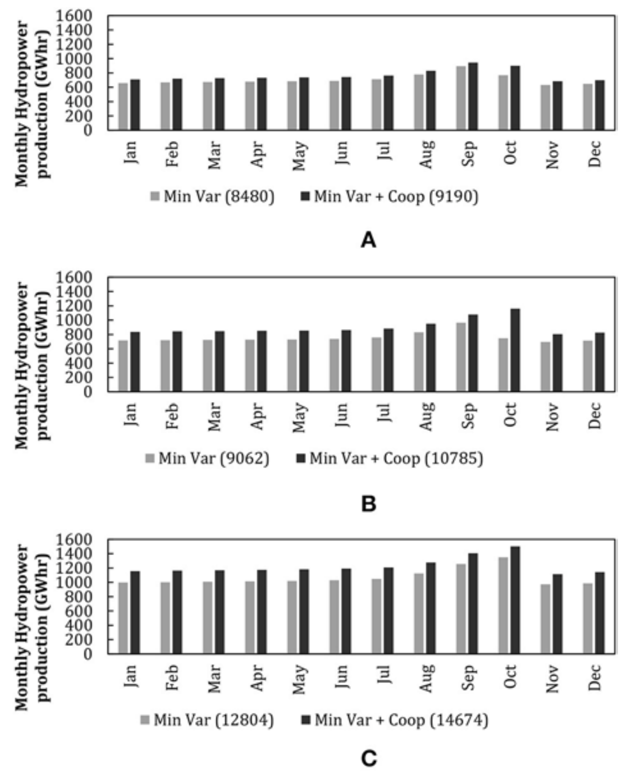

FIGURE 7 | Maximum monthly hydropower Production for **(A)** dry year scenario, **(B)** average year rainfall scenario, and **(C)** wet year scenario. For each precipitation scenario two operation scenarios are modeled: (i) Min Var: Operating the GERD such that a uniform hydropower production is maintained with minimum variability from month to month (ii) Min Var + Coop: Operating the GERD such that a uniform hydropower production is maintained with minimum variability from month to month and assuming the three stakeholder countries would cooperate in efficient agricultural investment with the agreement that historical flows of the UBN basin will be maintained.

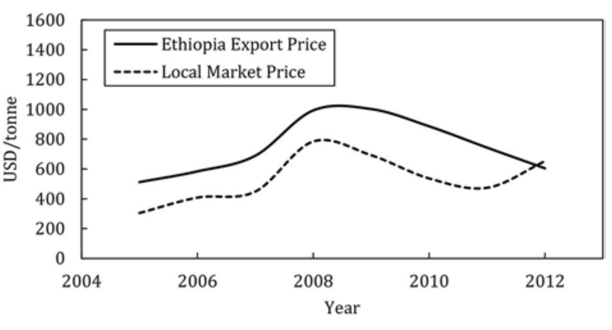

FIGURE 8 | A time series of Ethiopia's Teff export price and the local market price in Addis Ababa for the years 2005-2012 (Source: The national bank of Ethiopia and ERCA and EGTE).

model estimates the maximum uniform monthly hydropower that can be generated from the GERD to be about 700, 800, and 1,100 GWh for the dry, average, and wet year scenarios, respectively. However, an extra 1,000 GWh can be generated annually if the water is allocated to hydropower rather than expanding rain-fed agriculture upstream of the GERD in the three scenarios. This highlights the trade-off between allocating water for agriculture upstream of the GERD and saving the water for hydropower production. In order to test the sensitivity of the optimal allocation to teff price changes, the model is run using a range of teff market prices. **Figure 8** shows the Teff market price according to the national bank of Ethiopia and the Ethiopian Revenues and Customs Authority (ERCA), and the local Teff market price in Addis Ababa according to the Ethiopian Grain Trade Enterprise (EGTE). The price of 550 USD per ton is used to reflect the average market price of Teff in the model, which is below the lower end of the export prices of Teff from Ethiopia.

The land water allocation model finds that only when the price drops to half of the current market price or below, i.e., 225 USD per ton, the model chooses not to grow teff, since its market price becomes lower than the costs of inputs required to grow it. In this case, saving water for hydropower generation through the GERD becomes more economically attractive than growing oil crops and legumes upstream of the dam. However, if the teff market price exceeds 300 USD per ton, then teff agriculture becomes more valuable than hydropower generation through the GERD.

Figure 9 shows the total net benefits from both agriculture and hydropower plotted against the ratio between hydropower pricing and teff market price for two different scenarios:

(a) *The No-cooperation scenario:* in this scenario, we assume that the only interest is maximizing the total net-benefits of Ethiopia with no regards to impacts on downstream countries sharing the UBN basin waters. In this case, rain-fed agriculture is expanded to maximize the agricultural net-benefits.
(b) *The Cooperation scenario:* in this scenario, we assume that the three stakeholder countries are cooperating in expanding

the agriculture in the UBN basin efficiently such that the downstream flows are not impacted, and historical flows are maintained at the UBN basin outlet. In this case, all the UBN water flow is allocated for hydropower generation through the GERD.

The intersection of the total net-benefit plots of those two scenarios gives the ratio at which both hydropower and teff become equally profitable. This ratio is found to be around 0.21 Ton/MWH, above which saving water for hydropower production becomes more profitable than growing teff.

The allocation models are used here to illustrate the impact of constraining the outflow at the outlet of the UBN basin. We first assume the price of teff to be about $550 per ton to represent the current teff market price, and the price of electricity to be about 8 cents per kwh. In **Figure 10**, as the magnitude of the reduction in annual water flow is constrained to vary from 0 to 12 cubic kilometers per year, the additional net benefits from agriculture increases from 0 to about 600 Million USD. At the same time, the reduction in net benefits from hydropower production increases almost linearly from 0 to about 200 Million USD. As illustrated by **Figure 10**, if the current agricultural water consumption in the UBN basin is reduced to increase the historical UBN basin flow by about two cubic kilometers, that would generate about 10 Million USD hydropower net benefits but would at the same time reduce the agricultural net benefits by about 800 Million USD, which reduces the total net benefits significantly. This is due to the large potential for expanding the production of profitable crops such as teff, which makes the marginal value of a unit of water consumed in agriculture high. As agriculture is expanded further and the teff arable lands are exploited to their capacity, lower value crops such as legumes are expanded, and that is when the marginal value decreases until the slope becomes flat; when the total agricultural potential has been tapped. In order to find the optimal water allocation that maximizes the total net benefits, the added net benefits to agriculture should be maximized while minimizing the net benefits lost from hydropower as much as possible, which occurs at an additional water consumption of about 7.6 cubic kilometers. These results illustrate the tradeoff between agriculture and hydropower in the UBN basin.

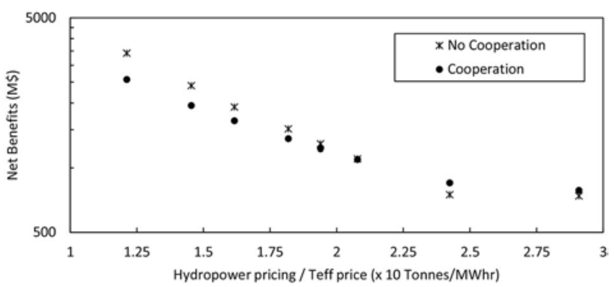

FIGURE 9 | The total net benefits plotted against the ratio of the hydropower pricing to Teff market price for cooperation and no-cooperation scenarios.

Figure 11 shows an alternative plot that shows the optimal hydropower pricing corresponding to a range of teff market prices at which the trade-off between agriculture and hydropower is neutralized. The figure is divided into two zones: a teff dominating zone where allocating the water to grow teff is more profitable, and a hydropower dominating zone where saving water for hydropower purposes is more profitable. The cross shows that the current teff market price and the proposed hydropower pricing by Ethiopia fall into the teff dominating zone at which the total net-benefits are not maximized. In order for Ethiopia to maximize its total net benefits, the hydropower sold to the neighboring regions needs to be priced to be at least 13

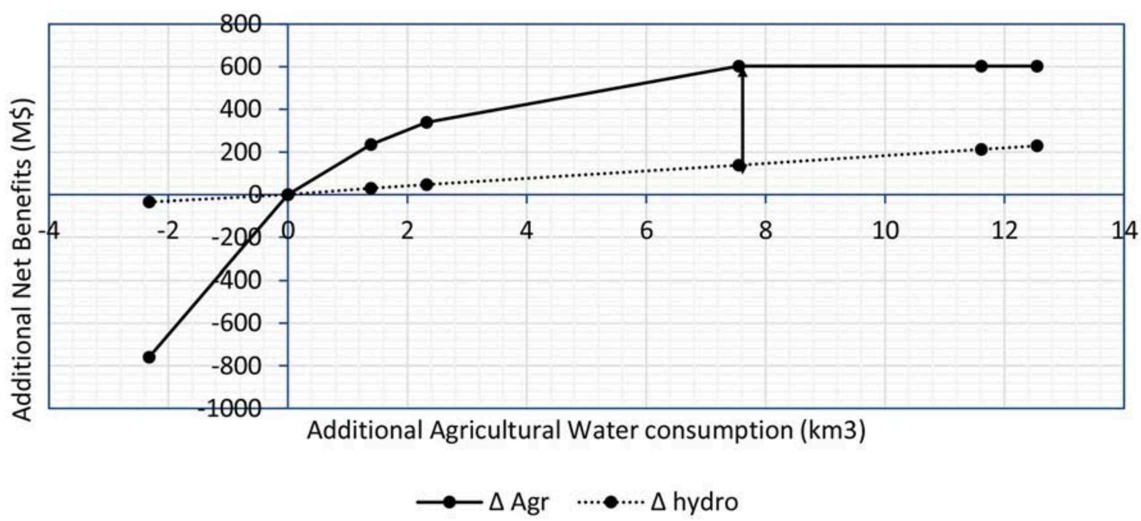

FIGURE 10 | Illustration of the trade-off between agriculture and hydropower and the optimal allocation in the UBN basin. The horizontal axis shows the additional agricultural water consumption compared to the current water land use, while the vertical axis shows the additional benefits either added to agriculture or lost from hydropower corresponding to that consumption. The green curve shows the net benefits added to agriculture if additional water is allocated to agriculture while the blue line shows the net benefits lost from hydropower corresponding to this extra water allocation to agriculture.

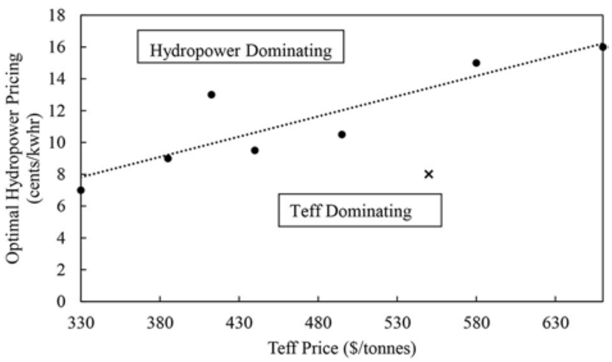

FIGURE 11 | The optimal hydropower pricing at different teff market prices (The red cross indicates the current market price for teff and the hydropower pricing set by Ethiopia). The horizontal axis shows different Teff market prices while the vertical axis shows the corresponding electricity price that should be set by Ethiopia to not lose benefits due to potential agricultural expansion. The cross corresponds to the nominal prices of $550 per ton for teff and $0.08 per kwh for electricity. This figure was calculated using on the long-term average UBN basin hydrology.

cents per kwhr, which is relatively high and almost equivalent to the price of electricity generated using fossil fuels.

This summarizes the water-food-energy nexus in the UBN basin. The optimal allocation to maximize the total net-benefits of the UBN basin land and water resources at the current crop prices is to allocate about half of the basin area to grow rain-fed teff with a corresponding water consumption of about 7.55 cubic kilometers. This water consumption is deducted from the water flowing through the GERD turbines, which reduces the annual hydropower production by a thousand GWh from the potential production if the hydropower production is to be maximized. The question here becomes whether to generate energy for meeting the country's demands is more important than maximizing the total net-benefits from using the basin resources. This analysis can be easily extended using long stochastic time-series to study the year to year rainfall variability and climate models projections forcing data to study the impact of climate change.

CONCLUSIONS

This paper presents a framework for optimal allocation of a river basin's land and water resources between rain-fed and irrigated agriculture and hydropower. This framework is applied on the UBN basin as a case study of a water-scarce transboundary basin with escalated conflicts between the stakeholder countries sharing its waters to help find win-win opportunities. The land-water allocation model finds significant potential for expanding rain-fed agriculture covering up to half of the basin area by adding soil enhancements. This agricultural expansion is expected to reduce the annual flow of the Blue Nile river by about 7.55 cubic kilometers. The model also finds that only three of the 11 irrigation schemes proposed in Ethiopia's master plan make economic sense and grow mostly sugarcane in these irrigated areas. The optimal operation for the GERD involves regulating the monthly releases through the turbines to be about three to four cubic kilometers, and fluctuating the storage to be slightly reduced before the rainy season and filled up during the rainy season. There is a clear trade-off between expanding the rain-fed agriculture potential in the UBN basin and saving the water for hydropower production at the GERD. This trade-off can offer an opportunity for a win-win solution for the Nile conflict if the countries decide to cooperate in investing in an efficient rain-fed agricultural expansion in the basin and sharing the benefits and costs.

DATA AVAILABILITY STATEMENT

All the datasets used for hydrology, soil, and topography are global publically available and all were properly cited online.

AUTHOR CONTRIBUTIONS

MA has made a substantial contribution to the conception and design of the work, analysis and interpretation of the data for the work. She has also drafted the work and agrees to be accountable for all aspects of the work in ensuring that questions related to the accuracy and integrity of the work are appropriately investigated and resolved. EE and MA have made a substantial contribution to the conception and design of the work.

ACKNOWLEDGMENTS

This is to acknowledge the contribution of Dr. Yossif A. Ibrahim who helped us greatly with data on irrigation projects in the Ethiopia master plan. Data on project specs and crops and construction costs. This data was crucial to address irrigated agriculture in the basin.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Environmental Science

REVIEW
published: 08 February 2019
doi: 10.3389/fenvs.2019.00008

The Development of the Water-Energy-Food Nexus as a Framework for Achieving Resource Security: A Review

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This paper presents a study of the evolution of the water-energy-food (WEF) nexus since its rise to prominence in policy and development discourses in 2011. Drawing from an extensive review of published literature, the paper presents various interpretations of the concept while also considering the novelty of the WEF nexus. The challenge of integrating and optimising the components of this multi-centric nexus is examined, with four case studies being presented. Various criticisms levelled at the WEF nexus, such as the neglect of livelihoods and the environment in assessments, are noted, together with governance considerations associated with this framework. Finally, the potential of the WEF nexus to contribute to the achievement of the Sustainable Development Goals is reviewed.

Keywords: water-energy-food nexus, framework, resource security, governance, sustainability development goals

OPEN ACCESS

Edited by:
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Morgan State University, United States

Reviewed by:
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Specialty section:
This article was submitted to Freshwater Science, a section of the journal Frontiers in Environmental Science

Received: *02 September 2018*
Accepted: *15 January 2019*
Published: *08 February 2019*

Citation:
Simpson GB and Jewitt GPW (2019) The Development of the Water-Energy-Food Nexus as a Framework for Achieving Resource Security: A Review. Front. Environ. Sci. 7:8. doi: 10.3389/fenvs.2019.00008

INTRODUCTION

Meadows et al. (1972) warned almost half a century ago, "If the present growth trends in world population, industrialisation, pollution, food production, and resource depletion continue unchanged, the limits to growth on this planet will be reached sometime within the next one hundred years." Some three decades later they stated that "the human economy is exceeding important limits now and that this overshoot will intensify greatly over the coming decades" (Meadows et al., 2004). Just a few years after this latter statement, average world food prices increased significantly, leaving a large portion of the global population unable to afford their basic nutritional needs (Mohtar and Daher, 2012). These increased food prices are an indication of growing natural resource scarcity (Ringler et al., 2013).

The finite and indispensable nature of freshwater also came to the fore during the first decade of the twenty-first century. In their 2011 publication, *Water Security: The Water-Food-Energy-Climate Nexus*, the World Economic Forum highlighted that in many locations around the globe, water has been consistently under-priced, groundwater has been depleted, and that unlike energy, water has no substitutes or alternatives (WEF, 2011). However, Sachs (2015) states that "Of all of the problems of reconciling growth with planetary boundaries, probably none is more urgent and yet more complicated than the challenge of the world's energy system."

Projections are that the global demand for resources is going to escalate on this "hot, hungry, crowded, and fast evaporating planet" (WEF, 2011). The NIC (2012) estimate that the growth in demand for food, water and energy by 2030 will be 35, 40, and 50 percent, respectively. This is due to an increasing population, urbanisation, and an additional three billion middle-class people by 2030 (WWF and SABMiller, 2014). There is also a dire need to enhance the livelihoods of the "bottom billion" who are undernourished, without access to electricity and clean water (IRENA, 2015).

Speaking on *World Water Day* in March 2011, the then Secretary-General of the United Nations, Ban-Ki Moon, noted that the interconnects between water, energy and food are among the greatest challenges that mankind faces. In November of that year, the *Bonn2011 Conference: Water Energy and Food Security Nexus–Solutions for the Green Economy* was convened. That meeting served as a catalyst for wider interest in the water-energy-food (WEF) nexus amongst academics, policy makers, national and international development agencies and donor countries. While some authors suggest that the WEF nexus has traits of a "nirvana concept," others have identified several shortcomings in nexus thinking, labelling it as an immature approach (Allouche et al., 2015).

In this review, search terms related to the paper's title were entered into the EBSCOhost, Web of Science, Science Direct, and Wiley Online databases. These searches yielded 111, 212, 135, and 53 results respectively, i.e., a total of 511 academic papers. After removing duplicates (104), articles were excluded based on a review of their titles (284) and abstracts (38). A further 32 articles were subsequently excluded during a full screening of the texts, yielding 53 academic articles that have contributed to this literature review. Fourteen grey literature sources that were identified during the review of the academic articles were subsequently included in the literature review process. This methodology was followed to remove bias, as far as possible, from the selection of academic and grey literature for inclusion in the compilation of this manuscript.

This paper initially examines what is understood by the term "WEF nexus." It continues to provide an analysis of whether the WEF nexus is a unique approach, or if it is simply a repackaging of an existing framework (even though a "repackaging" would not necessarily imply irrelevance). The challenge of integrating and optimising these three resource sectors, together with their trade-offs and synergies, is subsequently presented together with four case studies. Thereafter, one of the key criticisms levelled at the WEF nexus is considered, namely, whether the resource security goal of the WEF nexus, which the global economic community is seen to be driving, accommodates the environment and livelihoods. Finally, the possible benefits of the WEF nexus approach in terms of policy development and governance are reviewed.

WHAT IS THE WEF NEXUS?

The word *nexus* means "to connect" (De Laurentiis et al., 2016). This word conveys the interactions between two or more elements, be they dependencies or interdependencies. The WEF nexus is, therefore, the study of the connections between these three resource sectors, together with the synergies, conflicts and trade-offs that arise from how they are managed, i.e., water for food and food for water, energy for water and water for energy, and food for energy and energy for food.

Some authors argue that there is little agreement on the WEF nexus' precise meaning, contending that there are many competing (and often overlapping) conceptions (Benson et al., 2015; Al-Saidi and Elagib, 2017). Others suggest that the term can be viewed as a buzzword, i.e., a word that gains prominence due to "a combination of ambiguous meaning and strong normative resonance" (Cairns and Krzywoszynska, 2016). Gain et al. (2015) report that many developing countries are not even aware of the WEF nexus. Cairns and Krzywoszynska (2016) found that within natural resource discussions in the United Kingdom, the understanding and usage of the term *WEF nexus* is "plural, fragmented, and ambiguous." Their concern is that the broad use of the term could trivialise its importance.

Wichelns (2017) states that the selection of water, energy and food as the principal components of a nexus framework for guiding research and policy, although initially appealing, is somewhat arbitrary. Liu et al. (2018) note that while the energy sector speaks of the *energy*-water-food (EWF) nexus, hydrologists and water engineers call it the *water*-energy-food (WEF) nexus, while those in the agricultural fraternity use the term, the *food*-energy-water (FEW) nexus. Based on this variance in terminology, it is evident that the conceptual approach to the WEF nexus is generally dependent upon the perspective of the particular researcher or policy-maker (Bazilian et al., 2011). Allouche et al. (2015) agree that the term can mean different things to different people, arguing that while some consider the WEF nexus scope to be too narrow, excluding for example climate change and the environment, other authors view it as being relatively broad and link it to the green economy, poverty reduction and global resource security (Pandey and Shrestha, 2017).

The World Economic Forum's primary area of concern regarding the WEF nexus was initially water security, hence it is termed by some as the WEF *security* nexus. Different groupings who have embraced the WEF nexus approach have contrasting foci, e.g., sustainability, the green economy, trade-offs, livelihoods, climate, optimisation, modelling, or scarcity. Pahl-Wostl (2017) explains that the WEF nexus was strongly focused on resource security during the first four years after the *Bonn2011 Conference*, but since then the concept's use has broadened to address interdependencies and integration to achieve the sustainable management of resources.

While there is disagreement on what the term "nexus" means, this is not the first term that the academic and development community has struggled to define. Meadows et al. (2004) note that sixteen years after the Brundtland Commission mainstreamed the concept of sustainability (Brundtland, 1987) the global society was still trying to agree on what the term meant.

The debate regarding the nexus' precise meaning and application indicates that it is still an evolving concept (Allouche et al., 2015; Pandey and Shrestha, 2017). While there are differing interpretations of this framework, de Loe and Patterson (2017) suggest that what is paramount is "nexus thinking," as opposed to a specific strict definition of the WEF nexus.

IS THE WEF NEXUS CONCEPT NOVEL?

Many authors question whether the WEF nexus approach is novel (Allouche et al., 2015; Benson et al., 2015; Muller, 2015; Wichelns, 2017). The FAO (2014), for example, query whether the concept is just the "same old wine in new bottles," or if it contributes something new to the sustainable development discourse. It is also questioned whether the nexus is complete with only three sectors being represented. Climate change, the environment, land, governance, urbanisation, waste, or livelihoods are some of the other components that could be, and are, assessed together with the trio of sectors that make up the WEF nexus. To this end, Wichelns (2017) queries the selection of the three resource sectors in the WEF nexus and the widespread recognition that the concept is receiving, noting that it is not yet an agreed and tested framework.

Benson et al. (2015) argue that many of the ideas presented in the nexus philosophy already appeared in other strategies which entered policy discourses in the 1990s. When sustainable development was first proposed, it was stated that population growth, food security, energy, the environment, and urban development "are connected and cannot be treated in isolation one from another" (Brundtland, 1987).

Muller (2015) explains that the 1977 United Nations conference proceedings reveal that the world at that time was fully cognisant of the interdependencies between water, food and energy. This is evident when reading the seminal work, *The Limits to Growth,* wherein it is highlighted that the five major areas of global concern identified "are all interconnected in many ways" (Meadows et al., 1972).

Cai et al. (2018) note that since the Harvard Water Program in the early 1960s there has been a drive to address water research utilising an interdisciplinary approach. Wichelns (2017) reports that the need for greater integration of research and policy discourse across sectors and regions was expressed in international meetings as early as the late 1940s. In terms of the interconnected nature of all subjects of study in the biosphere, Muir (1911) stated that "When we try to pick out anything by itself, we find it hitched to everything else in the universe." There is truly "nothing new under the sun."

If the WEF nexus is not novel, then why has there been so much interest in the approach from organisations such as the World Economic Forum, the World Wide Fund for Nature, the United Nations and global companies like the Coca-Cola Company and SABMiller? Wichelns (2017) suggests that much of the interest in the nexus is as a result of the concern of the impact of climate change on water, energy and food security. Rasul and Sharma (2016) are in agreement, noting that all three resource sectors are influenced by climate change and that they, in turn, each contribute to that impact as a result of their discharges and/or emissions. Pandey and Shrestha (2017) contend that the concept of the WEF nexus has gained prominence as a contemporary way to understand and approach sustainable development.

In terms of the governance of water, one framework that was formalised in the early 1990s was Integrated Water Resources Management (IWRM). IWRM was initially embraced as the silver bullet of sustainable development because of its integrated analysis of sectors and resources (Kurian, 2017). The United Nations included IWRM as a component of the Millennium Development Goals (MDGs) (Benson et al., 2015). Bogardi et al. (2012) however argue that IWRM on its own is insufficient. Benson et al. (2015) suggest that the WEF nexus framework exhibits some innovative elements, such as holistically integrating different policy sectors, and contend that it could be highly complementary to IWRM.

While several authors argue that the interdisciplinary nature of the approach is not new, the primary reason for promoting the WEF nexus approach above that of IWRM is that it is multi-centric, with each sector being treated with equal importance, while IWRM is water-centric (Allouche et al., 2015; Benson et al., 2015; Abdullaev and Rakhmatullaev, 2016; Gallagher et al., 2016; Al-Saidi and Elagib, 2017; Liu et al., 2017; Owen et al., 2018). Cai et al. (2018) suggest that the WEF nexus may be accepted by a broader set of stakeholders than IWRM, especially those within the agricultural and energy sectors.

INTEGRATING AND OPTIMISING THE WEF NEXUS

Some critics of the WEF nexus argue that the analysis of one resource sector is sufficiently complex, suggesting that integrating multiple resource sectors simultaneously poses an appreciable challenge (de Loe and Patterson, 2017). Wichelns (2017) concurs, contending that given the lack of success in implementing Integrated Natural Resource Management (INRM) and IWRM in practice, another call for integration should be questioned. It has however been suggested that the critique of IWRM is well-founded because it is perceived to underestimate the importance of administrative boundaries, with its focus being hydrological catchments (Kurian, 2017). de Loe and Patterson (2017) contend that IWRM has failed to achieve the goals for which it was intended. Abdullaev and Rakhmatullaev (2016) agree, stating that the active promotion of a nexus approach could assist in solving the IWRM's "water box problem." Belinskij (2015) argues for utilising a nexus approach since it removes the institutional "silos" that are so prevalent in governance and policy circles.

Leck et al. (2015) warn that the multi-sector goal of the WEF nexus, with its associated trade-offs and interdependencies, could result in its downfall. They warn that although the nexus concept is attractive, it is challenging to implement. Yet, Wicaksono et al. (2017) argue that the fundamental notion of the WEF nexus has already been adopted in some regions and countries, although not necessarily under the banner of this framework itself. Daher et al. (2017), while acknowledging the complexity of modelling the nexus (i.e., computer-based modelling), emphasise that there is no one-size-fits-all model to address WEF-related issues. They continue to describe how localising and contextualising a nexus assessment will be vital to addressing trade-offs. An example of localising and contextualising the WEF nexus at a sub-national level is provided in "Case Study 1".

Another challenge for WEF nexus analyses stems from globalisation. The liberalisation of trade has meant that the interactions between water, energy, and food are very complex since materials and products are continually crossing international borders (Owen et al., 2018). Water moves between countries as an embedded component of food and other products as "virtual water" (Bogardi et al., 2012). Closely linked to

Case Study 1:

The province of Mpumalanga in South Africa is the energy hub of the country. It is the source of significant coal resources and most of the fossil-fuel-based power stations that burn much of the coal. However, "South Africa has only 1.5% high potential arable soils (soils best suited for cash crop production), and 46.4 % of this total area is in Mpumalanga" (BFAP, 2012). The development of coal mines, especially opencast operations, is continually reducing the area of high potential arable soils in South Africa (Simpson and Berchner, 2017). The continued pursuit of fossil-fuel based energy dependency in South Africa is, therefore, threatening food security. It is also negatively impacting upon air pollution (Greenpeace, 2018) and water quality (McCarthy, 2011). A WEF nexus-based assessment of South Africa indicates that policy related to the accelerated implementation of renewable energy generation must be adopted if the nation is to move toward a low-carbon, sustainable future.

Case Study 2:

With less than 5% of the world's land area, South Asia has to feed about one-quarter of the global population (Rasul, 2016). To ensure food self-sufficiency, many South Asian countries have adopted policies that encourage farmers to increase food production, including the provision of subsidies for irrigation, energy, and fertilisers, and the guarantee of minimum prices for wheat and rice. This has resulted in an alarming rate of decline in groundwater levels since these subsidies have discouraged farmers from being efficient in their use of both water and energy. "Thus, a nexus 'no-brainer' is to review and identify candidates for the phase-out of subsidies on water, energy, land and food" (Ringler et al., 2013). Current water and energy charges are often too low to affect behaviour. The irony is that by providing water and energy for agriculture at a low cost, food security can itself ultimately be threatened.

the concept of virtual water is large-scale land acquisitions (LSLAs). In order to secure their essential resources, several developed countries (e.g., the United Kingdom and Italy) have pursued LSLAs, predominantly in developing countries, such as Guinea, Sierra Leone, and Mozambique (Siciliano et al., 2017). These LSLAs are ultimately concerned with gaining access to land and water for energy (i.e., biofuel) and food production. What is concerning is that malnutrition and economic water scarcity often exist in countries where LSLAs have occurred. In so doing the wealthier nations, in seeking to secure resources for themselves through LSLAs, reinforce the concerns of several authors regarding the securitisation agenda, i.e., that livelihoods of the poorer members of the global society are neglected in the developed world's pursuit of macro-scale resource security.

Quantifying the movement of virtual water between nations and regions is not the only challenge. Liu et al. (2017) suggest that the scientific challenge associated with the WEF nexus is primarily related to the myriad of data required to undertake the necessary analyses. Further, water, energy and food are measured in different manners, with each having their own units of measurement.

In addition to the data and integration challenges associated with the WEF nexus, there are multiple spatial and temporal scales within which this framework can be viewed. These scales influence each other (Garcia and You, 2016). In terms of the spatial extent, a WEF nexus assessment could be undertaken at a city, basin, national, regional, or global level. An example of a regional assessment is provided in "Case Study 2." Although Muller (2015) questions the novelty and completeness of the WEF nexus, it is argued that what the WEF security framework does do is to move the spotlight of water resources management "from watersheds to problem-sheds, from what society should do for water to what water can do for society."

Regarding the temporal nature of a WEF nexus study, an instantaneous snapshot of the status of a WEF system could be developed. Alternatively, the metabolism of a city could be provided over a period, such as a month or a year. A further challenge related to seeking to optimise the WEF nexus is that a researcher could focus on human needs, trying to attain an equilibrium, while neglecting environmental considerations, climate change or poverty alleviation.

Although much of the literature associated with the WEF nexus is dismissive of the "silo" approach to resource management, some argue that "the baby should not be thrown out with the bathwater." Wichelns (2017), for example, notes that there are times when an in-depth study within a particular discipline is required. Artioli et al. (2017), however, suggest that the momentum that the WEF nexus approach has attained within policy circles will be difficult to curtail.

DOES THE WEF NEXUS ADDRESS RESOURCE SECURITY FOR ALL?

Gupta (2017) contends that the WEF nexus is a security nexus for societal well-being. Indeed, Hoff (2011) in the background paper for the *Bonn2011 Conference* highlighted the "need to secure local livelihoods and the non-negotiable human rights to water and food." Wichelns (2017) however, argues that livelihoods are often omitted in WEF nexus analyses, even though the poorest members of the global society are often impacted most severely by the policy changes that emanate from a nexus approach. This is because the achievement of food security at the household, city, provincial, or country level is more complex than balancing supply and demand on a macro-scale (Grafton et al., 2016).

There is an emerging resource security focus utilising the WEF nexus as the guiding framework which is motivated by the possibility that economic growth will soon be constrained by shortages of one or more of the sectors constituting this nexus (Salam et al., 2017). There has also been an increasing focus on water security within the private sector during the past decade (Leck et al., 2015), and Green et al. (2017) note that the private sector is often influential in decisions appertaining to the provision and management of water, energy, and food.

Spiegelberg et al. (2017) agree that there is a general economic motivation behind the WEF nexus, explaining that the literature focuses primarily on three fields of global growth, namely, the increase in population, urbanisation, and the burgeoning middle class in developing countries with their "Western" consumer demands. Biggs et al. (2015) go further, stating categorically that nexus frameworks have failed to adequately incorporate livelihoods into their thinking, i.e., resource security *for all*. They suggest that this is counterintuitive since supporting livelihoods is implicit in the attainment of sustainable development. This relegation of livelihoods is in conflict with one of the three guiding principles of the WEF nexus philosophy highlighted at the *Bonn2011 Conference*, which is that people and their basic human rights must be the basis of this approach (Salam et al., 2017).

Leese and Meisch (2015) suggest that whereas sustainability has historically focused on distributional justice, it is now often viewed in terms of resource security. The risks associated with the unavailability of water, energy, and food have become a global concern (WEF, 2011; NIC, 2012). Leese and Meisch (2015) argue that the WEF nexus' focus on securitisation, i.e., the security agenda centered on the risk of non-supply, is one that is driven by economic considerations, not the challenges related to livelihoods, which has traditionally been within the ambit of sustainable development. Further, they contend that the sustainability focus on equitable access to resources is being usurped by the threat to global productivity and living standards.

In summary, the concern of these authors is that sustainability is being securitised, i.e., one component of sustainable development is being focused upon to the detriment of the other components. The belief is that the World Economic Forum is prioritising this agenda and that improved macro-scale food security will not *ipso facto* result in a reduction in the prevalence of undernourishment, i.e., Sustainable Development Goal (SDG) 2. Nor will improved water security at a national level necessarily lead to an increase in the levels of access to clean water and improved sanitation facilities, i.e., SDG 6. Biggs et al. (2015) explain that "security" should not refer only to the availability of resources, but also to universal access to them.

Salam et al. (2017), however, contend that the amalgamation of water, energy, and food in a nexus framework to increase resource efficiency can be considered as a necessary way to achieve the SDGs. Rasul and Sharma (2016) agree, stating that the nexus outlook can assist in aligning the SDGs with planetary boundaries. The SDGs provide a basis upon which the WEF nexus can be developed (Gallagher et al., 2016).

To sustainably achieve resource security for all, the integrity of ecosystem services and the associated resource base must be maintained while access to resources is expanded and consolidated. This is presented schematically in **Figure 1**, where all the SDGs are directly or indirectly connected to food. Rockström and Sukhdev (2016), who developed this illustration, propose that the goals for eradicating poverty (SDG 1) and hunger (SDG 2) require gender equality (SDG 5), adequate jobs (SDG 8), and a decrease in inequality (SDG 10).

Ringler et al. (2013) explain that assessments utilising a nexus approach must consider both livelihoods and the environment. de Grenade et al. (2016) comment that while the "nexus" has various key strengths, it fails to adequately acknowledge the environment as its irreplaceable foundation. Planetary boundaries are however being threatened (Rockstrom et al., 2009) as predicted by Meadows et al. (1972). The challenge is to develop policies that support the sustainability of water, energy, and food resources, while simultaneously providing access to these resources for all levels of society. Achieving sustainability necessarily requires that the protection of the environment be prioritised.

GOVERNANCE CONSIDERATIONS ASSOCIATED WITH THE WEF NEXUS

It could be said, "let us eat, drink, spend, extract and pollute, and be as merry as we can, and let posterity worry about the spaceship earth" (Boulding, 1966). A philosophy such as this would fly in the face of sustainable development, which calls us to ensure that the needs of the current generation are not met in a manner that compromises the ability of our children to meet their own needs (Brundtland, 1987). Achieving a profound goal such as this requires a practical, holistic framework, and strong governance. Al-Saidi and Elagib (2017) suggest that a governance focus is a missing ingredient in the nexus debate.

Governance of the WEF nexus includes a wide range of private and public systems that manage the supply and demand of water, energy and food (Pahl-Wostl, 2017). Providing access to improved water sources, sanitation facilities and electrification is viewed by most citizens as a barometer of good governance and is reflected in both the Millenium Development Goals (MDGs) and SDGs. Benson et al. (2017) argue that effective governance for the nexus occurs when the integration of resource sectors is actively pursued, such that synergies between water availability, energy generation and food production are enhanced, while trade-offs are managed, and potential conflicts are averted. An example of the management of a WEF nexus trade-off, and the dissipation of a potential international conflict, is presented in "Case Study 3." Although the WEF nexus approach has gained significant momentum since 2011, it is however not yet widely adopted in either policy or development planning (Wicaksono et al., 2017).

Rasul and Sharma (2016) state that the nexus framework and climate change adaptation share aims and principles. Rasul (2016) suggests that one mechanism for enabling a policy framework for managing nexus challenges is to strengthen the role of the national planning commissions in the countries being assessed. This is necessary even in developed countries. Sharmina et al. (2016), for example, notes that most of the United Kingdom's land-use policies are compartmentalised, with the administration of the sectors occurring in silos.

Case Study 3:

In a WEF nexus assessment of the Mekong basin it was determined that a significant growth in the capacity and supply of power through hydropower developments could, amongst other impacts, reduce fish stocks and fish diversity, as well as the availability of water to downstream users (Smajgl et al., 2016). A policy of managing energy demand, as opposed to a focus on energy supply and capacity alone, could reduce the negative impacts of hydropower on food and water security within this large river basin. This policy intervention recommendation would probably not have been arrived at if a single-sector energy assessment, as opposed to a WEF nexus assessment, was undertaken.

Schreiner and Baleta (2015) in turn report that the nexus philosophy is becoming an important component of development planning, with synergies existing across international boundaries within a region. Ololade et al. (2017) concur regarding the potential of regional cooperation, although they note that even though South Africa's policy allows for the implementation of a WEF nexus approach, this form of integrated governance does not yet exist at a national level. Individual countries will need to develop their own WEF nexus governance structures before they can engage in international endeavours in this regard.

In terms of the spatial extent of nexus governance, Artioli et al. (2017) note the rapid rate of urbanisation worldwide, and suggest that cities can play a key role in adopting the WEF nexus approach. They further state that the urbanisation of the nexus approach is part of a movement toward integrated management and that the "smart city" is the most dynamic component of that general trend (Artioli et al., 2017).

Another aspect associated with WEF nexus governance is waste. Machell et al. (2015) explain that it is possible to sustainably supply and consume more water, energy and food by addressing the mechanisms of waste. Scanlon et al. (2017) agree, noting that scarcity in these three key resources can be partially managed by reducing demands. An example of the benefit that could be derived from the processing of waste is provided in "Case Study 4".

Pandey and Shrestha (2017) conclude that the WEF security nexus is widely accepted in international development circles. (Dawoud, 2017) emphasise that the challenge is how to implement a WEF nexus framework where the risks, challenges and opportunities are identified and considered by all relevant stakeholders. As Brundtland (1987) stated over three decades ago,

Case Study 4:

Machell et al. (2015) suggest that waste is an indispensable component often neglected in WEF nexus analyses and include waste as the fourth core component in their nexus framework conceptualisation. An example of waste reclamation, presented by Walker et al. (2014) suggests that urine separation could possibly recover 47% of the nitrogen from the food consumed in London. This could potentially yield an income of $33 million per year from fertiliser production. This practice would reduce waste, provide revenue that will contribute to water treatment costs, and provide a key resource for use within the agricultural sector.

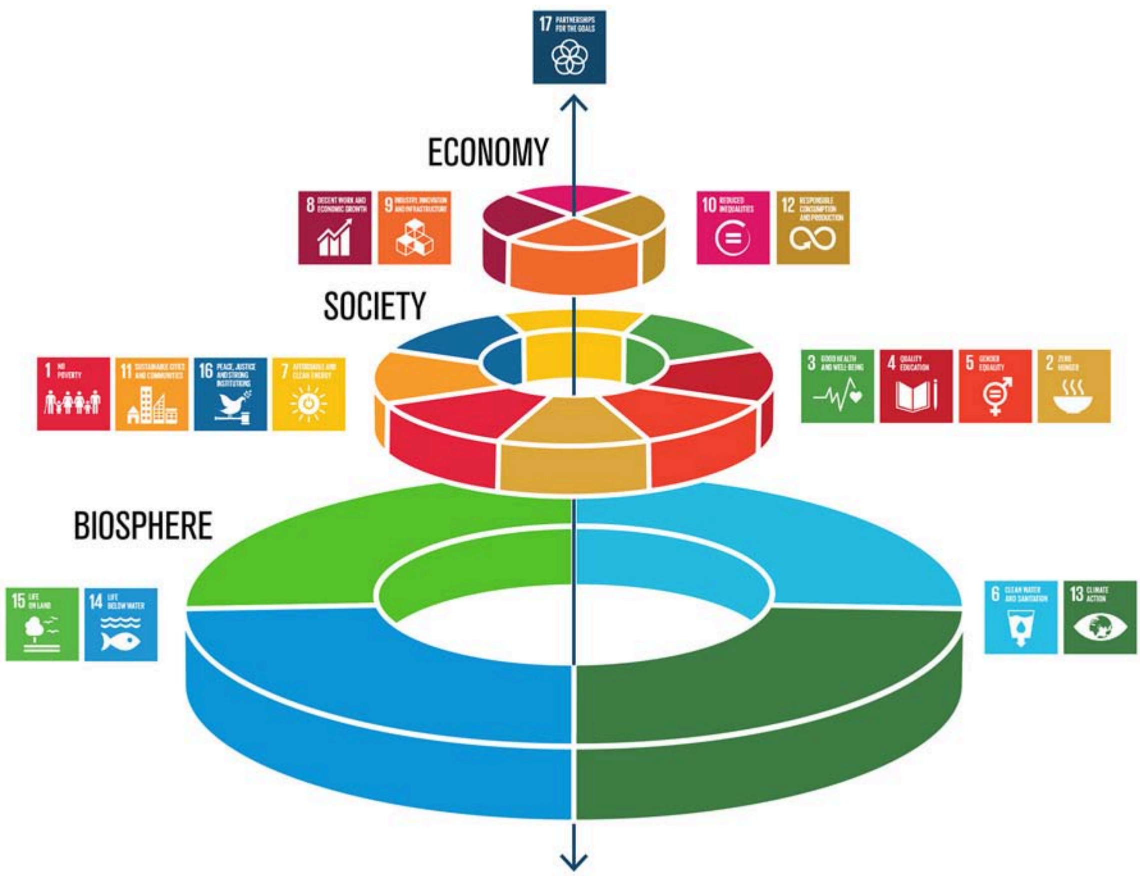

FIGURE 1 | A way of viewing the Sustainable Development Goals and how they are all linked to food—reproduced from the Stockholm Resilience Center with permission (Rockström and Sukhdev, 2016). All the SDGs are directly or indirectly connected to food. The goals for eradicating poverty (SDG 1) and hunger (SDG 2) require gender equality (SDG 5), adequate jobs (SDG 8), and a decrease in inequality (SDG 10).

"The real world of interlocked economic and ecological systems will not change; the policies and institutions concerned must."

The WEF nexus has also become important in both the drafting and the subsequent monitoring of the SDGs (Biggs et al., 2015). It could be said that the SDGs provide a test for the nexus approach (Ringler et al., 2013). Salam et al. (2017) argue that the interconnections between the SDGs emphasise the need for a nexus approach to achieve these goals. Boas et al. (2016) suggest that the nexus approach, together with its incorporation of the SDGs, is key to understanding why it has garnered such interest within the sustainable development fraternity.

CONCLUSIONS

The WEF nexus has been widely promoted in policy and development circles since 2011. This framework has potential strengths. It however also faces challenges if it is to be widely adopted.

In terms of possible weaknesses associated with the WEF nexus, a concern identified in the literature is that livelihoods and the environment are often omitted from these assessments. WEF nexus studies have, to date, to a large degree focused on global macro-scale resource security. This was not the intention when the concept was first promoted. For this framework to gain traction, particularly in light of the SDGs, it must be utilised to achieve adequate resource security for all, thus "leaving no one behind". It must simultaneously acknowledge and protect the environment as the irreplaceable foundation of the nexus.

A multi-centric approach will add complexity, especially when interconnections, trade-offs and drivers are incorporated into the assessment. The fact that a WEF nexus approach cannot be a one-size-fits-all model means that it must be scaled and/or modified (sometimes significantly) for different assessments, e.g., cities, countries, and regions, which is viewed as a weakness by some. The availability of complete, relevant data also poses a challenge to the practical implementation of the WEF nexus. The WEF nexus is a relatively new and developing framework.

While the nexus concept is not novel, novelty is not a prerequisite for relevance. If the multi-centric WEF nexus approach provides a better means of addressing the complex development and security challenges that the global community is facing than existing frameworks such as IWRM, then its potential adoption should be explored further. The WEF nexus framework is considered by many authors in both academic and grey literature as holding promise for guiding policy development and governance structures in a world that is facing climate change, population growth, and inequality in terms of access to resources. The linking of WEF nexus assessments with the SDGs is therefore imperative.

AUTHOR CONTRIBUTIONS

GS wrote the manuscript in consultation with GJ, who supervised the project.

FUNDING

This work is based on the research supported in part by the National Research Foundation of South Africa (Grant Number: 114692). GJ's academic position at the University of KwaZulu-Natal was supported by Umgeni Water through the Umgeni Water Chair of Water Resources Management.

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Conflict of Interest Statement: GS is employed by company Jones & Wagener (Pty) Ltd.

The remaining author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Environmental Science

ORIGINAL RESEARCH
published: 08 February 2019
doi: 10.3389/fenvs.2019.00007

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Stakeholder Perspectives on Sustainability in the Food-Energy-Water Nexus

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OPEN ACCESS

Edited by:
Jill A. Engel-Cox, National Renewable Energy Laboratory (DOE), United States

Reviewed by:
Irena Knezevic, Carleton University, Canada
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Specialty section:
This article was submitted to Science and Environmental Communication, a section of the journal Frontiers in Environmental Science

Received: *02 October 2018*
Accepted: *14 January 2019*
Published: *08 February 2019*

Citation:
Bielicki JM, Beetstra MA, Kast JB, Wang Y and Tang S (2019) Stakeholder Perspectives on Sustainability in the Food-Energy-Water Nexus. Front. Environ. Sci. 7:7. doi: 10.3389/fenvs.2019.00007

Interest in the various dimensions of environmental, economic, and social sustainability for food, energy, and water (FEW) systems, independently and collectively (i. e., the FEW nexus), has spawned an increasing amount of literature that seeks to understand the various linkages within the FEW nexus and provide guidance to inform decision-making to enhance sustainability. While the use of science and data can generate important and relevant information, it is not clear how important they are relative to relevant policy and the integration of policy within and across the individual FEW domains. In this work, we assessed perspectives on various considerations that pertain to sustainability in the FEW nexus. To do so, we identified numerous stakeholder groups who have interests throughout the FEW nexus, and conducted a survey of a subset of these groups. Although the responses differed across the stakeholder groups that we surveyed, the consistent result was that stakeholders generally understand that FEW systems are physically connected at high levels, and that policy is less integrated than desired. When forced to choose between priorities for science and data or for integrated policy to enhance sustainability, respondents from Academia and Extension preferred more science and data, whereas respondents who are, or more frequently interact with, practitioners and policy-makers preferred integrated policy. Overall, with other results and findings that are relevant for advancing sustainability and improving communication the FEW nexus, we conclude that the importance of science, data, and integrated policy depends on the context in which the stakeholders operate in the FEW domain.

Keywords: food-energy-water nexus, sustainability, stakeholders, perception, integrated policy, data, science, survey

INTRODUCTION

Due to their vital roles in providing essential resources, goods, and services to society, there is great interest in the functioning and sustainability of the resources and systems that provide food, energy, and water (FEW). The "FEW nexus" includes the necessary natural resources and their systems, the associated physical infrastructure, the institutions, and socio-economic systems that develop, use, guide, benefit from, and impact conditions in FEW (Hoff, 2011). Understanding the linkages within dynamic, nested, hierarchical, and evolving systems that comprise the FEW nexus, and considering them in decision-making and appropriate policy, could increase the efficient use of scarce resources, improve the quality and security of food, energy, and water supplies, as well as provide opportunities to grow economies and provide support for livelihoods (Hoff, 2011; World Economic Forum, 2011; Tidwell et al., 2014; Biggs et al., 2015; Wang et al., 2017).

Stakeholders in the FEW nexus typically have sector-specific goals and make decisions in silos (Howarth and Monasterolo, 2016; White et al., 2017) with a tendency to focus on short-term outcomes (Sterman, 2012). These motivations can lead to practices like desalination and first-generation biofuels (e.g., corn ethanol) that can increase the supply of one resource (e.g., water, energy) at the expense of another (e.g., energy, food) (Hussey and Pittock, 2012), or activities in one FEW domain (e.g., fertilizer application for agriculture) that can negatively affect the ability of systems in another FEW domain to provide usable resources (e.g., reduced water quality due to harmful algal blooms from agricultural runoff). Policy can be used to influence the direction of activities, but, despite the physical interconnections, policies in one FEW domain are often isolated from policies in another FEW domain and there is often limited effort to account for and manage the links (Hussey and Pittock, 2012). Such policy fragmentation across FEW systems is a governance problem that can lead to unintended consequences (Weitz et al., 2017). Greater policy coherence is critical (Rasul, 2016), and when the interactions and feedbacks between FEW sectors are understood and considered, policies that focus on one FEW sector can reduce negative effects, or create co-benefits, in another sector (De Strasser et al., 2016). As such, some have concluded that there is a need to increase the integration of policy for food, energy, and water so that policy considers components from more than one FEW system (Scott et al., 2011; Hussey and Pittock, 2012; Siddiqi et al., 2013).

Understanding the interactions and feedbacks in the FEW nexus should be informed by data, but, without roughly equal representations in the data of each of the elements of the FEW nexus (Howarth and Monasterolo, 2016), decision-making could emphasize one component of the FEW nexus, and the existence and collection of data does not alone provide the proper context for the appropriate formulation of policy (McCool and Stankey, 2004). There must be some translation of that data into knowledge and policy. Some tools that support decision-making in the FEW nexus include integrated assessment models, which may be developed with stakeholder inputs, and can perform scenario analyses to inform policy-making (Kraucunas et al., 2015; Miralles-Wilhelm, 2016). Tools that are suitable for sector-specific and short-term analyses include sector-specific optimization models with land, energy, and water constraints and tools for financial investments (Zhang and Vesselinov, 2016; Kaddoura and El Khatib, 2017). The calibration of decision-making tools is a data-intensive process, though, and there have been calls for more and better data on the FEW nexus (McCarl et al., 2017). Larger and more readily available data sets have the potential to be used by stakeholders in many ways, including for research to develop useful knowledge as well as by those who are likely to benefit from the data and knowledge directly. For example, the increased availability of data—especially that which is highly-resolved and individualized—has influenced how farmers make decisions in areas such as planting, nutrient management, and financial record-keeping (Wolfert et al., 2017). Yet addressing trade-offs and improving policy integration across FEW sectors is a political process that requires negotiation amongst stakeholders with distinct perceptions, interests, ideologies, and practices, as well as preferences for how to address issues within the FEW nexus (Weitz et al., 2017).

The concept of sustainability has environmental, economic, and social dimensions (Geissdoerfer et al., 2017). Various indicators of sustainability have been developed in order to gain insight into the functioning of individual components of FEW systems and to provide evidence of progress toward sustainability goals. Early development and selection of indicators were mostly oriented around scientific and technical conditions (McCool and Stankey, 2004), but have more recently addressed all three dimensions of sustainability (McBride et al., 2011; Dale et al., 2013; Efroymson et al., 2013; Biggs et al., 2015; Santiago-Brown et al., 2015). Yet it is often unclear what are the relative roles of various stakeholders—scientists, the public, and policy-makers, to be specific—in selecting and using sustainability indicators, which can result in conflict and confusion (McCool and Stankey, 2004). In some cases, the social aspects of sustainability goals have been less addressed than the environmental and economic aspects, in part due to disconnects between the early stages of the policy cycle, poor identification of issues and formulation of policy tools, and the latter stages of implementation and evaluation (Chapman et al., 2016). Other policies have emphasized the economic dimensions of development at the expense of environmental sustainability (Oñate and Peco, 2005).

The design of integrated policy can be challenging, in part due to the varying interests of relevant stakeholders who may prioritize different types of information and data, may have complex relationships with each other, and may be directly or indirectly affected by the policy and its outcomes. The FEW nexus, and its various components, is perceived by stakeholders in many ways (Petit and van der Werf, 2003; Lamarque et al., 2011; Cairns and Krzywoszynska, 2016), which can vary spatially (Lawford et al., 2013) and by stakeholder interest and involvement (Jacobs and Buijs, 2011; White et al., 2017) in individual FEW domains. Using Johnson et al. (2013) as a point of departure for identifying the roles of stakeholders in complex systems where environmental, economic, and social systems where sustainability is a concern, **Table 1** contains a conceptual presentation of the interests of various stakeholder groups that are relevant to the FEW nexus.

The varying perceptions of the FEW nexus among stakeholders necessitates increased integration of different perspectives, which can be achieved by incorporating stakeholders from a variety of backgrounds in research (Voinov and Gaddis, 2008; Kalcic et al., 2016; Inouye et al., 2017) to co-produce knowledge (Howarth and Monasterolo, 2017) and to a provide data and inputs to policy-making. Involving stakeholders in policy-making processes can increase

TABLE 1 | Stakeholder classification table identifying relevant FEWS stakeholder groups, their primary interests in each domain of FEWS, and their relevant involvement in each domain of FEWS.

Stakeholder group	Interests in agriculture/food	Interests in energy	Interests in water	Involvement in FEWS		
				AG/food	Energy	Water
DIRECT ACTORS						
Producers of agricultural outputs	Profit; competition; regulation; markets; technology	Input and output prices and supply	Regulation; input supply; output quality	X	X	X
Producers of agricultural inputs	Profit; competition; regulation; technology	Input and output prices and supply	Regulation; input supply, quality, and price	X		X
Producers of energy inputs	Profit; competition; regulation; technology	Profit; regulation; input and output prices and supply	Regulation; input supply, quality, price, and availability; output quality		X	X
INDIRECT ACTORS						
Agricultural supporting role	Profit; professional and business relationships; access to markets	Input and output prices and supply	Regulation	X		X
Agricultural product sellers	Profit; professional and business relationships; access to markets; product supply	Input and output prices and supply	Regulation	X		
Energy product sellers	Profit; product supply	Profit; input and output prices and supply; professional and business relationships	Input supply and availability		X	
Transportation companies	Profit; competition	Profit; input and output prices and supply; professional and business relationships	Regulation; input and output supply and availability	X	X	X
Utility companies	N/A	Input and output prices; output demand, professional and business relationships	Regulation; input supply, output quality		X	X
Engineering and construction firms	Profit; regulation	Input and output prices and supply	Regulation; input and output supply and quality	X	X	X
OVERSIGHT OFFICIALS						
Regulatory agencies	Regulation; educational opportunities; professional and business relationships	Regulation; educational opportunities; professional and business relationships	Regulation; compliance; input and output prices; professional and business relationships	X	X	X
Policy-makers	Regulation; professional and business relationships	Regulation; professional and business relationships	Regulation; compliance; professional and business relationships	X	X	X
CONCERNED PARTIES						
The public	Agricultural product supply, price, and quality; ecological impacts, health impacts,	Input and output prices, supply, and quality, health impacts	Input supply and quality; output quality and prices; health impacts	X	X	X
Agricultural commodity groups	Professional and business relationships; access to markets	Input and output prices	Regulation; input supply, quality, and availability; output quality	X		X
Public health agencies	Regulation; output quality	Input and output supply	Input supply, quality, and availability; output quality, health impacts	X		X
Emergency services	N/A	Energy operations safety	Input and output quality		X	
Recreation industries	Profit; regulation	Input and output prices and supply	Regulation; input supply, quality, and availability; output quality	X	X	X
Researchers	Data; professional and business relationships	Data; professional and business relationships	Data; professional and business relationships	X	X	X
Restaurants and supermarkets	Profit; input quantity, supply, prices, and availability; professional and business relationships	Input and output prices and supply	Regulation; input supply, quality, and availability; output quality	X	X	
Environmental conservation groups	Regulation	Regulation	Regulation; professional and business relationships	X	X	X
Non-governmental organizations	Profit; professional and business relationships	Input and output prices	Regulation; input supply, quality, and availability; output quality; professional and business relationships	X	X	X

(Continued)

TABLE 1 | Continued

Stakeholder group	Interests in agriculture/food	Interests in energy	Interests in water	Involvement in FEWS		
				AG/food	Energy	Water
Lobbyists	Regulation; professional and business relationships	Regulation; input and output supply; professional and business relationships	Regulation; input supply, quality, and availability; output quality	X	X	X
Academic extension officials	Professional and business relationships	Regulation; input and output prices	Regulation	X		X
Home and community developers	Regulation	Input and output prices and supply	Input supply, quality, and availability; output quality and price		X	X
Military and national security officials	Input prices, supply and demand; output prices, supply and demand; access to markers	Energy operations safety	Water quality and quantity safety	X	X	X

Based on Johnson et al. (2013).

understanding of system-wide FEW issues (Keskinen et al., 2015) and provide local knowledge and information about different types of needs that are not necessarily apparent to decision-makers (Carey et al., 2007; White et al., 2010).

There are substantial tensions in developing effective analytical frameworks that transcend the disciplinary boundaries that are associated with FEWs (Leck et al., 2015), and decisions that are made are often characterized as scientific, objective, and free of values, even though they mask particular systems of belief, in addition to conveying that issues of sustainability are related to physical and technical considerations rather moral, ethical, or political issues (McCool and Stankey, 2004; Fischhoff, 2018). Conflict between stakeholder groups can emerge because of different experiences and knowledge that various stakeholders bring to policy discussions, and issues for communication in the FEW nexus arise in part as a result of the cross-sectoral and transdisciplinary nature of the nexus—including potential differences in vocabulary, sets of skills, and expertise (Howarth and Monasterolo, 2016). Since competing belief systems are barriers to communication between stakeholders in science, in policy, and in the public (McCool and Stankey, 2004), the development and consideration of knowledge about differences in preferences for conducting science and research and generating data relative to integrated policy is important for advancing sustainability.

When stakeholder groups have varying views about aspects of policy, some may not be satisfied with the result (Adams et al., 2003). But this dissatisfaction can be partially mitigated if stakeholders experience some level of involvement and control throughout the policy development process (Khan and Gerrard, 2005), which they can do by providing input throughout the formation of policy (Wilsdon and Willis, 2004; Hering et al., 2013), responding to almost complete policies (Wilsdon and Willis, 2004), and engaging with other stakeholders (Elgin and Weible, 2013; Heikkila et al., 2014). Without stakeholder involvement, policies may not be implemented because of the lack broader support (Hering et al., 2013). Policy that is informed by science requires engagement between practitioners and academics (Bakker, 2012), because science for the development of useful knowledge that is conducted in silos can lead to outcomes that are not tethered to the needs of those who could benefit from the knowledge (Howarth and Monasterolo, 2016). It is beneficial for scholars to co-produce knowledge with practitioners and other stakeholders (Clark and Dickson, 2003), and to accept the political context of their work (Clark et al., 2016), in part because local knowledge that is paired with goals to maximize stakeholder responsiveness, rather than forcing prescribed policy on stakeholders, can increase engagement and acceptance (White et al., 2010).

There are a number of barriers to better integration of policy, including (a) missing, incomplete, and proprietary data; (b) fragmented existing policy and regulatory frameworks; and (c) inertia and path-dependency in the research community (e.g., academic silos) and the emphasis on solutions that are optimal technically in lieu of those that are holistic (Hussey and Pittock, 2012). While increased collaboration across individual FEW domains can help to address needs for data and for policy (Keskinen et al., 2015), and between those that conduct research or develop policy and those that implement and are affected by that policy, it is unclear if the conduct of more research and science to develop more data on the FEW nexus is a priority over the development of integrated policy that is relevant to the FEW nexus. Stakeholders throughout the FEW nexus engage with data and policy in many ways, and for multiple benefits: policy and data can help stakeholders make better-informed decisions, whereas feedback from stakeholders can facilitate more comprehensive and informed research and policy (Johnson et al., 2013).

Since stakeholders in the FEW nexus engage with policy and data in a variety of ways, what should inform decision-making within the FEW nexus? Should effort be invested in developing useful data and knowledge and—perhaps to relevant sustainability indicators or combinations of them—or should the decision-making be implicitly encouraged to consider the linkages and outcomes of more than one of the FEW systems?

To investigate the relevance of science, data, and integrated policy to enhance the sustainability of FEW systems, we conducted a survey of select stakeholder groups who engage with the FEW nexus in different ways. Others have solicited perceptions that are pertinent to FEW systems from stakeholders in non-governmental organizations (NGOs), the U.S. government, relevant industry, academia, forest harvesting and management, environmental conservation, education and training, consulting, and others who focus on socio-economic conditions (e.g., Hickey et al., 2007; Dwivedi and Alavalapati, 2009). Here, we surveyed stakeholders from three major groups that tend to focus on research and the production of knowledge at a university, those whose role is to bridge the university with the people in the state, and those who are practitioners and engage with policy in numerous ways. These groups were chosen in part because of varying relationships with the production and use of data and of policy and to provide a diverse set of stakeholder groups, which is useful for communication (NAS, 2017). Section 2 provides information on the survey and the characteristics of the stakeholder groups who were surveyed. The results of that survey are presented in section 3. Section 4 contains a discussion of the relevance of stakeholder perceptions and involvement in the FEW nexus.

MATERIALS AND METHODS

As part of a project that is funded by the U.S. National Science Foundation, we established a Research Advisory Council (RAC) that is convened for a series of annual and semi-annual meetings. The RAC is a group of stakeholders who are involved in various capacities in FEW issues in the Great Lakes Region, which roughly lies at the intersection of the Great Lakes, the Eastern Corn Belt, and the Great Lakes Megaregion, and includes the U.S. states of Ohio, Indiana, Illinois, Wisconsin, and Michigan—from which members of the RAC were drawn. These states had a total population of 46.9 million in 2017. This area contains a variety of fossil and renewable energy resources, substantial agricultural activity, and watersheds that drain into the five Great Lakes in the United States and Canada. Some of the issues for sustainability in the region include the development of algal blooms in Lake Erie, the environmental and social consequences of fossil fuel development—including past coal production and present hydraulic fracturing for oil and natural gas—and the economic and social consequences of the decline in manufacturing jobs.

The members of the RAC were selected by a theoretically-based quota sample, with the intention to have a mix of people who could represent different key attributes (e.g., across FEW sectors, working at different scales) and to ensure some representation for each of the states in the region. Potential members were identified though peer and expert networks, and were invited to participate sequentially. After each wave of invitations, the composition of the RAC membership was recalibrated to ensure that the desired combinations of sectors, scales, and states were achieved. The RAC is comprised of 22 individuals who serve in a variety of roles and institutions, including state agencies, non-profits, and industry, and served a secondary role as one of the three samples for this case study. While the perspectives of those on the RAC are not necessarily generalizable to all of the stakeholders throughout the FEW nexus (**Table 1**), the sample captured a variety of perspectives and represented many of the major players who are involved in FEW decision-making in the Great Lakes Region. The survey was administered in paper at the beginning of the first of a number of 2-day workshops, and RAC members who were not able to attend that meeting in person received an online version that was identical to the paper version.

We also administered the online survey to two other populations: (1) faculty associated with Extension for the land-grant university, and (2) faculty affiliated with the interdisciplinary program in environmental science that awards M.S. and Ph.D. degrees. These Academics have their primary appointments in departments and schools in the physical, natural, engineering, and social sciences across the university. Extension faculty were chosen in part because of their role in bridging activities between the academia and the citizens of the state, and in part because agricultural extension in the United States has encountered decreasing influence on the farming community; farmers have been receiving increasing amounts of information from retailers and other consultants, and use new technologies (e.g., mobile phones and apps) to access data (e.g., market prices, potential buyers) to help them make on-farm decisions (Dissanayeke and Wanigasundera, 2014). As such extension may be becoming less prominent, but many farmers still consider extension to be a reliable source of information (Prokopy et al., 2015). In theory, Extension should represent a middle-ground in perspective between the RAC members and the Academics, and our survey data illuminates if these boundary-spanning activities and perspectives are prevalent. As with the RAC sample, the Extension faculty and Academics who were surveyed do not necessarily represent all of the individuals in these types of roles, but they do represent a broad range of relevant perspectives on FEW decision-making in the Great Lakes Region.

Collectively, the survey population included stakeholders who are primarily engaged in research and teaching (Academics), primarily engaged in interfacing between the academics and the public who are served by the land-grant institution (Extension), and primarily engaged with organizations that control or engage with physical or policy inputs or outputs in one or more FEW domains (RAC).

Respondents answered a series of questions to assess their engagement in each FEW domain; their engagement with the dimensions of sustainability, the interaction with, and influence of, policy related to each FEW domain; and the governmental level at which policy-making is most impactful on their work. Other questions gauge barriers faced in working in the FEW nexus in addition to the groups of people that most influence them. All of the questions were assessed on Likert-type scales, and all responses were anonymous. The specific survey questions are included in the **Supplemental Information**. All of the survey materials were reviewed by content and methodological experts during their development, and the materials were approved by, and administered in accordance with, the guidelines of the Institutional Review Board.

To determine the significance of differences in the responses, we used non-parametric tests of significance to avoid assumptions about the distributions underlying the data. In particular, we used the Kruskal–Wallis test to detect if there are significant differences between the three groups of respondents for the same survey question, or between survey questions for the same group of respondents. If significance was detected at the 5% level and more than two samples were compared in the Kruskal–Wallis test, we used the Nemenyi *post-hoc* test to identify the individual significant differences between pairs of respondents or questions. We also used the Wilcoxon signed rank to determine if the responses from a stakeholder group was significantly different from neutral [i.e., 3 on a scale from 1 (low) to 5 (high)]. The Kruskal–Wallis and Wilcoxon signed rank tests were performed in Python 3.7.0 using the SciPy library (Jones et al., 2001). The Nemenyi tests are performed in Python 3.7.0 using the Scikit-Posthocs library (Pohlert, 2018). In the results that follow, we present the *p*-values from these statistical tests, with at most two significant digits. To avoid conclusions that are based on the use of a relatively arbitrary standard for determining statistical significance (i.e., $p \leq 0.05$), we highlight *p*-values that are less than or equal to 0.10. We chose this level in part because the focused size of the sample in this case study limits statistical power, and we sought to avoid conflating the lack of statistical significance with the lack of practical importance (Gelman and Stern, 2006).

RESULTS

Demographics of Respondents

In total, 57 stakeholders with diverse backgrounds responded to the survey. Prior published studies using surveys have had less or comparable levels of respondents (e.g., Andreu et al., 2009; Dwivedi and Alavalapati, 2009). The 18 respondents from the RAC (14 were on paper) included individuals who work for the government (5), a non-profit (9), industry (2), academia (1), and philanthropy (1). The 19 respondents from Extension come from four program areas: 4-H Youth Development[1] (2), Agriculture and Natural Resources (12), Community Development (3), Family and Consumer Sciences (1), and not indicated (1). The 21 Academics who responded to the survey are from primary disciplines in the natural sciences (7), engineering and physical sciences (9), and the social sciences (5). The response rates in each group resulted in comparable sample sizes across the three stakeholder groups.

Approximately half of the respondents from the RAC and from Extension reported that they highly engage with food issues, while almost two-thirds of the respondents from the RAC and over 80% of the respondents from Extension reported that they highly engage with agriculture. In comparison, the Academic respondents reported low levels of engagement with food and agriculture, with <20% of the sample engaged with food and one-third engaged with agriculture. Typically, food and agriculture are grouped together in the literature on FEW systems, but the responses to the survey suggest that food and agriculture are in fact partial subsets of each other.

Overall, respondents from the RAC interact with a broader array of professionals than those from Extension or Academia. For example, RAC members interact with lobbyists and public utility staff while no one from Extension or Academia indicated involvement with these groups. Further, Academics expressed low frequency of engagement with the general public, while the respondents from the RAC and from Extension indicated very frequent involvement. In general, Academic respondents did not frequently interact with non-academics, and thus their sources of data and engagement with policy may differ from respondents in the other stakeholder groups.

Across the three stakeholder groups, only 15–30% of each group reported that they are highly engaged in the energy domain. This low level of involvement is in contrast to the response for the water domain; respondents from the RAC and from Academia indicated that they have high engagement with issues for water, but those from Extension indicated low engagement in this domain. The low reported engagement with water by respondents from Extension is interesting in light of their reported high engagement in agriculture and their assessment that physical systems for food/agriculture and water are highly integrated (**Table 2**). It is possible that these respondents did not believe that there are concerns to address with respect to water, due to the relatively abundant surface and groundwater resources in the region. But such a lack of concern would be in contrast to regional issues pertaining to harmful algal blooms that have increasingly been occurring in Lake Erie, and how Extension programming is focusing on adopting best management practices to limit the amount of nutrients that leave the agricultural field.

Stakeholder Perception of the FEWS Nexus

Table 2 shows how the respondents from each of the stakeholder groups assessed the physical integration of FEW systems. There was relatively high agreement that the physical components of FEW systems are interconnected, with 70% or more of the respondents from each stakeholder group assessing that all of the combinations of FEW systems are physically integrated. But the responses varied by group in the degree to which they assessed the physical interconnectedness. Academics tended to assess the physical integration at higher levels than the other stakeholders, with on average 90.4% of the respondents assessing the high physical integration, whereas respondents from Extension had the lowest average assessment of this physical integration (84.3%). The combinations of FEW systems that involve energy were the least likely to be considered to be physically integrated, particularly by respondents from Extension and from the RAC. Although, the RAC members who are affiliated with energy viewed energy systems to be more interconnected with the other FEW systems than those who did not identify as such.

Respondents from the RAC had different assessments of the degree to which the various systems are physically integrated (Kruskall–Wallis, $p = 0.016$), but the *post-hoc* Nemenyi test did not suggest that the responses for any specific pairs of systems were significantly different. The three groups of respondents

[1]4-H is a youth development and mentoring program that includes about 6.5 million youth throughout the world.

TABLE 2 | Agreement of respondents that physical systems for FEW are integrated.

System 1/System 2	RAC	Extension	Academics	*p*-value
Food/agriculture and energy	82.4%	70.6%	87.5%	0.34
Food/agriculture and water	100.0%	94.1%	93.8%	0.085*
Food/agriculture and ecosystems	87.5%	94.1%	87.5%	0.26
Energy and water	82.4%	76.5%	93.3%	0.15
Energy and ecosystems	76.5%	76.5%	86.7%	0.31
Water and ecosystems	94.1%	94.1%	93.8%	0.023**
p-value	0.016**	0.36	0.19	

*Percentages represent the proportion of respondents who indicated that the combinations are physically integrated at the two highest levels they could assess on the Likert-type scale: "a good deal" or "to a great extent". The p-values are from Kruskal–Wallis tests on the H0: the different groups of respondents have the same response to the survey question (rows), or H0: the group of respondents have the same response to the various survey questions (columns). Significance: **≤5%; *≤10%.*

had different assessments on how well Water and Ecosystems are physically integrated (Kruskall–Wallis, $p = 0.023$) and on how Food/Agriculture and Water systems are physically integrated (Kruskall–Wallis, $p = 0.085$). The *post-hoc* Nemenyi test suggested that the significant difference was between the RAC and Academics ($p = 0.03$); while the percentages in **Table 2** appear to be similar, the aggregation of responses of "a good deal" and "to a great extent" mask that the Academics had more "to a great extent" responses than did the other two groups of respondents. Differences in the dispersion of the underlying data such as this explains the significance of these and other statistical tests, despite the percentages in tables appearing to be similar.

Much smaller fractions of the respondents assessed that current policy for FEW is highly integrated (dashed bars in **Figure 1**). At 35.6% of all of the respondents, current water policy and current environmental policy were most often considered to be highly integrated, whereas the other combinations of current policies with FEW had at most 12% of all of the respondents assess that they are highly integrated. Overall, Academics were the least likely to assess that current FEW policies were highly integrated (7.8% on average), and respondents with Extension were the most likely (20.1% on average). The respondents from Extension most often assessed that current policy for food/agriculture is integrated with current policy for the other components of the FEW nexus, which is likely to be consistent with the majority of the respondents being from the Agriculture and Natural Resources program area.

The Kruskal–Wallis test indicated that there was a difference in the assessments between the integration of current policy for energy and for environment, which was the only combination of FEW policy integration that had significantly different assessments from the respondents across the stakeholder groups ($p = 0.022$; see **Table S1** for the results of the significance tests). The subsequent *Post-hoc* Nemenyi test showed that the significant difference was between the RAC and Academics respondents ($p = 0.025$).

The combination of **Table 2** and **Figure 1** also shows that all of the stakeholder groups consistently assessed higher levels of physical integration than policy integration. This disparity does not necessarily suggest that there should be more policy, but **Figure 1** shows that the respondents assessed that there should be more integrated policy for FEW than there is at present. Respondents from Extension consistently assessed less need for integrated policy relative to current policy, whereas respondents from the RAC assessed larger disparities between ideal policy integration and current policy integration for FEW systems involving food/agriculture than did the other stakeholder groups. Despite these general differences, the assessments of the difference between the current integration of FEW policy and the ideal integration of FEW policy were significant for all of the combinations of FEW policy and for all of the stakeholder groups, with the exception of the assessment of the difference between current and ideal integration of water and environmental policy by respondents from Extension ($p = 0.064$) (see **Table S1**).

Stakeholder Consideration of Sustainability and Interaction With Relevant Policy

Table 3 shows that at least 75% of the respondents from the RAC and from Extension consider all three dimensions of sustainability in their work. The respondents from Academia only considered the environmental outcomes at a similar level, but this may reflect the fact that these stakeholders are affiliated with an environmental science degree program and, by virtue of disciplinary specializations, only a subset would be interested in economic or social outcomes in their work. The consistently high consideration of economic and social outcomes among the respondents from the RAC and from Extension may suggest that these groups interact more directly and consistently with a broader array of the people and institutions in **Table 1** than the Academics.

The respondents from the three stakeholder groups had significantly different levels of consideration for the environmental and economic aspects of sustainability. The *post-hoc* Nemenyi tests indicated that the consideration of environmental outcomes differed between the RAC and the Academics ($p = 0.057$), and that the consideration of economic outcomes differed between the RAC and the Academics ($p = 0.036$) and between the Academics and those in Extension ($p = 0.004$).

Across the three groups of stakeholders, respondents reported being involved with, or influenced by, relevant policy at lower levels than the outcomes that they consider in their work

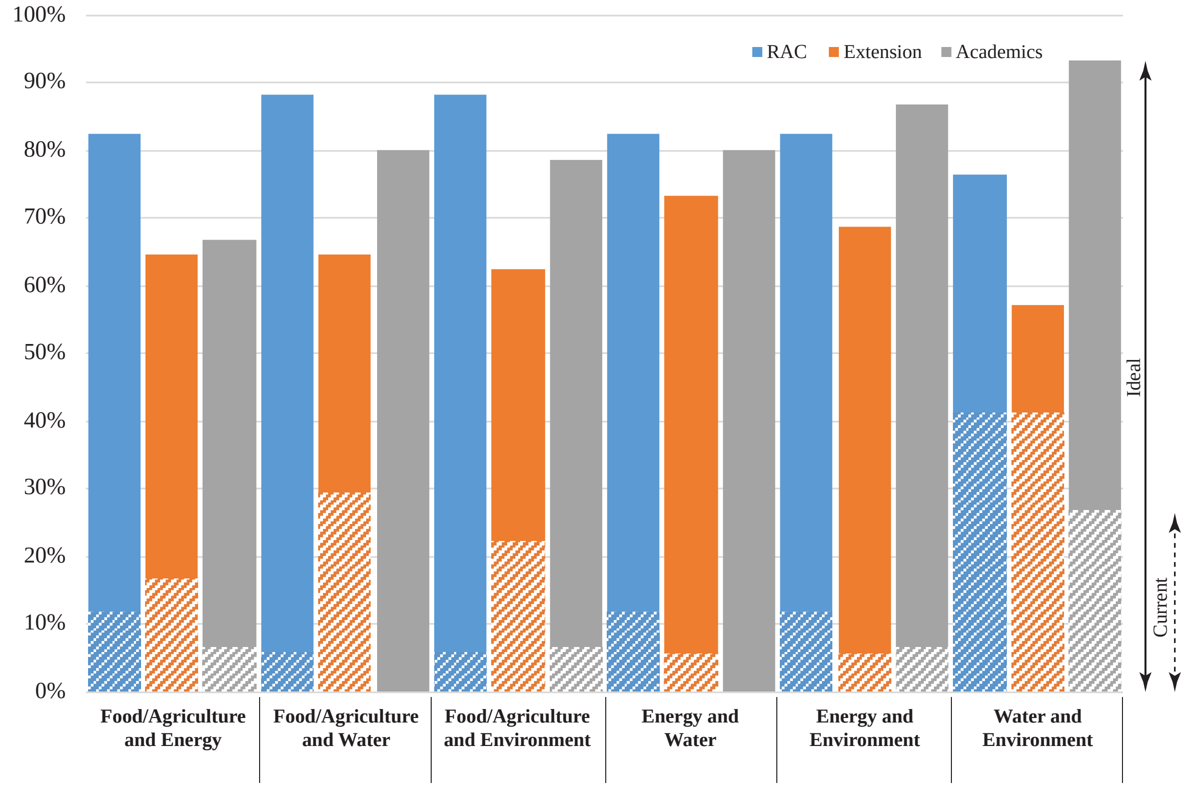

FIGURE 1 | Agreement of respondents that current policy is integrated (Dashed) and the ideal integration of policy (Solid). Percentages represent the proportion of respondents who indicated that the combinations are physically integrated at the two highest levels they could assess on the Likert-type scale: "a good deal" or "to a great extent".

TABLE 3 | Respondents' consideration of components of sustainability and their interaction with associated policy.

	Consider outcomes			Involved with or influence policy		
	Environmental	**Economic**	**Social**	**Environmental**	**Economic**	**Social**
RAC	82.4%	82.4%	76.5%	82.4%	64.7%	29.4%
Extension	75.0%	93.8%	75.0%	58.3%	50.0%	33.3%
Academics	87.5%	31.3%	43.8%	77.8%	23.5%	17.6%
p-Value	0.043**	0.002***	0.16	0.052*	0.070*	0.16

*The values are percentages of respondents who selected one of the two highest levels on the 5-point Likert-type scale. For "Consider Outcomes", these two highest options are "Frequently" or "Very Frequently"; for "Involved with or Influence Policy", the scale ranged from "Not At All" to "A Great Deal", and the percentages are the aggregation of responses in the two highest levels that are above the midpoint ("a moderate amount"). The p-values across the bottom row are from Kruskal–Wallis test of the significance between the stakeholder and their consideration of the components of sustainability and between their interaction with the associated policy. H0: the RAC, Extension, and Academic respondents have the same level of consideration on the components of sustainability or interaction with the relevant policies. Significance: ***≤1%; **≤5%; *≤10%.*

(**Table 3**). Respondents from the RAC tend to interact more with policy than do respondents from the other stakeholder groups, with an average of 58.8% with high interaction relative to 47.2% for Extension and 39.7% for Academic respondents. All of the respondents across the three stakeholder groups interact most often with environmental policies, followed by economic policies, and finally social policies, but the respondents from Extension have more similar levels of interaction across the three types of policies than the RAC and Academic respondents.

The Kruskal–Wallis tests indicated that the Academics gave different consideration to the different components of sustainability ($p = 0.003$, see **Table S2**); the *post-hoc* Nemenyi test suggested that the difference between consideration of environmental outcomes and the social outcomes was significant ($p = 0.026$), as was the difference between consideration of the environmental outcomes and the economic outcomes ($p = 0.007$). The responses from the RAC and the Academics indicated that the respondents from these stakeholder groups are neither involved with nor influence policy for environmental, economic, and social outcomes to the same degree ($p = 0.0006$ and $p = 0.018$ in **Table S2**). The *post-hoc* Nemenyi tests suggested that the difference for respondents from the RAC was significant between policies for social outcomes and policies for economic outcomes ($p = 6.2^{*}10^{-4}$), whereas for the Academic respondents the difference was between policies for social outcomes and policies for environmental outcomes ($p = 0.034$).

The *p*-values in **Table S2** show that there was no significant difference for any of the Stakeholder groups between the level of consideration for environmental outcomes and policy for those outcomes. In contrast, the level of consideration for the economic aspect of sustainability was different from the level of interaction with policies for economic outcomes by the Extension respondents ($p = 0.039$) and by the Academic respondents ($p = 0.097$). Further, the responses for the social aspect of sustainability were significantly different from the level of interaction with policies for those social outcomes for all of the stakeholder groups.

In general, while there was an acknowledgment of the need for more integrated policy (**Figure 1**), the results in **Table 3**. Suggest that the considerations for this policy could prioritize the environmental dimensions over the economic and social dimensions of sustainability.

Stakeholder Priorities for Science, Data, and Policy

Respondents were consistent in their assessments of the importance of, and need for more, science, data, and integrated policy FEW systems (**Figure 2**). Between 93.3% (Extension) and 100% (Academics) of the respondents agreed that "It is important to have more science and data on food, energy, and water," and 64.7% (RAC) to 73.3% (Extension) of the respondents disagreed with, "There is enough science and data currently being generated on food, energy, and water." For integrated policy, 73.3% (Extension) to 94.1% (RAC) of the respondents agreed that, "It is important to have better integrated policy for Food, Energy, and Water," and 60.0% (Extension) to 70.6% (RAC) disagreed with, "There is enough integrated public policy currently being generated on food, energy, and water." The Kruskal–Wallis test suggested that there was a difference between the stakeholder groups in their responses to the importance of more science and data ($p = 0.018$ in **Table S3**), and the *post-hoc* Nemenyi test identified this difference in the responses between the RAC and the Academics ($p = 0.019$). When the responses for more science and data were compared with those for more integrated policy within stakeholder groups, the respondents from Extension and from Academia each had different responses on the importance of more science/data vs. integrated policy.

Respondents from the RAC and from Academia identified that they are generating more science and data than public policy in their work, whereas respondents from Extension were roughly split between the two dimensions. But, as **Table S3** shows, none of these responses were significant. In contrast, members of the RAC responded with the tendency to use more public policy than science and data in their work ($p = 0.016$), but the Academic respondents reported a tendency to use more science and data than policy that was not significant. Extension did not show a preference either way. The generation of policy requires some degree of translation of science and data to inform the attempts to reach desirable outcomes, but **Figure 2** suggests that none of the three stakeholder groups are predominantly involved with this translation activity. These disparities might contribute to the low levels of integrated policy at present (**Figure 1**).

Consistent with the greater use of policy than science and data, the respondents from the RAC diverged from Extension and from Academia when forced to choose between spending on research and better data and better integrated policy (**Figure 3**). Respondents from Extension and Academia favored research and data for FEW, whereas members of the RAC were more disposed toward integrated public policy for FEW. This divergence may be explained by the more frequent use of public policy by the RAC than the other two stakeholder groups (**Figure 2**). In fact, 20–30% of Extension and Academic respondents, respectively, placed all of the importance on more research and data for FEW, and none of the members of these stakeholder groups placed all of the importance on more integrated public policy for FEW. Moreover, respondents could not choose to balance science and data equally with integrated public policy, and 60–70% favored more research and better data. In contrast, RAC members indicated a clear preference for integrated public policy. None of the respondents from the RAC placed all of their preference for spending on research and data, but 20% of these stakeholders did so for integrated policy and 73.3% favored spending on integrated policy. These differences were significant ($p = 0.0003$), and the *post-hoc* Nemenyi test indicated that the differences were between the RAC and the other stakeholder groups ($p = 0.0017$, RAC vs. Academics; $p = 0.0033$, RAC vs. Extension).

Stakeholder Assessment of Potential Barriers to FEW Sustainability

Figure 4 shows how the respondents assessed various potential barriers to science and data and integrated public policy across four groups: (1) the quality of the science and the data, (2) the quality of the policy, (3) outcomes of policy and governance, and (4) impediments to implementation. The responses suggest that the stakeholders are not concerned about the effects of the quality of the science and the data, with higher proportions consistently assessing that the potential barriers were low. The majority of the non-neutral responses from the stakeholder groups—which ranged from 41.2% (RAC) to 52.6% (Extension)—assessed that conflicting science/data is a low barrier. The *p*-values in **Table 4** indicate that the responses from Extension ($p = 0.078$) and the responses from the Academics ($p = 0.042$) differed from neutral. Similarly, more members of Extension and of the Academics assessed that the lack of good science was a low barrier (52.6 and 47.4%, respectively), whereas members of the RAC were relatively mixed on this assessment. These results from Extension and from Academia differed from neutral (at the 10% level, $p = 0.078$ and $p = 0.079$, respectively, in **Table 4**). Further, higher levels of respondents from the RAC (56.3%) and from Academia (52.6%) assessed inadequate science to make decisions as a low barrier, while the respondents from Extension

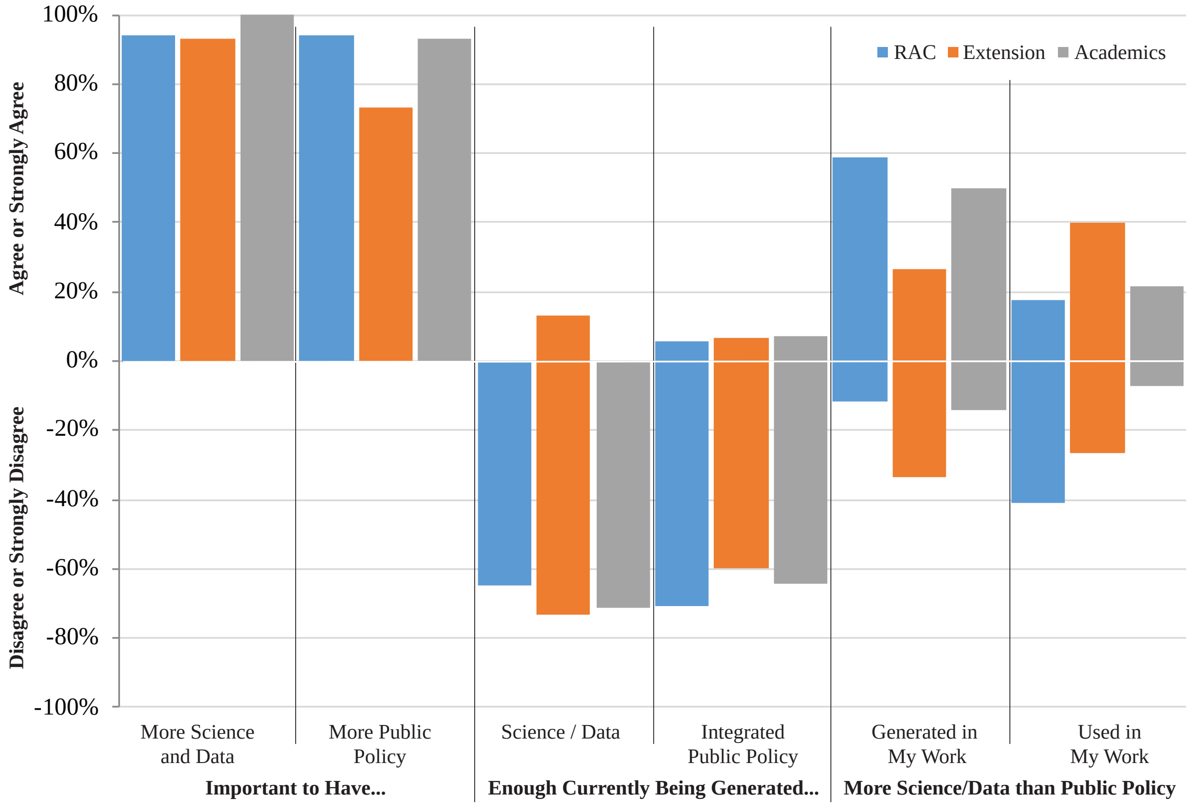

FIGURE 2 | Stakeholder perceptions of the importance, use, and levels of science and data and public policy. The columns do not sum to 100% if some respondents chose the neutral "neither agree nor disagree".

were relatively split, although none the responses from these stakeholder groups were significantly different from neutral. These mixed responses could be a result of the diversity of these stakeholders in a group and their varying roles within the FEW nexus. For example, a RAC member who is involved with a commodity group could view good science differently than someone who works in a federal or state agency. As such, the use of data may vary by their varied roles and thus may be more of a barrier for some than others. Similarly, those in Extension have different roles, albeit with less heterogeneity than those in the RAC, and the assessments by those respondents could depend on their focus. For example, there is a plethora of salient data relating agricultural practices and nutrient management to the minimization of harmful algal blooms, but there is not as much present focus soil health; and those in 4H might be more interested in education. Responses regarding the barriers could partly depend on a respondent's role within Extension, and their participation in particular activities. Overall, however, these results could indicate that the stakeholders have faith that the quality of the science and the data that are generated is adequate for use in enhancing the sustainability of the FEW nexus.

In contrast to the trend toward lower concern about science and data, respondents tended to assess the policy-related barriers to be high or the results were mixed. The lack of good policy was the only policy-related barrier that was assessed to be a high barrier from all of the stakeholder groups, with a range from 41.2% (Extension) to 44.4% (Academics), but **Table 4** shows that these assessments did not differ from neutral. The majority of the respondents from the RAC assessed that all of the potential policy barriers were high barriers; in fact, their assessments of lack of policy integration efforts and lack of good policy differed from neutral ($p = 0.023$, $p = 0.016$, respectively). But the other stakeholder groups tended to be split in their assessments, although the Academic respondents seem to lean toward the assessment that potential policy-related barriers are low—with their assessment of policy fragmentation differing from neutral ($p = 0.081$). There was a difference between responses from members of the RAC and Academia regarding policy fragmentation and lack of policy integration (**Table S4**). The apparent divide between respondents from the RAC and from Academia may expose differences in how these stakeholders are involved with the FEW nexus. For example, Academics may be more concerned with data because of their dominant role in generating knowledge from it, whereas those in Extension and the RAC in their boundary spanning roles may be concerned with other, and perhaps more numerous, factors (e.g., regulations, prices) that are more related to public policy.

The questions that were related to the outcomes of policy and governance and the impediments to implementation reflect several potential structural and systematic barriers. All of the

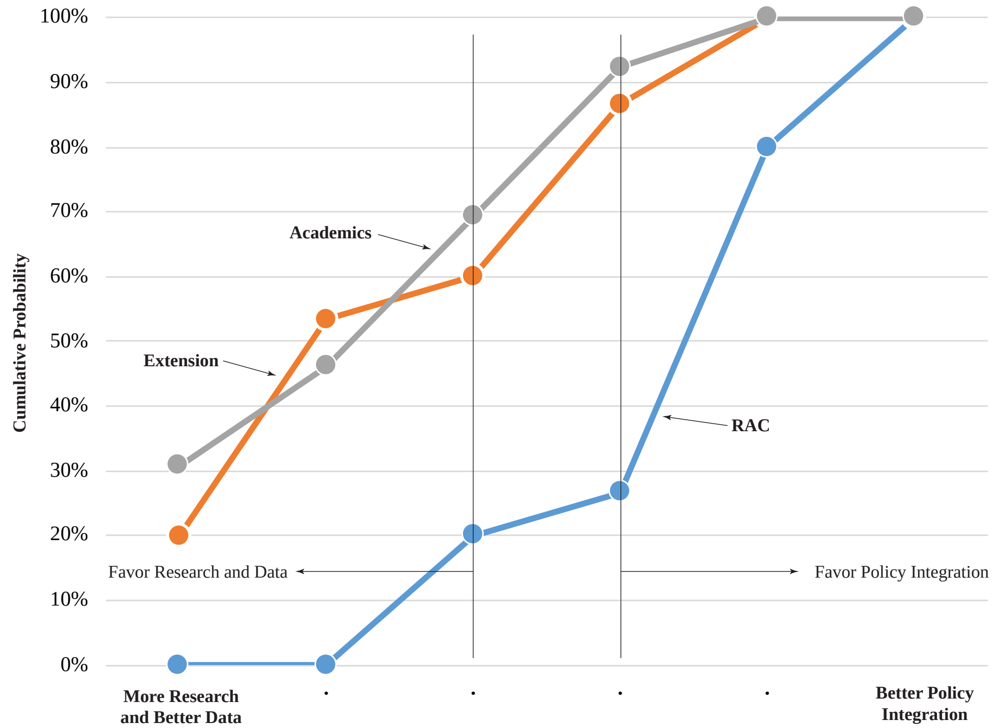

FIGURE 3 | The preference of the respondents for spending along a spectrum between more research and better data and better policy integration.

respondents assessed insufficient funding as a high barrier, with a range from 52.9% (RAC) to 57.9% (Extension and Academia), which differed from neutral for respondents from all of the stakeholder groups ($p = 0.042$, RAC; $p = 0.028$, Extension; $p = 0.002$, Academics). The lack of incentives could be perceived to be similar to insufficient funding, but the respondents appear to have understood some of the differences: 42.1% of the respondents from Extension and 57.9% of the Academic respondents assessed them to be low barriers, both of which differed from neutral ($p = 0.10$ and $p = 0.007$, respectively), but respondents from the RAC were split in their assessment. The assessments of the degrees to which too little or too much regulation were consistent within the stakeholder groups. Respondents from the RAC were tempered in their consideration of regulation—both of their assessments of too little and too much regulation were split between high and low barriers. But respondents from Extension tended to favor less regulation with their assessment that too much regulation was a high barrier (55.6%) and too little regulation was a low barrier that differed from neutral (83.3%, $p = 0.0005$). In contrast Academic respondents had the opposite assessment and tended to favor more regulation, with too little regulation being a high barrier (42.6%) and too much regulation being a low barrier that differed from neutral (68.4%, $p = 0.0004$). This difference between responses from members of Extension and of Academia on too little and too much regulation was significant ($p = 0.004$ and $p = 0.001$, respectively; **Table S4**), and could be due to the daily "on the ground" work that Extension pursues with landowners who face regulatory impacts (e.g., permitting, inspections, operating procedures), while Academics do not consistently encounter regulations on issues pertaining to FEW in their daily research and work.

Assessments of the impediments to implementation were largely split between being high and low barriers. For example, respondents from the RAC considered lack of coordination with other organizations and agencies to be a high barrier (50.0%), which differed from neutral ($p = 0.074$), but respondents from Extension and from Academia leaned toward it being a low barrier (38.9 and 48.1%, respectively). Having little influence on decision-making had the same trend: respondents from the RAC assessed it as a low barrier (47.1%), and respondents from Extension and Academia were split. As with these other impediments to implementation, assessments of the effect of public resistance by respondents from the RAC differ from those by the other stakeholder groups: RAC assessed public resistance as a high barrier (43.8%), and Academics as a low barrier (47.4%), which differed from neutral ($p = 0.068$). The difference between RAC and Academics related to public resistance could reflect the fact that Academics tend not to interact with the public as much as the other stakeholders.

DISCUSSION

To enhance the sustainability of individual FEW systems as well as their linkages within the FEW nexus requires advances in scientific understanding of the systems and their components

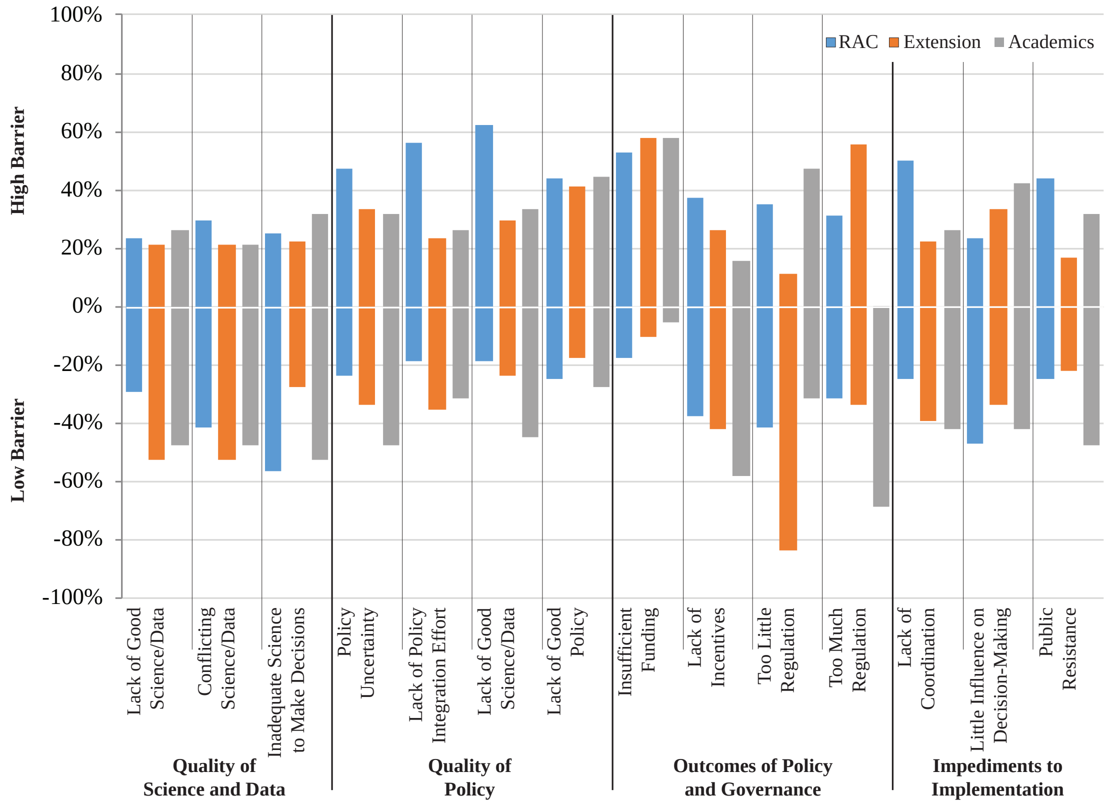

FIGURE 4 | Percentage of respondents who assessed the degree to which they encounter various potential barriers—a "high barrier" summarizes respondent selections of the two highest levels, and a "low" barrier summarizes respondent selections of the two lowest levels.

(Bazilian et al., 2011) as well as integrated policy to guide the appropriation and use of the FEW resources and address the resulting externalities (Rasul and Sharma, 2016). Success in communicating about, and within, the FEW nexus requires a collaboration across disciplines, which is difficult in part because of the different norms and practices across disciplines, and between scientists and practitioners and other stakeholders (NAS, 2017; Fischhoff, 2018). We investigated how various stakeholders perceive and assess important characteristics of the FEW nexus as a case study, with particular attention to issues for science and data and policy and its integration. This investigation involved an assessment of interests by various stakeholder groups who are involved in the FEW nexus and a survey of three populations that contain various FEW stakeholders. The stakeholders that were involved in this assessment are a small sample of all of the stakeholders within the entire FEW nexus, and as such can provide a snapshot of the perspectives among different groups of relevant FEW stakeholders in the Great Lakes Region.

Integrated management of FEW systems must have collaborative action of diverse stakeholders (Helmstedt et al., 2018), and in this work we illuminated some similarities and differences in the perspectives of major stakeholder groups in the FEW nexus. Other related studies that have elicited perceptions in the FEW nexus have had findings such as: regional and economic development are perceived to be major drivers of changes in water quality and effects on energy and food production, and that changes in political and economic systems are the major contributors to substantial changes in the FEW nexus (Lawford et al., 2013); differences in assessments of how well forests are managed and whether the amount of data and information that is required by legislation is sufficient, and that information exchange is inhibited by the costs of monitoring and reporting (Hickey et al., 2007); and concerns that management measures are hindered by limited economic resources, an emphasis on scientific research over research on efficient management strategies, lack of public awareness and support, an absence of coordination among public agencies, insufficient legislation, and limited enforcement of legislation (Andreu et al., 2009). In our results, while there were differences between the stakeholder groups that we assessed, there was considerable agreement that the physical systems for FEW are interlinked, and that related policy should be integrated at much higher levels than at present. Such results may not be unsurprising, given that it may be easier to envision resource flows, inputs, and outputs than it is to change the organization of the institutions that develop and enact regulations and policy—which tend to be organized often by the resource or the service (e.g., water, electricity) (Scott et al., 2011; Hussey and Pittock, 2012). But the emergence of the understanding

TABLE 4 | *p*-values from Wilcoxon signed-rank tests on barriers to FEWS sustainability.

		RAC	Extension	Academics
Quality of science and data	Lack of good science/data	0.61	0.078*	0.079*
	Conflicting science/data	0.54	0.078*	0.042**
	Inadequate science for decisions	0.22	0.24	0.14
Quality of policy	Policy uncertainty	0.17	0.50	0.15
	Lack of policy integration efforts	0.023**	0.16	0.16
	Policy fragmentation	0.016**	0.34	0.081*
	Lack of good policy	0.17	0.12	0.12
Outcomes of policy and governance	Insufficient funding	0.042**	0.028**	0.002***
	Lack of incentives	0.52	0.10*	0.007***
	Too little regulation	0.21	0.0005***	0.34
	Too much regulation	0.36	0.17	0.0004***
Impediments to implementation	Lack of coordination	0.074*	0.22	0.13
	Little influence on decision-making	0.49	0.67	0.35
	Public resistance	0.17	0.22	0.068*

*H_0: The responses are neutral (3) on the scale of 1 (low) to 5 (high). Significance: ***≤1%; **≤5%; *≤10%.*

that the regulatory and policy guidance should address the interactions between systems, implicitly or explicitly, in order to advance sustainability broadly suggests that there could be better integration of food/agriculture, energy, and water policy in the future.

Of the respondents from the stakeholder groups that we surveyed, Academics were typically least involved in policy overall, and they were also the least likely to view FEW policies as integrated. This lack of involvement with policy may be natural due to their predominant role as researchers and teachers, usually with a focus in an individual field of inquiry. The lower level of involvement with policy may also lead to the perception by the academic respondents that the policy is not well-integrated, but it is also possible that the lack of involvement with policy could provide Academic stakeholders with a more objective perspective. Regardless, the consistent assessment across the respondents of the disparity between actual and ideal levels of policy integration does not necessarily suggest that there should be more policy for FEW, but instead more *integrated* policy for FEW.

With some qualifications, there is evidence that the respondents considered the quality of policy to be a higher barrier to enhancing sustainability than the quality of the data. This evidence may be a product of how the determination and implementation of policy is mediated by ethics, values, compromises, and tradeoffs (Cochran and Malone, 2014), and the fact that data require analysis and interpretation before being translated into policy. With such mechanisms that intervene in the analysis and interpretation of data, and its subsequent codification into policy, it is perhaps probable that satisfaction with the quality of the data may be higher than satisfaction with the quality of related policy. These intervening mechanisms may also help to explain why the academic stakeholders considered "little influence on decision-making" to be a barrier to enhancing sustainability. It is also interesting to note that the Academics assessed too little regulation to be a barrier, whereas the respondents from Extension assessed too much regulation to be a barrier.

All of the stakeholder groups assessed that enhancing sustainability for the FEW nexus requires more science and data, and that doing so also requires more integrated policy. But when forced to choose between spending on creating more science and data or more integrated policy, the stakeholder group that uses more policy in their work (i.e., the RAC) preferred to spend more on policy, while the stakeholder groups that use more science and data in their work (i.e., Extension and Academia) preferred to spend more on science and data. Academics, who by virtue of their role as researchers seeking to develop knowledge, may be more likely to prefer an emphasis on science and better data. This preference may result from their daily interaction with, and understanding of, the research processes that over time relax assumptions and simplifications in the research questions and the methods. The preference for more science and data by respondents from Extension may also result from the typical role of Extension in connecting developments and understanding within the state university (e.g., from Academics) to citizens of the state. In fact, there is indication that extension may be successful in influencing some on-farm activities for larger sustainability concerns: behavioral data from farmers in the Maumee Watershed (Ohio, Michigan, and Indiana, USA) indicates that some conservation practices (e.g., soil testing) to reduce issues with nutrient loading into waterways and the negative effect on water quality are on the rise, while others (e.g., use of cover crops, subsurface placement of fertilizer) are constant over time (Wilson et al., 2018).

There may be institutional barriers that limit engagement in particular areas, or stakeholders may not make the connection between activities and outcomes, particularly when they are separated by time and place. For example, respondents from Extension did not assess the importance of their engagement with water issues, even though a number of the agricultural practices about which they inform farmers and landowners are motivated by concerns for water quality. Emphasis has been placed on "best management practices" (e.g., subsurface placement of nutrients, implementation of nutrient management plans, soil testing) to reduce the application and runoff of nutrients in order to reduce the size and likelihood of downstream hypoxic zones (Mallin et al., 2006; Rabotyagov et al., 2010) and harmful algal blooms (Anderson et al., 2002; Kalcic et al., 2016).

The responses to the survey contain evidence that suggests that the considerations for FEW policy might prioritize the environmental dimensions over the economic and social dimensions of sustainability. But we caution against such an interpretation because the responses might reflect the makeup of the sample, corresponding concerns, and expertise rather than those of all of the stakeholders in a specific region. While we do not necessarily expect the trends to change much with a larger or broader sample from the Great Lakes Region, it is possible that different priorities or realms of engagement could emerge. For example, given less interaction with stakeholders outside of academia that was reported by the respondents from Academia, the low level of consideration for social elements of sustainability could reflect a desensitization by the Academic respondents to these issues (Howarth and Monasterolo, 2016). But it may also be that the environmental dimension may be more relevant to, or understandable by, the stakeholders than are the social or economic dimensions, even though those who work more closely with the public (Extension and RAC) reported that they consider the economic and social outcomes more than the environmental outcomes, and respondents from the RAC assess public resistance to be a high barrier to enhancing sustainability. Further, some specific issues in this region (e.g., harmful algal blooms in Lake Erie) have received a substantial amount of media coverage and prioritized funding, which may render some environmental dimensions more salient to the stakeholders in our sample.

Some of the results may also be products of the ways in which the respondents engage in the FEW nexus. In particular, the respondents from the RAC and from Extension were largely from food/agriculture sector (60–80%), but this sector was underrepresented in the Academic respondents (<20%). In addition, the energy sector was underrepresented in all three stakeholder groups (15–30%), which may result in responses that suggest that energy is less physically integrated with the other FEW systems.

Although this work is narrow in scope, given the selective sampling methods that we used, the conclusions could have wider implications. The general trends and directionality of the relationships are likely to exist in other FEW systems outside the Great Lakes Region because of the relative separation of practitioners, members of Extension, and Academics in their spheres of work. For example, we found that perspectives within Extension tended to be similar to the perspectives of Academics more often than with the more general members of the RAC. Extension is often perceived as a middle ground connecting Academia to practice. However, our findings suggest that Extension may occupy this role to a lesser extent than anticipated. Perhaps the home within state university systems positions members of Extension to be more in-line with Academics. Given the integrated nature of FEW systems, it may be important to carefully consider the role of Extension and how best to leverage their strategic position to help better bridge the gap between Academics and stakeholders like those represented on the RAC. Having the disconnects between different stakeholder groups in their priorities, whether science and data focused or policy-focused, has the potential to impede innovative progress on FEW issues if each group is working toward different goals. There are many types of work within FEW nexuses, but further integration, understanding, and protection of the systems are likely to be goals that are shared by all of the stakeholders. Our results illuminate some distinctions between different stakeholder groups, but they also highlight the potential for missed opportunities for collaboration with members across stakeholder groups. Further integration of stakeholder groups may allow for more progress toward the common FEW nexus goals that underlie much of this work.

Integrating management of FEW systems requires resolving differences in spatiotemporal relationships over multiple scales, closing resource loops, and producing information that can be acted upon (Scott et al., 2011; Helmstedt et al., 2018). It is thus important to consider the scale of knowledge needs by stakeholders (Howarth and Monasterolo, 2016), otherwise messages that are tailored for stakeholders at one scale (e.g., regional) might not be useful by others that are relevant (e.g., local). Since the stakeholders whom we surveyed represent a subset of interests, involvement, and foci within the FEW nexus that we identified in **Table 1**, in **Figure 5** we present the likely ranges in scope (degree of interconnection of the system) and scale (spatial extent of consideration) in which the various FEW stakeholder groups may engage in issues that are related to FEW.

Stakeholders within the FEW nexus clearly have overlapping and nested interests and considerations in both science and data (**Figure 5A**) and integrated policy (**Figure 5B**). The scopes and scales in **Figure 5** are not independent; smaller scopes and scales are nested within larger scopes and scales, and the boundaries that separate consideration by stakeholders may be artificial and not consistent with the physical extents. For example, a watershed can extend into multiple states, and the jurisdictions of relevant agencies can also overlap but they may not be defined by the extent of the physical system. In addition, the individual components of the FEW nexus operate at different and overlapping spatial scales, such as when the water withdrawal of thermoelectric power plants responds to electricity demand on the grid, but affects the downstream water quantity and quality at the watershed level. Integrating management of FEW systems requires resolving differences in spatiotemporal relationships over multiple scales, closing resource loops, and producing information that can be acted upon (Helmstedt et al., 2018).

As the scope expands to include the social and economic contexts, and the scale tends to increase, defining and achieving sustainability in the FEW nexus may be more challenging. The lack of a commonly accepted definition of the concept of the FEW nexus (Stein et al., 2014; Cairns and Krzywoszynska, 2016) as well as the lack of a universal metric for evaluating the success of work conducted within the FEW nexus (Tevar et al., 2016) contributes to the heterogeneity of work currently considered to be a part of the FEW nexus. Accordingly, **Figure 5** indicates that interests in science and data may be related to smaller scopes and scales than interests in policy.

The depictions of the ranges of interests for stakeholders throughout the FEW nexus in **Figure 5** could be used as a

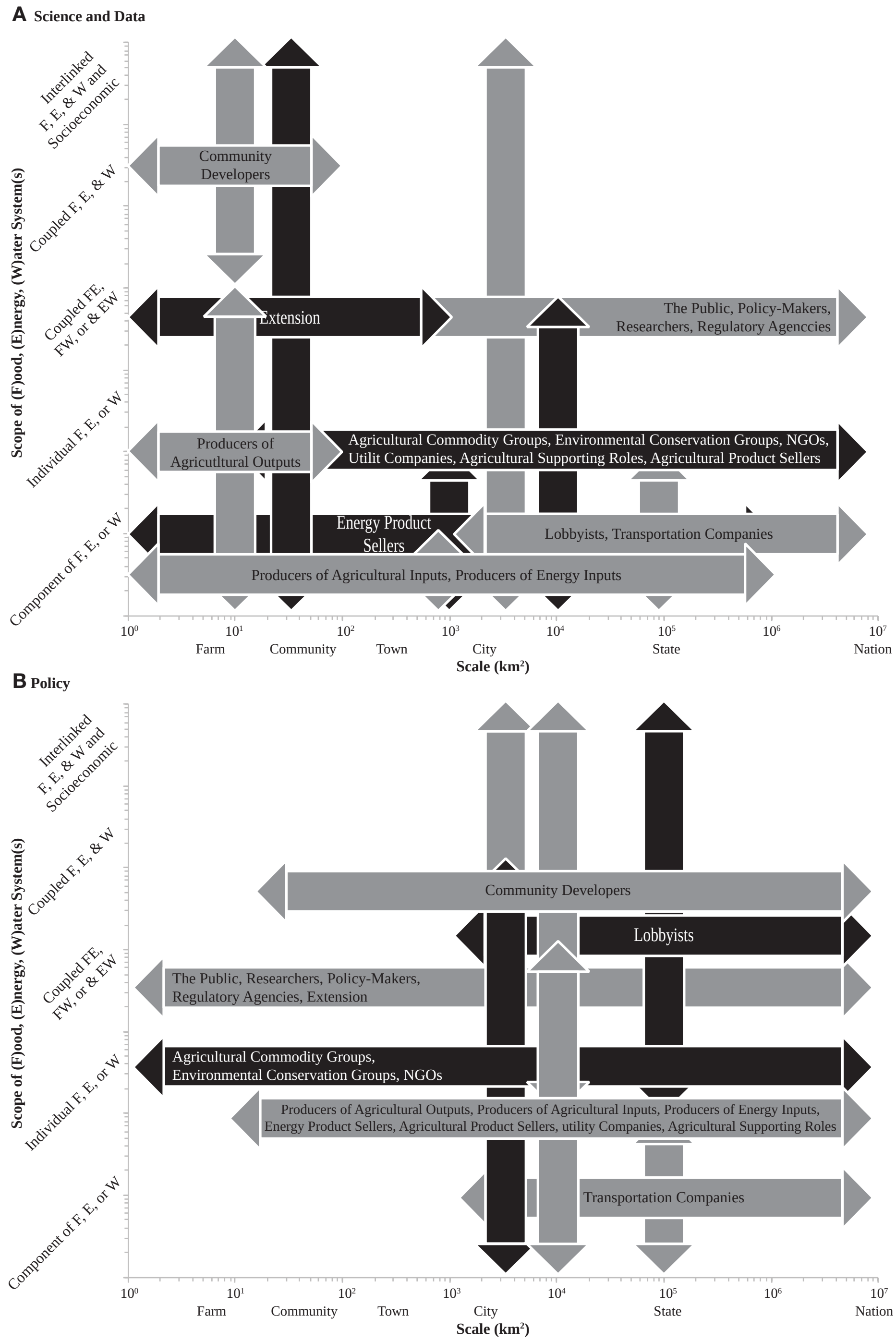

FIGURE 5 | Scopes and scales pertinent to the FEW nexus problems and where various stakeholders are likely to be interested: **(A)** science and data, and **(B)** policy. The arrows indicate the likely ranges in which the stakeholder groups are involved with the FEW nexus. Differences in greyscale for the arrows are meant to add clarity and do not indicate differences between stakeholder groups.

point of departure to discuss and further investigate how the joint outcomes of decision-making by multiple stakeholders depend on the relative importance of science and data vs. integrated policy promote decisions that induce better economic, environmental, or social outcomes. Such Pareto-improving goals should seek to yield benefits that do not decrease environmental, economic, and social conditions or the welfare of FEW stakeholders.

Sustainability science entails the co-production of knowledge that occurs when doing work in complex, overlapping systems

(Clark et al., 2016), such as the FEW nexus. The FEW nexus also includes human actors, and as such the purposeful production of knowledge for action is best-served by incorporating stakeholder input in order to more fully understand the issues, trade-offs, and dynamics of the complex system(s) (Cash et al., 2003). Depending on the scope and scale of consideration within the FEW nexus, there may be opportunities for self-organized practices that enhance the sustainability at multiple levels if actors are aware of the scarcity of the resources, they have good knowledge of the system, and the social backdrop is favorable (Ostrom, 2009). Interactions at different organizational levels can lead to emergent properties that the individual components do not (Liu et al., 2015), as such it is necessary to scientifically understand the characteristics of these properties and incorporate them into policy—which by definition must be integrated. Overall, given the feedbacks and interactions between science, research, data, and policy for sustainability in FEW nexus, in combination with varied roles and interests of relevant stakeholders, this work suggests that distinctions between the importance of one aspect (e.g., data) and another (e.g., policy) may be artificial, and that proper attention must be given to the nuances of the issues, the policies, the people and their interests, and the physical, economic, or social systems that are involved.

ETHICS STATEMENT

This research was conducted with the approval of the Institutional Research Board at Ohio State University (2018E0285 and 2018E0361). The Ohio State University holds Federalwide Assurance (FWA) #00006378 from the Office for Human Research Protections (OHRP) in the Department of Health and Human Services (DHHS). This FWA is an agreement between DHHS and Ohio State to review and approve research involving human subjects in accordance with the ethical principles outlined in the Belmont Report and the DHHS regulations 45 CFR Part 46.

AUTHOR CONTRIBUTIONS

JB: conceptualization, methodology, investigation, writing original draft, writing review and editing, visualization, supervision, project administration, and funding acquisition. MB: conceptualization, methodology, investigation, writing original draft, writing review and editing, and project administration. JK: conceptualization, writing original draft, and writing review and editing. YW: conceptualization, formal analysis, writing original draft, and writing review and editing. ST: conceptualization, writing original draft.

FUNDING

We gratefully acknowledge funding from the U.S. National Science Foundation Innovations at the Nexus of Food, Energy, and Water Systems (INFEWS) grant SES-1739909.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2019.00007/full#supplementary-material

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Environmental Science

ORIGINAL RESEARCH
published: 12 February 2019
doi: 10.3389/fenvs.2019.00003

Holistic Water-Energy-Food Nexus for Guiding Water Resources Planning: Matagorda County, Texas Case

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OPEN ACCESS

Edited by:
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Swiss Federal Institute of Aquatic Science and Technology, Switzerland*

Reviewed by:
*Nidhi Nagabhatla,
United Nations University Institute for Water Environment and Health, Canada*
*Xingcai Liu,
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Specialty section:
This article was submitted to Freshwater Science, a section of the journal Frontiers in Environmental Science

Received: *30 August 2018*
Accepted: *04 January 2019*
Published: *12 February 2019*

Citation:
Kulat MI, Mohtar RH and Olivera F (2019) Holistic Water-Energy-Food Nexus for Guiding Water Resources Planning: Matagorda County, Texas Case. Front. Environ. Sci. 7:3. doi: 10.3389/fenvs.2019.00003

Nations, particularly those with well-established infrastructure, have started to look for new, innovative solutions to address the expected, inevitable high demand for primary resources. The WEF (water-energy-food) Nexus approach, which holistically considers the dynamic interlinkages between water, energy, and food resources, has come to the forefront within scientific and practice communities. Supporters assert that sustainable solutions can be revealed through the use of this approach, rather than conventional approaches that often overlook the interlinkages. The authors developed a holistic framework to provide sustainable scenarios that include feasible infrastructure interventions. The framework focuses on water and associated links with other resources, includes a unique analytic tool for quantifying scenarios, and ultimately produces a sustainability analysis of each scenario. Optimal scenarios are offered that consider site-specific dynamic resource interlinkages. The platform was applied to the case study of Matagorda County, Texas, identified as one of the most water-stressed regions in the state of Texas by the Texas Water Development Board, the state's executive agency for water resources management. High demands from energy and agriculture sectors in the county and sharp population increase in the upper basins, which include the city of Austin, have put great pressures on the water resources of Matagorda County. Farmers have been forced to change their crops from high to lower water-demand crops, in spite of apparent and relatively abundant local water resources. The findings of the case study present a most sustainable scenario, including infrastructure interventions that will increase the annual income of agriculture sector from $188 million to $239 million. The approach also helps preserve resources while reducing annual water and energy demand by 22 million m3 and 21 million kWh, respectively, and does not sacrifice on-going municipal and industrial water use or energy production in Matagorda, Texas.

Keywords: water planning, resource security, infrastructure interventions, interlinkages, sustainability, resource allocation, nexus modeling, tradeoffs

INTRODUCTION

Under the intertwined influences of population increase, climate dynamics, urbanization, and environmental deterioration, various water issues are emerging into the global arena. Conventional engineering and management decision making processes for water resources tend to primarily consider cost and quantity parameters. However, long term, optimal, sustainable water allocation, and management decisions require a more holistic approach that considers all stakeholders and the associated, interdependent systems, such as energy costs, footprints of water production and distribution, and tradeoffs of water allocation between sectors (agriculture, energy production, and ecosystems).

The case proposed in this study focuses on Matagorda County, Texas, where lucrative rice farms once flourished, but where recent water shortages have caused dramatic shifts in cropping patterns. In addition, Matagorda County is home to one of Texas' two nuclear power plants, which consume approximately one-third of the existing water supply. While recently issued, additional nuclear power plant licenses will more than double energy production, these new plants will also further exacerbate the stresses on Matagorda's natural resources. Consideration of the tradeoffs between these multiple demands is critical to the sustainable management of the County's primary resources: the current water gap is growing and will become worse in the future.

Background and Literature Review

The lack of fresh water and sanitation leads to disease, poverty, and either migration toward more water-abundant valleys or development of local infrastructure solutions, such as surface water conveyance or withdrawal from underground resources (Hassan, 2003). Ancient societies in North Africa, Asia, and the Middle East were situated near fresh water resources, mainly rivers, to ensure easy access for domestic, irrigation, and livestock purposes. The industrial revolution of the eighteenth century brought population booms, rapidly rising living standards, and growing demand for water for industrial, energy, and mining production purposes. Throughout history, developments in material science, such as cast iron, affordable concrete, and pumping technologies, have made it easier to convey water, leading to dramatic increases in the quantities of water used (Duffy, 2013). By the twentieth century, water usage quantities increased dramatically as access to water became easier.

However, this tremendous increase in water use caused new challenges: high demand, environmental deterioration, and allocation issues, and carried complicated influences on various sectors. For example, a farmer accustomed to irrigating an agricultural field only if direct access to water was available (pre twentieth century), could irrigate fields far removed from the water source after the technological innovations of the twentieth century. Many criteria, hydraulic sufficiency, financial capability, adequacy of materials, water quality, water rights, etc. have emerged and must be taken into account. Today, technological opportunities notwithstanding, the issues are more complex.

Pervasive developments and increasing standards in various fields led the scientific community to seek new methods to offer solutions against the complexities (Arnold and Wade, 2015). Thus, the systems thinking and systems theory is applied to real life applications since World War II in an effort to solve complex issues while also considering interlinked parameters and components (Steven, 2011). Systems theory includes the three major pillars of sustainability: economic, social, and environmental, and facilitates an improved understanding of the interlinkages between the three (Cattano et al., 2011). Thus, the water-energy-food (WEF) nexus approach was established using the systems theory.

During the 2010s, the WEF nexus became an important topic in in the scientific literature. As it is a relatively new approach, there is no sound consensus on its definition. FAO describes WEF nexus as "*a useful concept to describe and address the complex and interrelated nature of our global resource systems, on which we depend to achieve different social, economic and environmental goals*" (FAO, 2014). Securities of the primary resources are central concerns of this nexus (Bizikova et al., 2013). The approach helps promote a more sustainable future by identifying the dynamic inter-relationships between WEF resource systems. The disciplines behind each of these systems are not replaced, but built upon to provide solutions for insecurities in the inextricably linked primary resources (Mohtar and Daher, 2012). Attitudes toward water planning illustrate that the WEF nexus approach can provide an overall increase in the efficiency and sustainability of resource use: the nexus focuses on system efficiency, rather than on the individual sectors comprising the system (Hoff, 2011). From the global United Nations Sustainable Development Goals (SDGs) to regional and local goals, the WEF Nexus has become central to discussions of the potential balance of interests and perspectives between the private and public sectors and civil society regarding the allocation of the same resources (Mohtar and Lawford, 2016).

There has been numerous contributions in recent literature on the development and applications of the water-energy-food (WEF) system in modeling, system integration, data analytics, and governance. Despite the potential, this system approach in managing the complex WEF system there is a lag in implementing and adopting this approach in real life decision making. Beside the lack of appropriate tools, data and knowledge, there is a general skepticism surrounding this approach as to its applicability and ability to save resources and cost saving resulting from adopting these holistic approaches (Daher et al., 2018). There is a general lack of documented cases to this effect showing tangible savings in capital and resources as a result of the WEF nexus approaches. This study sheds some light on these saving using a real case study and attempts to serve as a case study of such benefits.

As specific to the water resources management, the recent trend in public policies indicate that managing water resources systems should be the main focus rather than investing on infrastructure. Supporters of the trend tend to assume that the sustainability can only be achieved when we direct new rules in water resource allocations whereas others claim we still need to improve and build efficient water infrastructure (Kemerink et al., 2016). In this manner, this study associates both approaches and creates an environment to enable optimum

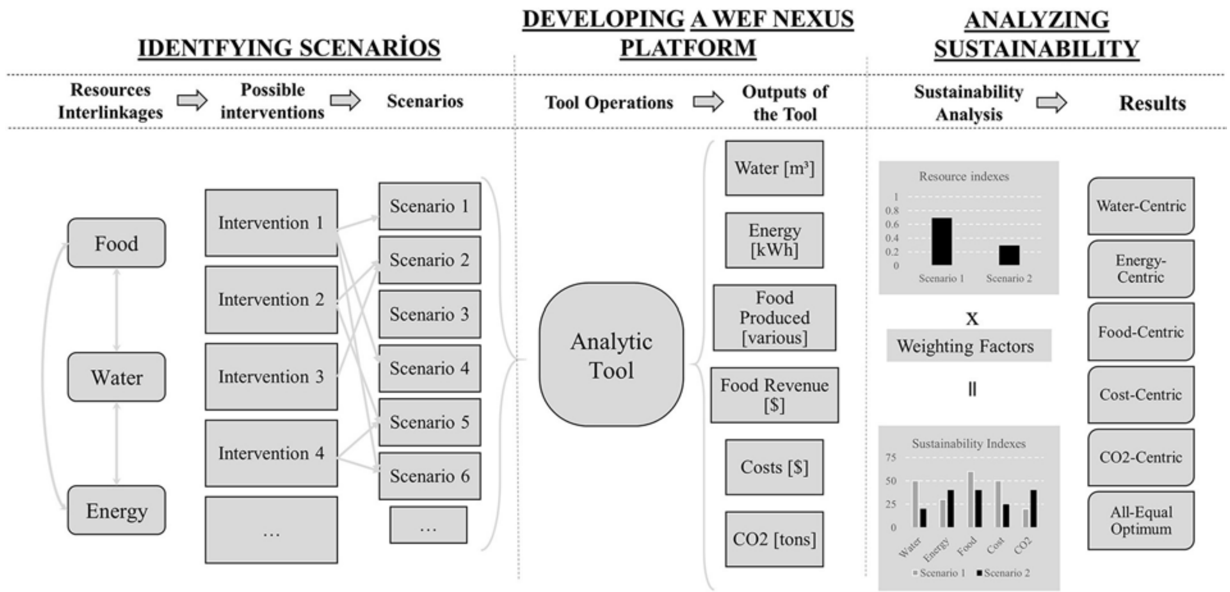

FIGURE 1 | Water—Energy—Food Nexus Framework.

water infrastructure investing considering trade-offs between water users.

Overall, this study develops a WEF Nexus model that identifies the causes of water stress, and provides scenarios, including feasible infrastructure interventions, from which to draw sustainable recommendations that take into account the nexus interlinkages unlike conventional methods. In doing so, the study builds an analytic tool to assist quantifying trade-offs and a sustainable analysis system to assess sustainability in the selection of water-related infrastructure projects. A real case study is needed to demonstrate whether the WEF nexus approach model developed here helps save capital and primary resources.

Research Hypothesis

A holistic WEF Nexus approach to water resources planning reduces cost, saves primary resources utilization while providing the same primary resource services. The primary objectives of the study are to:

I. *Identify scenarios*: consisting of infrastructure interventions that can mitigate risk and vulnerability in securities of primary resources (water, energy, food).
II. *Develop a WEF nexus platform*: a systems level water-energy-food nexus platform, including a tool to quantitatively assess tradeoffs in developed scenarios.
III. *Analyze Sustainability*: develop criteria for obtaining optimal scenarios and analyze them based on economic, social, and environmental sustainability, and their tradeoff implications for water, energy and food resources.

METHODOLOGY

The methods for achieving these three objectives: (I) identifying scenarios, (II) developing a WEF nexus platform, (III) analyzing sustainability, are generalized to hotspots that experience water scarcity. The framework, as seen in **Figure 1**, is summarized as an overview of the methodology. The proposed analytical framework relies on the interconnections between primary resources (i.e., water is needed for food production; irrigation requires energy), and consists of the three stated primary objectives. The detailed steps, shown in **Figure 1**, must be accomplished to reach outcomes. Long-term sustainability projections are based on the analysis of data from a specific year; these are then projected to the year of interest. The case study stated in the following chapter shows how the method

TABLE 1 | Scenarios and interventions.

Interventions		**Intervention 1**	**Intervention 2**	**Intervention 3**	**Intervention 4**	**Intervention 5**	**Intervention 6**	**.**	**.**	**.**	**.**
Scenarios	1		✓						✓		✓
	2			✓							
	3			✓			✓				✓
	4						✓		✓		
	5	✓				✓		✓			
	6	✓					✓	✓	✓		
	7	✓			✓						✓
	8		✓							✓	✓
	.		✓			✓					
	.				✓		✓		✓		
	.					✓	✓				

Each scenario is a combination of interventions. Check marks indicate the scenario on the column has the intervention on the row.

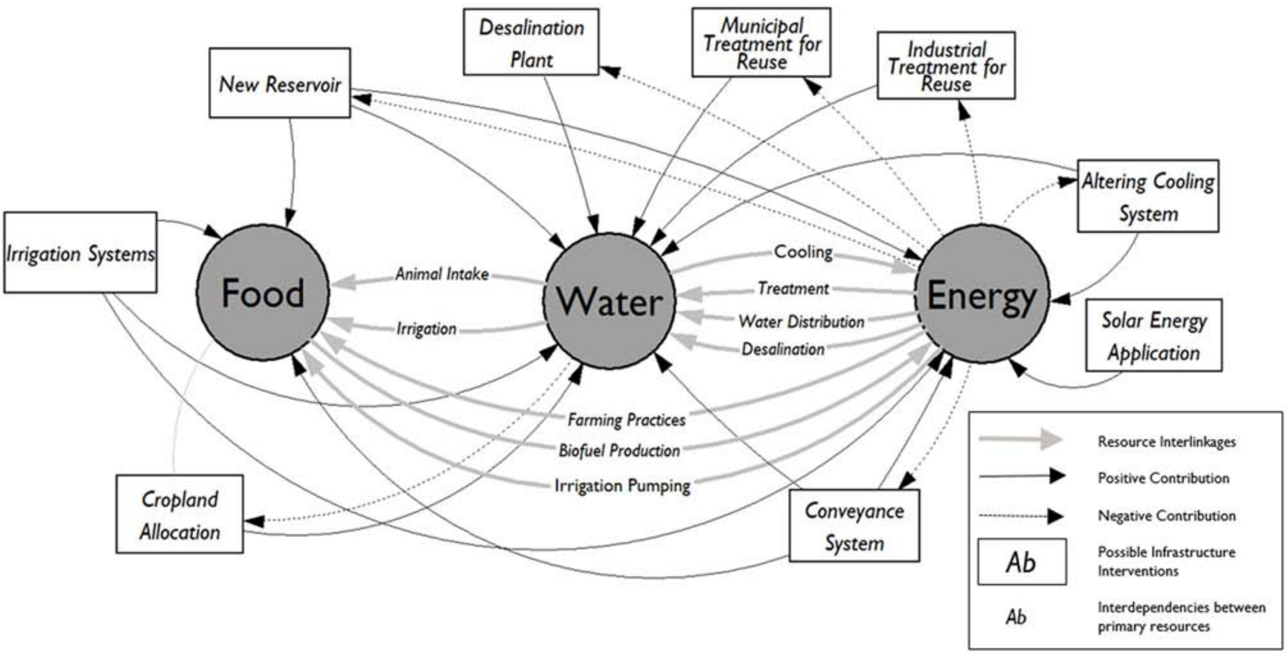

FIGURE 2 | Schematic Overview of the WEF Nexus Model.

is practiced in for a real life case. Assumptions needed and data collected specifically for the case study can be found in **Appendix 2**.

Identifying Scenarios

The water-food, water-energy, and food-energy nexus are reflected in the general resource allocation for the study area, making it possible to analyze the stresses that cause insecurity in water resource availability. Further, investigating these nexus provides a basis for interventions that help improve securities of the WEF resources, thereby ensuring a more sustainable future. The interventions may include on-farm irrigation systems, altered crop patterns, new reservoirs, improved water distribution infrastructure, altered energy plant cooling systems, solar production of energy, and cost of water distribution systems.

Interventions vary with local necessities and availabilities. It should be kept in mind that while an intervention may be feasible, it may also be unsustainable and therefore, not advisable. In this methodology, a holistic, globally applicable nexus model is presented. However, feasible interventions to the vulnerable study region should be determined based on local objectives and restrictions. Also, environmental constraints should be used as limitations for providing sustainable future. For water allocation, environmental flow requirements, and groundwater withdrawal recommendations should not be exceeded in any case scenario.

Possible interventions are used to form *scenarios* (**Table 1**). A large number of scenarios can be developed across multiple sectors (agriculture, energy production, water, industry, etc.). For the study area, the number of scenarios is limited due to time and calculation restrictions. For example, if 10 possible interventions were developed for a study area, then "10!" different scenarios can be developed using them. However, selecting a number of scenarios that reflect major possibilities can be sufficient to draw recommendations.

Developing WEF Nexus Platform

This approach considers the WEF resources to be inextricably linked to one another. Thus, it is imperative that the interlinkages be investigated before the analytics are built. **Figure 2** illustrates the layout of the nexus model and its interconnections. Water is needed for food production due to the requirements of irrigation and animal intake. Food production requires energy as pumping is required for irrigation and other farming practices (i.e., tillage, fertilization, planting). Biofuel crops can benefit energy production, but require that land be allocated for their production. Energy is dependent on water: most types of energy require cooling, often provided by freshwater. Energy is essential to the use of water resources: in treatment, distribution, and desalination. Thus, sustainable development of an economy centered on water, energy, and crop resources should focus on the interlinkages of these three and the manner in which they influence each other.

These nexus interlinkages must be quantified for further analysis. To this purpose, the authors developed a unique analytic tool based upon input scenarios in which each scenario has a given set of possible interventions that provide the data of study area, such as irrigation applications, selected crops and the lands allocated to grow them, water use and supply, energy production and consumption, food production, farming practices. The tool is capable of providing quantitative results for each scenario in terms of the total water demanded and supplied, energy

TABLE 2 | Quantitative result parameters obtained from the tool.

Symbol	Parameter	Unit
W	Water	m^3
E	Energy	Kilowatt-hours (kWh)
F	Food produced	Based on the crop or animal (bushel, lb etc.)
R	Food revenue	US dollars ($)
C	Costs	US dollars ($)
CO_2	Carbon footprint	Ton (ton)

demanded and produced, agricultural revenue, CO_2 emission, and cost of related infrastructure projects (**Table 2**). The analytics of the tool can be seen in **Appendix 1**. Sustainability analysis is performed using the quantitative results to help determine the preferred scenarios in accordance with various perspectives of sustainability.

Analyzing Sustainability

The sustainability analysis of scenarios consists of two main steps: normalization and stakeholder perspective. First, normalization is necessary to bring diverse outputs and units of the scenario onto a single plane, thus, diverse units are omitted. The quantitative results obtained from the tool are normalized for each scenario to provide resource indices (**Appendix 4**). Resource indices are ranked from 0 to 1.0 and the outputs normalized considering the largest value of the outputs. Second, the stakeholder perspective must be reflected: stakeholders have divergent views on the resources. All resource indices are multiplied by pre-determined weighting factors (**Table 3**). Weighting factors, summed to reach 1.0, are applied to the resource indices; higher values are assigned based on given importance of the resource.

In this study, the analysis has (1) water-centric, (2) food-centric, (3) energy-centric, (4) CO2-centric, (5) cost-centric, and (6) all-equal perspectives. The subtraction of the sum of multiplication of resource indices and weighting factors from 1.0 provides sustainability indices (see **Table 3** for weighting factors). The sustainability indices make it possible to rank scenarios with respect to water-centric, energy-centric, food-centric, cost-centric, CO_2-centric, all-equal perspectives. It is important to note that, for a given scenario, it is desirable to lower the demands of water, energy, cost, and carbon-dioxide emissions, whereas agricultural revenue is high in terms of sustainability. The sustainability index formulations shown in the **Appendix 4** indicate that resource indices of agricultural revenue become negative in the summation, while other indexed outputs from the tool remain positive. Consequently, water-centric, food-centric, energy-centric, cost-centric, CO_2-centric, and all-equal outcomes are presented. The outcomes of the study are the recommended scenarios.

KEY STUDY: MATAGORDA COUNTY

Site and Problem Descriptions

Matagorda County, Texas, sits near the center of the Texas Gulf Coast. Matagorda is surrounded, from a distance, by the major cities of Houston, Austin, and San Antonio. The Gulf of Mexico borders Matagorda County, including Tres Palacios and Matagorda Bay on the western half of the county and the East Matagorda Bay on the eastern half. All are sheltered from the Gulf by the Matagorda Peninsula (TWRI, 2017). The population numbers around 36,598 (US Census Bureau, 2015). The major cities of the county are Bay City and Palacios. The main sectors of employment are agriculture, energy production, and chemical production (MCEDC, 2016).

The Texas Water Development Board (TWDB), a major water-related agency in the state, presents water plans in 5-year cycles. The 2017 State Water Plan (TWDB-2017) indicates an expected shortage of 240 Mm3 in the year 2020 for Matagorda. More than half of the total water demand will be unmet, given existing water supplies. Long-term plans indicate that this gap will continue, making Matagorda County one of the most water stressed among the 254 counties of Texas (TWDB, 2016a).

WEF Nexus Interlinkages in Matagorda

The water shortage in the county is primarily due to the requirements for irrigation and the steam production of electric power, which consume 62 and 31% respectively of Matagorda's total water demand (TWDB, 2016a). Both industries are crucial to the economy of Matagorda County: neither is expected to fade away in the foreseeable future. Matagorda County offers a unique example for a WEF Nexus study, as there is competition for usage of water resources between two sectors: the agriculture and energy industries.

Most of the county's land is allocated for agriculture, either cultivated crops or pastureland (**Figure 3**) (Homer et al., 2015). Agriculture is the major water consumer in Matagorda County: over 600 ranches and more than a thousand farms operate there. Historically, Matagorda is famous for its rice farms, which consume large quantities of water. Recent droughts, the rising demands from population growth in the surrounding metropolitan areas, and energy production have dramatically influenced crop types: today, farmers in Matagorda grow large quantities of sorghum, cotton, soybeans, and corn rather than rice (MCEDC, 2016).

Several water utilities and industries in Matagorda County produce, convey, and utilize the WEF resources of the county. However, the amount of water consumed by municipal and industrial (M&I) users is much less than that consumed by agriculture and energy production. Historical water use estimates of TWDB indicate that municipal water requirements are supplied entirely from fresh groundwater, while industrial water users rely on the Colorado River and the Gulf Coast Aquifer. In 2015, groundwater consumption was 1.75 Mm3 and surface water consumption, excluding power production, was 11 Mm3 (TWDB, 2016,b), making industrial activities the main WEF nexus player in the county. By far the largest industrial company is a nuclear plant, one of two such plants in Texas. The South Texas Project (STP) is the single largest water consumer in Matagorda County and provides power to Houston, Austin, San Antonio and other surrounding areas. By 2020, the county is expected to see the highest demand for water from steam electric power production among the 254 counties of Texas: 130 Mm3 (TWDB, 2016a). This tremendous quantity of water, accounts for

TABLE 3 | Weighting factors.

Outputs	Symbol	Perspectives of stakeholders					
		Water-Centric	Food-Centric	Energy-Centric	CO_2-Centric	Cost-Centric	All-Equal
Water	W	a1	b1	c1	d1	e1	f1
Energy	E	a2	b2	c2	d2	e2	f2
Food	R	a3	b3	c3	d3	e3	f3
Cost	C	a4	b4	c4	d4	e4	f4
CO_2	CO_2	a5	b5	c5	d5	e5	f5
Total:		1.00	1.00	1.00	1.00	1.00	1.00

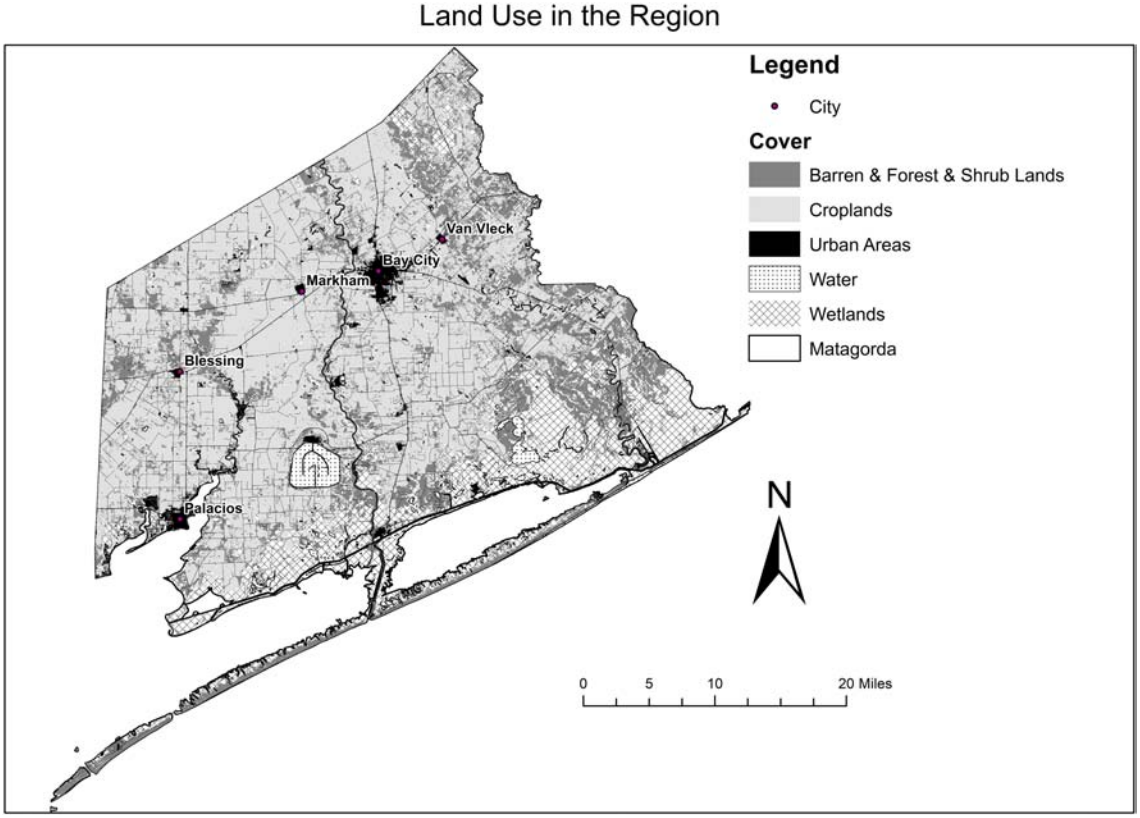

FIGURE 3 | Land Use in the Case Study Region (TNRIS, 2016).

one-third of total water resources of the county and is directly consumed by STP for cooling purposes. STP plans to expand the plant in the future (**Table 4**).

STP is cooled by a 2,830 ha "Main Cooling Reservoir" (MCR): a constructed cooling reservoir, enclosed by a large ring-dike. The MCR has a volume of 250 Mm3 during normal operation (Wurbs and Zhang, 2014). A pump intake station on the banks of the Colorado River refills the cooling reservoir from losses due to evaporation or seepage. While most of the water needs are supplied by the river, groundwater, and precipitation also contribute. The MCR water is consumed by natural evaporation, induced evaporation due to heat (around two-thirds of produced energy is ejected as heat into the environment), seepage or released back into the river.

General Procedure and Data Collected

While applying the methodology proposed above to the case study, some local and regional adjustments were included. In all scenarios proposed in the case study, the reliability of water allocation for M&I users was determined to be 100% and ensuring that the demands of M&I users, including energy production, will always be met. Agricultural water supply could be lower, and may not meet the anticipated demand of agricultural consumers. The analysis for the case study considers long-term sustainability. The year of 2070 (~50 years forward)

TABLE 4 | The general information of reactors of STP nuclear generation plant [Source: IEAE power reactor information system (IAEA, 2016)].

Reactor unit	Net capacity	Gross capacity	Construction beginning date	License expiration date
Unit 1	1,280 MW	1,354 MW	1975	20 August 2027 (extension pending)
Unit 2	1,280 MW	1,354 MW	1975	15 December 2028 (extension pending)
Unit 3 (Planned)	1,350 MW	N/A	License Issued (2016)	40 years after construction/activation
Unit 4 (Planned)	1,350 MW	N/A	License Issued (2016)	40 years after construction/activation

was selected and all data for the case study is projected to that year.

Texas legislation requires limitations and constraints in water use (Wurbs, 2015): in this study, existing water rights and permits of users were considered as constraints and were not violated. The other limitations that can be considered environmental for the case study are environmental flow needs for river water use directed by Texas Commission on Environmental Quality (TCEQ) and recommended groundwater withdrawal values by Texas Water Development Board (TWDB) (section A.2).

As the nexus case study needs a comprehensive analysis, various types of data were required. All the details of the data collected can be seen in the **Appendices** (section A.2) Assumptions specified for this case study are shown in Case Study Assumptions. Thus, the ultimate WEF nexus model for the case study was drawn after analyzing the data and describing the system components, boundaries, stakeholders, and observers. The developed analytic tool was then modified based on the model for the case study.

Scenario Building

Possible interventions related agricultural practices, water resources, and energy resources were identified as solutions to existing and anticipated water shortages for the study area. The following possible interventions are proposed for Matagorda County: alter land allocation, improve on-farm irrigation systems, supply new conventional and unconventional water resources for agricultural consumption and municipal and industrial water reuse, alter cooling systems and supply alternative water resources to the nuclear energy plant, and build a new solar farm in the county. Twenty-five scenarios were developed; each uses a combination of the stated interventions. The base scenario ("business as usual" or BAU) proposes no interventions and is used to compare the developed scenarios. **Table 5** shows the embedded interventions, for example, scenario-8 has only intervention 4, while scenario-9 has interventions 1, 3, 4, and 5. The tool was applied to each scenario and quantitative results produced.

Sustainability Analysis

Quantitative results were normalized to obtain resource indices as described in the methodology section. The resource indices were then multiplied by weighting factors, as specified for the key study (**Table 6**). For water-centric, food-centric, energy-centric, cost-centric, and CO_2-centric perspectives, the highest value (0.40) was assigned to the highest important outcome. The remaining outputs were weighted equally at 0.15, as their importance was desired to be considered in the nexus study. The sum of each weights of perspectives was 1.0. As for the last perspective, all-equal, all weights were assigned the same: 0.20 for each. Consequently, each analysis accounts for influences of interventions to water, energy, food portfolios, and its financial and CO_2 emission costs.

RESULTS AND DISCUSSIONS

The trade-offs between primary resources are explicit and the required data are relatively accessible for Matagorda County compared to other regions. These enable us to apply the methodology in details. Therefore, we can validate and assess the methods developed. Applying the study elsewhere in the world will require some attentions. First, the application of the study in other regions (especially in developing countries) would require more assumptions regarding data although the methodology of the study is designed to be applicable everywhere. It can reduce the accuracy of the study. Second, some aspects of WEF interlinkages that the case study are does not cover may need to be taken into account such as hydropower and biofuel depending upon the new study area. Next, local and regional legislative constraints should be included. As an illustration, Texas legislations including existing rights that cover Matagorda County played an immense role while determining the constraints of the study. However, other parts of the world will have different legislations that need to be examined before building scenarios. Also, we used existing environmental constraints that have already been applied in the county such as envitonmental flow and groundwater withdrawal values. Specific environmental considerations may be applied to new study areas. Last but not least, existing practices and availabilities are site-specific issues. The current and anticipated practices in farming, water use, energy use etc. should be taken into account when the methodology is applied to other real life case studies from different parts of the world.

Results of the case study are presented in two phases: quantitative results (analytic outputs) of each scenario, and outcomes of the sustainability analyses that indicate rankings of scenarios, based on various perspectives of sustainability. Twenty-five developed scenarios were examined. The WEF nexus analytic tool provided quantitative results for each of these scenarios. Some of the outputs were further analyzed to identify and recommend the most sustainable scenarios (**Figure 4**). In each graph, the x axis represents the scenarios and the y-axis presents output records.

TABLE 5 | Scenarios and possible infrastructure interventions systems embedded in the scenarios.

Interventions		**Land allocation**				**Irrigation application**		**New water resources**								**Municipal water**		**Inustrial water**		**Cooling system**				
		Current practices	**More land and more water-intensive crops**	**More land and less water-intensive crops**	**Current Ag. land and less water demanded crops**	**Conveyance system improvement**	**On-farm irrigation system improvement**	**New reservoir**	**Seawater Desalination (Va)**	**Seawater Desalination (Vb)**	**Brackish Groundwater Desalination (Va)**	**Brackish Groundwater Desalination (Vb)**	**Houston Water Reuse (Va)**	**Houston Water Reuse (Vb)**	**Houston Water Reuse (Vc)**	**%50 municipal wastewater reuse**	**%80 municipal wastewater reuse**	**%50 industrial wastewater reuse**	**%80 Industrial wastewater reuse**	**Current practices (River water diversion)**	**Water Intake From the New Reservoir**	**Water use from sea**	**Reuse of houston wastewater**	**Building s solar power station**
Scenarios	1	✓				✓														✓				
	2	✓				✓		✓									✓		✓	✓				
	3	✓				✓	✓	✓															✓	
	4	✓				✓	✓	✓		✓										✓	✓			
	5	✓				✓	✓	✓			✓										✓	✓		
	6	✓				✓	✓	✓									✓		✓		✓	✓		
	7	✓				✓	✓			✓	✓						✓					✓		
	8	✓				✓	✓	✓						✓			✓		✓				✓	✓
	9	✓				✓	✓	✓				✓					✓		✓			✓		✓
	10	✓				✓	✓	✓	✓			✓				✓					✓	✓		✓
	11		✓																	✓				
	12		✓			✓	✓	✓								✓		✓					✓	
	13		✓			✓	✓	✓		✓	✓						✓			✓	✓			✓
	14		✓			✓	✓	✓	✓			✓					✓					✓		
	15		✓			✓	✓	✓		✓		✓			✓		✓		✓		✓	✓		✓
	16			✓																✓				
	17			✓		✓	✓	✓				✓				✓		✓		✓	✓			
	18			✓		✓	✓	✓		✓				✓		✓		✓					✓	✓
	19			✓		✓	✓	✓		✓		✓					✓		✓		✓	✓		✓
	20			✓		✓	✓	✓			✓				✓		✓			✓	✓			✓
	21				✓															✓				
	22				✓	✓	✓	✓									✓		✓	✓	✓			
	23				✓	✓	✓	✓		✓							✓					✓		✓
	24				✓	✓	✓	✓				✓					✓		✓		✓	✓		✓
	25				✓	✓	✓	✓				✓	✓				✓						✓	✓

Va, Vb, Vc are the volume of water resources representing 61,674,000 m3 [50,000 acre-feet], 123,348,000 m3[100,000 acre-feet], 185,022,000 m3[200,000 acre-fee] respectively.

TABLE 6 | Preferred weights for case study.

Output parameters	Symbol	Water-Centric	Energy-Centric	Food-Centric	Cost-Centric	CO_2-Centric	All equal
Water demand (m3)	W	0.40	0.15	0.15	0.15	0.15	0.20
Energy demand (kWh)	E	0.15	0.40	0.15	0.15	0.15	0.20
Agricultural revenue ($)	R	0.15	0.15	0.40	0.15	0.15	0.20
Cost ($)	C	0.15	0.15	0.15	0.40	0.15	0.20
CO_2 emission (ton)	CO_2	0.15	0.15	0.15	0.15	0.40	0.20

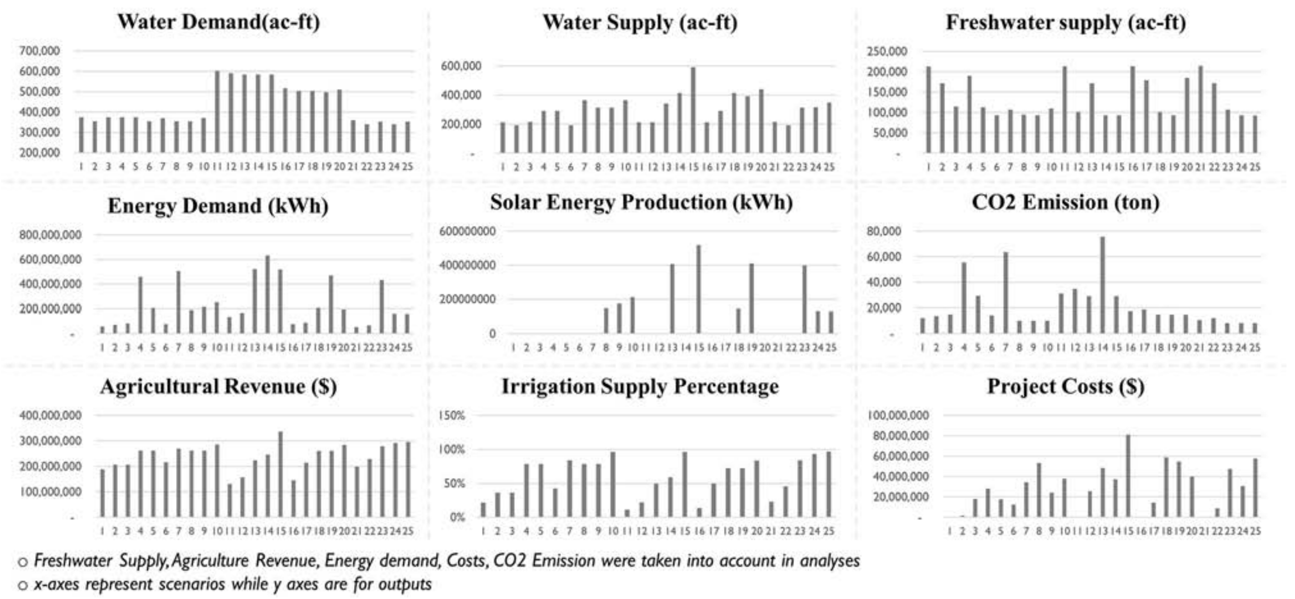

FIGURE 4 | Outputs Obtained from the Tool.

Several kinds of numerical outputs become available for each scenario, as seen in **Figure 4**. However, only some outputs that have a wide spectrum of reflectance of the water-energy-food nexus were selected for the sustainability analysis. The determined weighting factors (**Table 6**) were multiplied by the normalized output values to enable stakeholders to reflect their views. After the completing the sustainability analyses, the sustainability indices, ranked from 0 to 1, are produced (**Figure 5**). Outcomes of the sustainability analysis are the rankings of the scenarios based on sustainability analyses. Scenarios were ranked based on (1) water-centric, (2) food-centric, (3) energy-centric, (4) CO2-centric, (5) cost-centric, and (6) all-equal perspectives.

The first scenario (S-1), is a base scenario for which there is no new intervention ("business as usual"). The results of sustainability analysis for all-equal perspective, which is an objective perspective, show that scenario 9 (S-9) is the best scenario in terms of sustainability. The least sustainable scenario is S-14. The base scenario (S-1) is also used for validations. The interventions recommended by S-9, S-1, S-14 can be seen from the scenarios (**Table 5**). **Table 7**, seen below, presents the quantitative results of sustainability analysis of the 3 main scenarios (best, base, and worst).

Water demand of the county is 460 million m3 for S-1 (the base scenario), while it is 438 M m3 for S-9 (the most sustainable scenario) and 720 M m3 for S-14 (the least sustainable scenario). It is desired for a sustainable scenario to have less water demand, as in S-9.

When it comes to water supply, outputs show that S-14 provides highest water supply, with 678 Mm2. Although it seems that a greater water supply means more sustainability, the water supply sources of S-14 (seawater, brackish groundwater, water reuse within the county), water reuse reduces sustainability because of energy and cost outputs (see **Appendix 5** for the amounts of other water supply sources used).

The highest energy demand value can be seen in S-14, which is nearly 13 times higher than the base scenario with more than 750 M kWh. When S-1 and S-9 are examined, it can be seen that S-9 has higher energy demand, 144 M kWh by S-9, 60 M kWh by S-1. However, S-9 proposes a solar farm to supply energy demand and therefore S-9 is the most desirable scenario in terms of energy demand due to lower energy needs from conventional sources. The energy produced by solar farm is 105 M kWh annually and

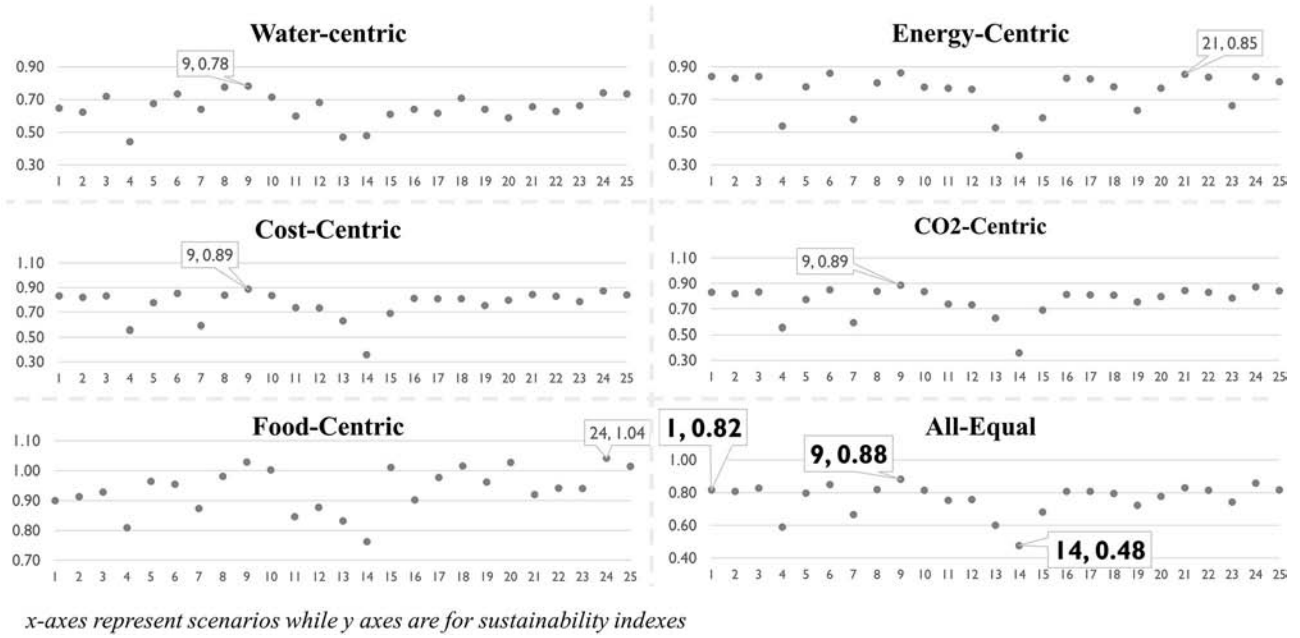

FIGURE 5 | Outcomes of Sustainability Analysis.

TABLE 7 | Outputs of Best, Worse Sustainable and Base (Business as usual) Scenarios.

Output parameters (Annual)	Presented scenarios		
	Base scenario S-1	Best scenario S-9	Worst scenario S-14
Water demand (million m^3)	460	438	720
Energy demand [After solar contribution (million kWh)]	60	39	754
Solar energy produced (million kWh)	0	105	0
CO_2 emission (ton)	12,200	10,100	1,02,400
Ag. revenue (million $)	188.0	239.1	270.6
Project costs (million $)	0.2	19 .2	57.8
Irrigated cropland percentage	21%	61%	57%

reduces energy demand to 39 M kWh (see **Table 7**). Comparisons of CO_2 emission as an environmental cost in the scenarios show that the less detrimental S-9 is the best scenario: it is a little less than S-1.

Three major stakeholders (agriculture, industry, and municipality) driving WEF resources were analyzed. The agriculture sector suffers from lack of water, which negatively influence the agricultural economy in the count; the other sectors have continued their activities as desired. The interventions provide economic benefits to the agriculture sector. The methodology of the study states that municipal and industrial consumers will continue their activities in any case scenario without any interference (see methodology). Their water and energy requirements for industry and municipal users will be met (water supply firm yield maintained), so the sectors will have the usual expected annual benefits. As a result of financial analysis, S-9 becomes the most sustainable scenario, providing approximately an extra annual $32 million in direct income. This extra income is a direct benefit of the agricultural sector and was calculated after considering costs of interventions. It is significant to note that most of the population depends on agricultural sector in Matagorda County. Therefore, economic well-beings of the other sectors, thus, are expected to grow with external benefits of the annual $32 million.

Overall, this case study prioritizes water security while considering food and energy interlinkages. Thus far, we looked at all-equal analysis that considers all perspectives of stakeholders equally. When it comes to other analyses, the outcomes of the sustainability analysis indicate S-9 is the preferred scenario in terms of cost, CO_2 emission, water, and all-equal analyses. From the perspective of energy, one of the main pillars of this study, S-21 ranks as the most sustainable scenario, whereas S-24 is the most sustainable scenario from the food perspective. The study, therefore, asserts different advisable scenarios for the various existing stakeholders or observers in the case of Matagorda County. All the interventions will have financial cost due to the project costs of interventions if/when the outcomes of the study are applied. However, the benefit will be much greater than cost. In fact, agricultural revenue will increase $32 million annually. The annual extra income of S-9, the most sustainable scenario, provides the opportunity for water planners to enhance economic sustainability while preserving WEF resources through better resource allocation.

CONCLUSIONS

As one of the solutions to anticipated global and regional high demands for primary resources, a new approach, the water-energy-food nexus approach, has received greater scientific attention. The nexus approach asserts that common conventional approaches to water resources planning do not completely include inextricable dynamic linkages of the resources, thus result in a less sustainable future. The WEF nexus model used in this study helps produce advisable scenarios including possible interventions from which stakeholders, observers, and policy makers can then make informed decisions. The Matagorda County case study is well-suited for a nexus approach model: water resources have been under pressure due to electric power production and agricultural production which suffers from diminishing water availability.

The outcomes of the case study indicate that Scenario-9 (S-9) is the most sustainable scenario. S-9 proposes modernizing irrigation systems, reusing wastewater, building a new structure for water storage, altering the cooling system of the energy plant, treating brackish groundwater, and setting up a solar farm. The interventions embedded in S-9 will undoubtedly bring extra financial cost. Ultimately, the benefits outweigh the costs. In fact, annual income in the county increases by $32 million compared to the current "business as usual" scenario, even under extreme conditions, such as drought and high population increase. This financial gain is in the agricultural sector, which has suffered recently due to lack of water. Prosperous agricultural commerce is expected to strengthen other sectors as well: a considerable portion of the population depends on the agriculture sector in Matagorda. Increased irrigated cropland provides increased food production, which actually provides extra income. Along with the financial benefits, the results of the case study indicate that the WEF nexus approach helps preserve primary resources. The annual energy demand from conventional sources is reduced by 21 million kWh. Also, annual demand for water is reduced by 22 million m3. All these benefits are provided without sacrificing existing and planned industrial activities, electric power production and the municipal water supply. In other words, municipal and industrial water supplies meet the demands in any case scenario. All interventions are performed considering environmental, financial and legislative constraints.

Consequently, this study provides water resource planners an opportunity to quantify the tradeoffs between primary resources, and bring all stakeholders to a single basis regarding the use of financial and WEF resources while also protecting the natural environment. Further contributions to the WEF nexus platform built into the study, such as adding environmental responses including water pollution to possible infrastructure interventions and stakeholder willingness can enhance the sensitivity of the model proposed.

AUTHOR CONTRIBUTIONS

MK conceived of the presented idea. MK and RM developed the methodology, developed a tool, and performed the computations. MK, RM, and FO contributed to the design of the research, to the analysis of the results and to the writing of the manuscript.

ACKNOWLEDGMENTS

The authors wish to thank Jordan Buescher for the input to the original scope of the work, Mary Schweitzer for editorial efforts, and Ministry of Agriculture and Forestry of Turkey for their support toward this research. This paper is based in part on a presentation at the XVI World Water Congress in Cancun, Mexico in May 2017, organized by the International Water Resources Association (IWRA) that appeared in the Congress proceedings. We are grateful to the IWRA for permission to use this information.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2019.00003/full#supplementary-material

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

NOTATION LIST

C: Total costs ($)
$CO2_{ag}$: CO2 emission happen in agriculture (ton)
$CO2_{co}$:CO2 emission happen because of cooling water conveyance (ton)
$CO2_{m\&i}$: CO2 emission because of M&I water use (ton)
C_i: Annualized cost of each strategy project ($)
C_j^*: Project cost index
C_j: Project cost for scenario j ($)
$CO2$: Total CO_2 emission (ton)
$CO2_j^*$: Carbon-dioxide index
$CO2_j$: Carbon-dioxide amount for scenario j (ton)
E: Total energy requirements (kWh)
E_{ag} = Energy requirement for all agricultural activities (kWh)
E_{ag}: Energy need for agriculture sector (kWh)
E_{cw} = Energy need for treating and conveying city water (kWh)
E_{desal} Energy need for desalinating and conveying sea or brackish water resources (kWh)
E_{en}: Energy need for water transportation for cooling (kWh)
E_{en-cw}: Energy need for conveying city wastewater (kWh)
E_{en-gw}: Energy need for conveying groundwater water (kWh)
E_{en-sea}: Energy need for conveying seawater (kWh)
E_{en-sw}: Energy need for conveying surface water (kWh)
E_{fo}: Energy requirements for farming operations (kWh)
E_{gw} = Energy requirement for pumping groundwater resources from underground (kWh)
E_i: Various energy consumptions in the nexus (kJ)
E_{in}: Energy needed for industrial water supply (kWh)
E_j^*: Energy index for scenario j
E_j: Energy demand for scenario j (kWh)
$E_{m\&i}$: Energy need for municipal and industrial water supply (kWh)
$E_{m\&i}$: Total energy needed for municipal and industrial water supply (kWh)
E_{mu}: Energy needed for municipal water supply (kWh)
E_{pu-in}: Energy needed for pumping industrial water supply (kWh)
E_{pu-mu}: Energy needed for pumping municipal water supply (kWh)
E_{sw} = Energy requirement for transporting surface water from river or reservoir to farm (kWh)
E_{tr-in}: Energy needed for treating industrial water supply when reuse process applied (kWh)
E_{tr-mu}: Energy needed for treating municipal water supply when reuse process applied (kWh)
F_i: Total yield of a specific crop type (miscellaneous unit)
F_i: Yield of a specific crop (miscellaneous unit)
$\max(W)$: Maximum water demand among all scenarios (m3)
$\max(E)$:Maximum energy demand among all scenarios (kWh)
$\max(R)$: Maximum agricultural revenue among all scenarios ($)
$\max(C)$: Maximum project cost amount among all scenarios ($)
$max(CO2)$: Maximum Carbon-dioxide amount among all scenarios (ton)
L_i: Land allocated for a specific crop (m^2)
U_i: Unit of projected market value ($/miscellaneous unit)
Pop :Population of the study area in a projected year (person)
P_i: Precipitation received during the growing period (m)
R_i: Revenue of a certain crop ($)
R: Total agricultural revenue ($)
R_j^*: Agricultural revenue index
R_j: Agricultural revenue for scenario j ($)
S_i: Seasonal irrigation requirement for a specific crop (m)
W: Total Water Requirements (m^3)
W_h: Water evaporated due to heat dissipation (m^3)
W_{ag}: Total agricultural water requirement (m^3)
W_c: Total water need for all of the crops totally for irrigation scheduling (m^3)
W_{cw}: Volume of city water used for irrigation (m^3)
W_{desal}: Volume of desalinated water used for irrigation (m^3)
W_{en}: Water need for energy production (m^3)
W_{gi}: Green water for a specific crop (m^3)
W_{gw}: Volume of groundwater used for irrigation (m^3)
W_i: Water need for a specific crop (m^3)
W_{ii}: Water need for irrigation scheduling for a certain crop (m^3)
W_{in}: Annual industrial water use (m^3)
W_j^*: Water index for scenario j
W_j: Water demand for scenario j (m3)
W_l: Total annual livestock water requirements (m^3)
W_{ld}: Daily drinking water per head (m^3)
W_{lo}: Other daily water requirements of livestock (m^3)
$W_{m\&i}$: Annual municipal and industrial water use (m^3)
W_{mu}: Municipal water use (m^3)
W_{ne}: Water amount due to natural evaporation from the pond (m^3)
W_{re}: Released water from the cooling pond (m^3) (it is assumed zero due to missing data)
W_{se}: Water goes to groundwater through seepage (m^3)
W_{sw}: Volume of surface water used for irrigation (m^3)
W_t: Total irrigation need (m^3)
W_{wpc}: Annual municipal water use per capita (m^3 / person)
$Y_{Projected}$: Regulated trend of unit values for a certain crop yield (miscellaneous unit/m^2)
Y_i: Unit of projected yield value for a specific crop (miscellaneous unit/m^2)
$Y_{\max}$:Maximum historic unit yield values for a specific crop (miscellaneous unit/m^2)
Y_{trend} :Linear trend of unit yield values for a specific crop (miscellaneous unit/m^2)
Δ: Tons of CO2 per kJ energy (ton/kJ) (Varies depending upon the energy source.
α = Energy needed for unit volume of water, which might include desalination and treatment process depending on water type (kWh/m^3).

frontiers in Environmental Science

POLICY AND PRACTICE REVIEWS
published: 01 March 2019
doi: 10.3389/fenvs.2019.00023

Hydrologic and Agricultural Earth Observations and Modeling for the Water-Food Nexus

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In a globalizing and rapidly-developing world, reliable, sustainable access to water and food are inextricably linked to each other and basic human rights. Achieving security and sustainability in both requires recognition of these linkages, as well as continued innovations in both science and policy. We present case studies of how Earth observations are being used in applications at the nexus of water and food security: crop monitoring in support of G20 global market assessments, water stress early warning for USAID, soil moisture monitoring for USDA's Foreign Agricultural Service, and identifying food security vulnerabilities for climate change assessments for the UN and the UK international development agency. These case studies demonstrate that Earth observations are essential for providing the data and scalability to monitor relevant indicators across space and time, as well as understanding agriculture, the hydrological cycle, and the water-food nexus. The described projects follow the guidelines for co-developing useable knowledge for sustainable development policy. We show how working closely with stakeholders is essential for transforming NASA Earth observations into accurate, timely, and relevant information for water-food nexus decision support. We conclude with recommendations for continued efforts in using Earth observations for addressing the water-food nexus and the need to incorporate the role of energy for improved food and water security assessments.

Keywords: Earth observations, water-food nexus, NASA, food security, water security, modeling, applications

OPEN ACCESS

Edited by:
Jill A. Engel-Cox, National Renewable Energy Laboratory (DOE), United States

Reviewed by:
Stefanos Xenarios, Nazarbayev University, Kazakhstan
Sushel Unninayar, Morgan State University, United States

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Specialty section:
This article was submitted to Freshwater Science, a section of the journal Frontiers in Environmental Science

Received: *29 August 2018*
Accepted: *07 February 2019*
Published: *01 March 2019*

Citation:
McNally A, McCartney S, Ruane AC, Mladenova IE, Whitcraft AK, Becker-Reshef I, Bolten JD, Peters-Lidard CD, Rosenzweig C and Uz SS (2019) Hydrologic and Agricultural Earth Observations and Modeling for the Water-Food Nexus. Front. Environ. Sci. 7:23. doi: 10.3389/fenvs.2019.00023

INTRODUCTION

In a globalizing and rapidly-developing world, reliable and sustainable access to water, food, and energy are inextricably linked to each other and basic human rights. With world population estimated to reach between 9 and 10 billion by mid-century (UN DESA, 2015), demand for water and food is estimated to increase by 40 and 35%, respectively by 2030 (U. S. National Intelligence Council, 2013). Globally, the agricultural sector consumes on average two-thirds of accessible freshwater on the planet (Clay, 2004; Prince and Fantom, 2014). Agriculture further impacts water resources through land degradation, changes in runoff, and unsustainable use of ground water (Alauddin and Quiggin, 2008). Given the magnitude of the challenge of providing safe and reliable access to water and food a system-wise approach is required to protect against current and future risks of insecurity.

The linkages between water, food, and energy make sustainability and security difficult to disentangle. A "nexus" approach is required that recognizes the interdependencies across sectors for optimizing resources sustainably (Rasul and Sharma, 2016). The United Nations (UN) now states "The water-food-energy nexus is central to sustainable development...The inextricable linkages between these critical domains require a suitably integrated approach to ensuring water and food security, and sustainable agriculture and energy production worldwide" (http://www.unwater.org/water-facts/water-food-and-energy/).

The idea for a nexus approach was introduced at the Bonn 2011 Nexus Conference (Endo et al., 2017), a meeting organized by the German government in preparation for the UN Conference on Sustainable Development, known as Rio+20. The objective of the Bonn 2011 Nexus Conference was to brainstorm solutions to complex, sustainable development problems and to develop recommendations for improving upon the previous UN Earth Summit, Rio1992, which fell short of delivering on its sustainable development goals. As a result of Bonn 2011, the nexus emerged to challenge existing international, national, and sub-national policies, and transition from a sectoral approach to solutions that embrace a cross-sectoral, coherent, and integrated perspective. Moreover, an integrated approach helps decision-makers address externalities and trade-offs between food, water, and energy sectors such as: the degradation of ecosystem services; rapidly increasing demand for resources through population growth; an expanding middle class, with changes in diets; urbanization; globalization; and climate change (Hoff, 2011).

Given the global and cross-scale nature of the water-food-energy nexus, Earth observations (EO) from satellites and models have made important contributions to both scientific research and decision-making. Agriculture is inherently a nexus issue,

Water security

The United Nations University (2013) defined water security as "…the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability."

Food security

The UN Food and Agriculture Organization (FAO) defined food security as "…when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food which meets their dietary needs and food preferences for an active and healthy life." (World Food Summit, 1996).

and EO have a history in addressing agriculture and the water-food nexus. Since the launch of the National Aeronautics and Space Administration's (NASA) first Landsat mission (originally named Earth Resources Technology Satellite [ERTS]) in 1972, global agricultural monitoring has been one of the longest operational applications for satellite imagery (Leslie et al., 2017). By 1979, the National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) multispectral instrument allowed for monitoring vegetation greenness from space, with global coverage on a daily basis. AVHRR allowed scientists to create vegetation indices such as the Normalized Difference Vegetation Index (NDVI) for monitoring seasonal changes in vegetation condition (phenology), as well as drought stress derived from NDVI anomalies (Anyamba and Tucker, 2012). Along with the rise in EO have come rapid increases in high-performance computational resources, which favor the open development and execution of Earth system models customized for agricultural and water resources modeling [e.g., NASA Goddard Earth Observing System Model (GEOS-5; Rienecker et al., 2008), NASA Goddard Institute for Space Studies Model-E (Schmidt et al., 2014), and NASA Land Information System (LIS; Kumar et al., 2006)]. In the context of crop yields, **Figure 1** is a schematic of how retrospective datasets and their near-real time production can provide water-food nexus decision support. Meanwhile, forecasts require a probabilistic perspective as uncertainties interact across climate and crop response models, providing alternative scenarios for decision support.

In addition to state-of-the-art technology, NASA uses an applications approach to missions, fostering innovative uses of NASA EO in organizations' policy decisions for societal benefit (Brown et al., 2013; Brown and Escobar, 2014). This is accomplished by following guidelines for the co-production of useable knowledge in sustainable development (Clark et al., 2016). Commitment to this approach is demonstrated by the Group on Earth Observations, a voluntary organization comprised of intergovernmental, international, and regional organizations (GEO, 2005), which promotes the use of EO in sustainable development policy. GEO has a Water-Energy-Food (W-E-F) Community Activity, which uses EO, analytics, and new governance approaches to integrate across the water, energy, and food sectors. Objectives are to develop new datasets and applications and to enable their integration for the W-E-F nexus to benefit the water, energy, and food Sustainable Development

Abbreviations: AgMIP, Agricultural Model Intercomparison and Improvement Project; AMIS, Agricultural Market Information System; CADRE, Crop Condition Data Retrieval and Evaluation database; CGRA, Coordinated Global and Regional Assessments; CM4AMIS, Crop Monitor for AMIS; CM4EW, Crop Monitor for Early Warning; CMIP, Coupled Model Intercomparison Project; EC JRC, European Commission Joint Research Centre; ECMWF, European Centre for Medium-Range Weather Forecasts; EO, Earth observations; ESA, European Space Agency; FAO, UN Food and Agriculture Organization; FAS, Foreign Agriculture Service; FEWS NET, Famine Early Warning Systems Network; FLDAS, FEWS NET Land Data Assimilation System; G20, Group of Twenty - 19 countries and the European Union; GEO, Group on Earth Observations; GEOSS, Global Earth Observation System of Systems; GEOGLAM, GEO Global Agricultural Monitoring; GEOGLOWS, GEO Global Water Sustainability; GLAM, Global Agricultural Monitoring; MODIS, Moderate Resolution Imaging Spectrometer; NASA, National Aeronautics and Space Administration; NCEP, NOAA National Center for Environmental Prediction; NDVI, Normalized Difference Vegetation Index; NOAA, National Oceanic and Atmospheric Administration; PM, Palmer Model; RAPs, Representative Agricultural Pathways; SDGs, Sustainable Development Goals; SMAP, Soil Moisture Active Passive; SMOS, Soil Moisture Ocean Salinity; USDA, US Department of Agriculture; USGS, US Geological Survey; W-E-F, Water Energy Food; WFP, World Food Program; USAID, US Agency for International Development; UN, United Nations.

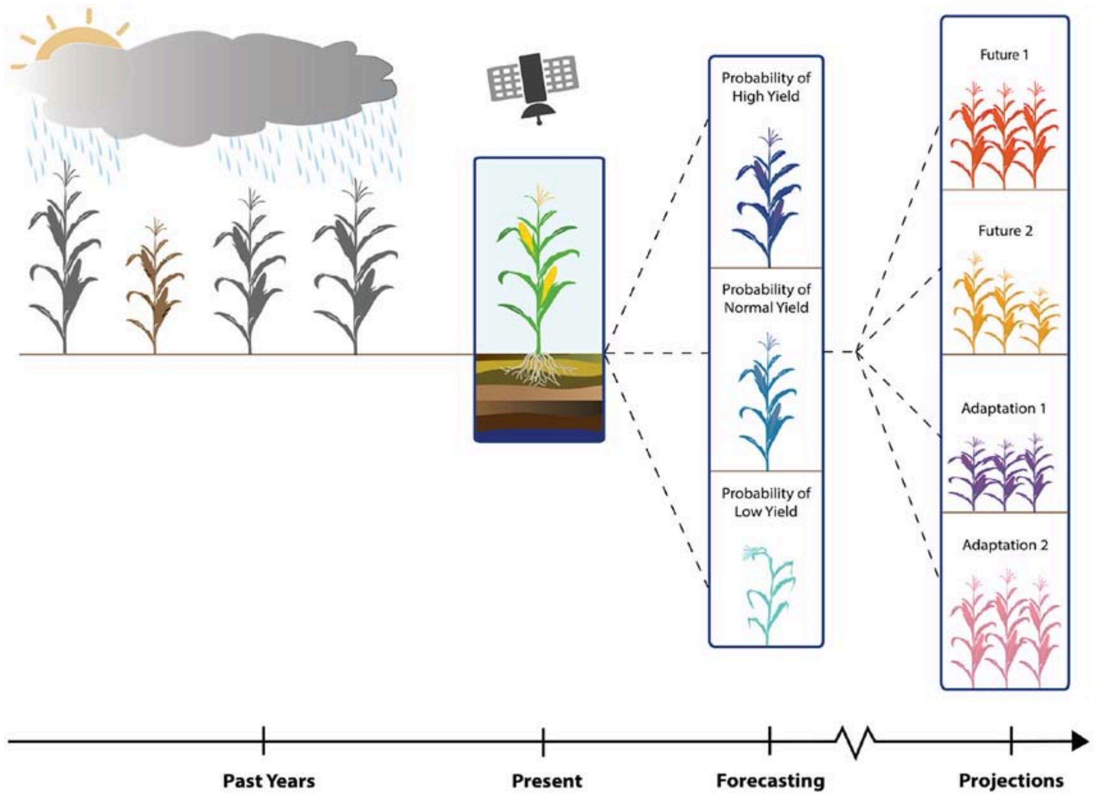

FIGURE 1 | Retrospective, real-time, forecast, and projection modes for agricultural applications. Resources include weather observations, satellites, and crop model projections. The focus is on understanding historical anomalies, providing detail on current state, providing probabilistic forecasts, and projecting alternate scenarios affected by factors within and beyond the farming system.

Goals (SDGs; GEO, 2016). Data sharing among these initiatives is promoted through The Global Earth Observation System of Systems (GEOSS), which aims to build a Community of Practice around enhancing stakeholder engagement, and improving *in situ* measurements, data assimilation, and modeling capabilities (Lawford et al., 2013). The GEO W-E-F activity builds upon the success of the GEO Global Agricultural Monitoring (GEOGLAM) Initiative (detailed in section Crop Monitors for AMIS and Early Warning) as well as the GEO Global Water Sustainability (GEOGLOWS) water activities that use EO to mitigate hydrologic extremes and degraded water quality.

Given the global and cross-scale nature of agriculture and the water-food nexus, EO from satellites are essential for providing the data and scalability to monitor relevant indicators across space and time. This improved understanding of agriculture and the hydrological cycle can provide water-food nexus decision support. The case studies presented below provide insight into how these initiatives promote the transformation of EO into usable knowledge for sustainable development policy.

APPLICATION CASE STUDIES

The following case studies provide real-world examples of scientists and end-users following the guidelines for co-developing useable knowledge for sustainable development (Clark et al., 2016), in the context of food and water security. The sustained partnerships with decision makers allow us, as EO researchers, to continuously provide state-of-the-art products that stakeholders deem accurate, credible, and legitimate, and thus support decision-making and policy. The extent to which end-users adopt a water-food nexus approach will guide their information requests and, in turn, the products that EO scientists provide. Beyond the direct stakeholders these data are made publicly available which enhances transparency, and potential for innovations from the broader water-food nexus community of researchers and policy makers. The case studies largely ignore the energy component of food and water security. In the paper's conclusions we discuss how greater consideration of energy could strengthen EO's role in food and water decision-making.

Crop Monitors for AMIS and Early Warning

When food prices spiked in 2011, the G20 decided to act against food price volatility, promote market transparency, and to improve early warnings of crop shortages and failures. Given the long history of EO and agriculture, they requested a proposal from the GEO Agricultural Monitoring Community of Practice (Becker-Reshef et al., 2010) to use satellite-based EO to enhance crop production projections. From this, the GEO Global Agricultural Monitoring Initiative (GEOGLAM) and Agricultural Market Information System (AMIS), were born, and endorsed by the G20 through its 2011 Action Plan on Food Price Volatility and Markets. Together these programs provide timely and transparent information on agricultural markets (Parihar et al., 2012; Whitcraft et al., 2015a). In 2012, the world again witnessed simultaneous declines in crop conditions across multiple important grain producing areas: the United States, Kazakhstan, and Russia. GEOGLAM's use of NASA's MODIS NDVI anomaly via the Global Agricultural Monitoring (GLAM) system enabled one of the earliest detections of this major food production issue (Becker-Reshef et al., 2010).

The synoptic, early warnings provided by EO positively impacted both food security and market stability by empowering policy makers and farmers to formulate food security action plans before crisis hit. Given this success, GEOGLAM launched the monthly, global Crop Monitor for AMIS (CM4AMIS). Operational since September 2013, the CM4AMIS leverages existing monitoring systems to build international consensus around the conditions of wheat, maize, soybean, and rice in the countries responsible for >80% of production. The Crop Monitor consensus building process, informed by EO, has the capacity to account for water and energy constraints on agricultural production. National and regional assessments are based on expert opinion and field campaigns/surveys (if available) combined with baseline datasets (crop type mask and crop calendars). To assess spatially varying crop and water conditions experts rely on EO datasets including NASA MODIS-based NDVI and NDVI anomaly (Bréon and Vermote, 2012), NOAA NCEP Reanalysis 2 Temperature Anomaly and Precipitation Anomaly (Kistler et al., 2001; Kanamitsu et al., 2002), European Centre for Medium-Range Weather Forecasts (ECMWF) Cumulative Temperature Anomaly and Precipitation Anomaly (Matricardi et al., 2004; Berrisford et al., 2011; Dee et al., 2011), Soil Moisture Anomaly from the European Space Agency (ESA) Soil Moisture Ocean Salinity (SMOS) retrievals processed by NOAA NESDIS (Reichle et al., 2008; Bolten et al., 2010; Kerr et al., 2012), EUMETSAT Soil Water Index Anomaly from ASCAT scatterometer onboard the Metop-A satellite (Wagner et al., 1999; Bartalis et al., 2006; Naeimi et al., 2009), USDA-NOAA Evaporative Stress Index based on modeled output and geostationary observations (Anderson et al., 2007, 2010), and USGS Actual Evapotranspiration Anomaly (Senay et al., 2013). In the future, products from the Harmonized Landsat and Sentinel dataset (Claverie et al., 2018) will be used, which can resolve phenomenon like irrigation. We acknowledge that remotely estimates are limited by their different characteristics (e.g., optical sensor temperature retrievals require cloud free conditions, which may be rare during the rainy season). Because of this, convergence of evidence and expert opinion are required to synthesize the best possible information.

The outcome of the Crop Monitor process are maps of conditions and their associated drivers (wet, dry, hot, cold, extreme event), textual summaries of conditions (excellent, favorable, watch, poor), and pie charts that show conditions of crops by share of global production and global exports (**Figures 2A,B**). These monthly reports, released the first Thursday of each month for conditions as of the 28th of the previous month, provide qualitative assessments of conditions, which provide intuitive, readily comprehensible snapshots of global crop conditions to a non-EO community. As of June 2018, the CM4AMIS has nearly 40 partners from around the world reporting on their countries and regions of expertise, and has become a trusted source of information for AMIS, National Ministries of Agriculture, and those interested in grain markets.

In 2016, building on the utility and impact of the CM4AMIS, GEOGLAM launched the Crop Monitor for Early Warning (CM4EW) with the early warning community, including Famine Early Warning Systems Network (FEWS NET), European Commission Joint Research Centre (EC JRC), and World Food Program (WFP). The CM4EW focuses on countries at risk of food insecurity, water insecurity and their relevant crops and drivers. The CM4EW utilizes the same input data, and consideration of expert opinion and consensus as the CM4AMIS (**Figures 3A,B**). While expert opinion may implicitly include water and energy considerations, contributors to the CM4EW explicitly include additional drivers in their regional assessments: delayed onset of rainy season, pests and disease, and socio-political factors (see legend in **Figure 3B**), all of which may be influenced by water and energy availability. The CM4EW has directly resulted in several examples of policy and action to strengthen food security. The unique convening power of the GEOGLAM Crop Monitor system enabled the UN FAO, the EC JRC, the WFP, and the FEWS NET to, in February 2016, release a joint statement on the dire outlooks for food supply in southern Africa as a result of the strong 2015–2016 El Niño (UN FAO, 2016). By April 2016, USAID's Office of Food for Peace provided USD 47.2 million in emergency food assistance and the Government of Lesotho provided an additional USD 10 million to address food, water, health and sanitation needs (USAID, 2016).

Most recently, the Crop Monitor has been implemented operationally at the national level in Tanzania and Uganda, as well as Kenya and Vietnam (in development, as of June 2018). In May 2017, the CM4EW revealed Uganda was vulnerable to widespread crop failure due to drought (Uganda Department of Relief Disaster Preparedness, and Management, 2017). This information was used to trigger USD 4 million from the Disaster Risk Financing fund to create temporary employment and offset agricultural losses by supporting 31,386 households (∼150,000 people) in Karamoja region. Early season satellite data, provided by the Crop Monitor, provided clear evidence of impending crop failure allowing policy makers to act proactively rather than reactively, as has been the case in the past (Martin Owor, Commissioner in the Office of the Prime Minister Uganda personal communication; 17 April, 2018). This end-user feedback demonstrates the value added to international food security by the EO and international consensus work that characterizes the GEOGLAM Crop Monitor.

Moving forward, the Crop Monitor will continue regional and national implementation and develop international "system of systems." Additional efforts will investigate the use of quantitative indicators of crop conditions that consider the interlinkages between food, water, and energy systems for improved production outlooks.

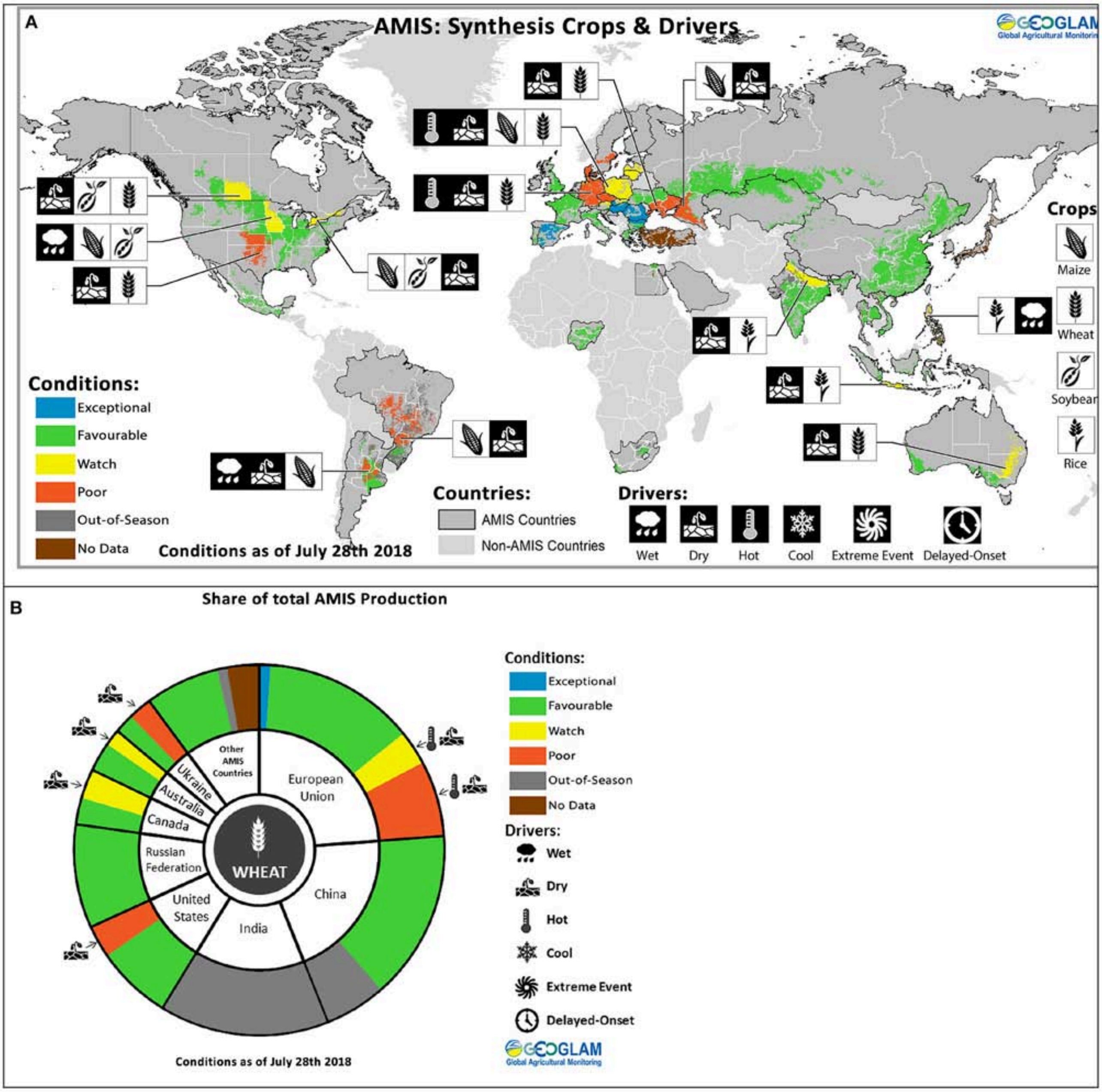

FIGURE 2 | (A) July 2018 CM4AMIS contains maps of conditions and their associated drivers (wet, dry, hot, cold, extreme event). **(B)** Pie charts show conditions of specific crops, e.g., July 2018 wheat, by share of global production and global exports.

Water Availability Monitoring for Food and Water Security

Remotely sensed rainfall, vegetation, soil moisture, and temperature data are critical for organizations that monitor agricultural conditions and food security (see also sections Crop Monitors for AMIS and Early Warning and Improving the USDA-FAS Soil Water Information). Until recently, however, less attention has been given to the water security dimension of food security. To address this gap in monitoring and forecasting, FEWS NET and NASA are co-developing the FEWS NET Land Data Assimilation System (FLDAS; McNally et al., 2017). FLDAS uses remotely sensed and reanalysis inputs to drive land surface (hydrologic) models, to produce a global archive of historic hydroclimate conditions as well as routine updates for monitoring current events (1982-present). These data are publicly available from NASA Goddard Earth Science Data and Information Services Center.

In addition to routine modeling, the FEWS NET team at NASA Goddard Space Flight Center's Hydrological Sciences Laboratory maps water availability for the African continent at

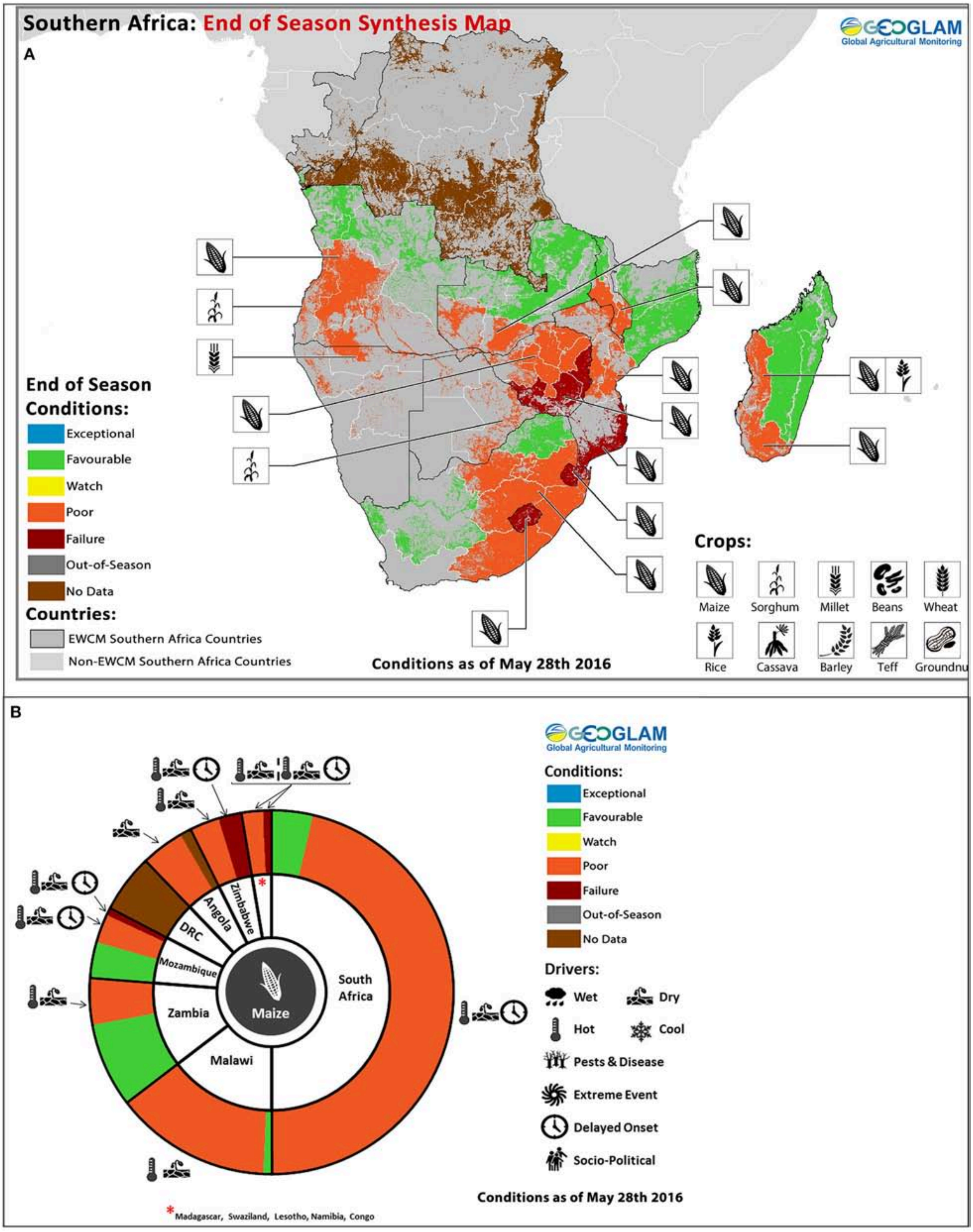

FIGURE 3 | (A) CM4EW synthesis map for Southern Africa, May 2016. CM4EW reports contain the same information as CM4AMIS, and additionally include a "failure" condition when production is expected to be >25% below average, as well as additional drivers: delayed onset of rainy season, pests and disease, and socio-political factors. **(B)** Pie charts show conditions of crops, e.g., May 2016 maize, by share of national production.

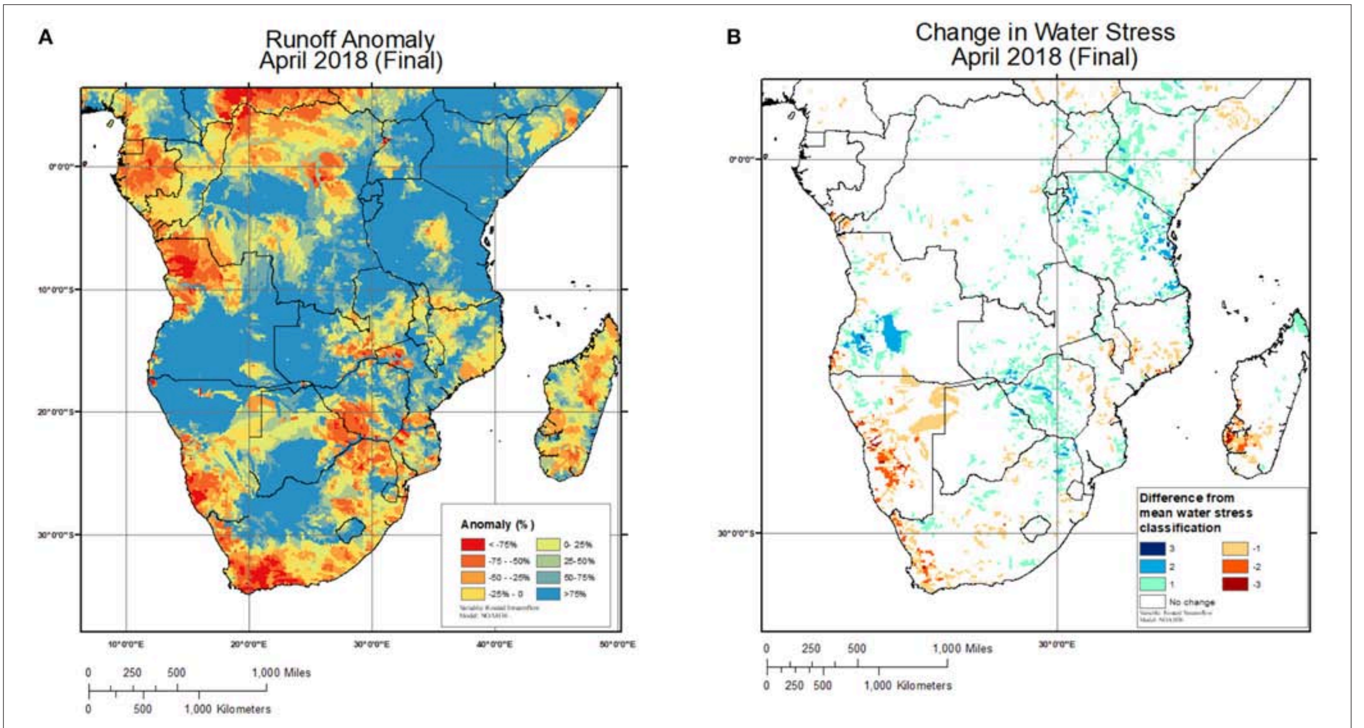

FIGURE 4 | (A) Streamflow anomalies show surplus for much of the region, and 0–75% basin average streamflow deficits for April 2018 in Southern Madagascar. **(B)** Water Stress Change, based on annual Falkenmark classifications show that Southern Madagascar (and Western Cape) is 1–3 classes more stressed than a typical April. Maps updated twice a month at https://lis.gsfc.nasa.gov/projects/fewsnet-southern-africa.

a monthly scale, both in terms of monthly streamflow anomaly and annual water stress, i.e., streamflow per capita (**Figure 4A**). A novel aspect of the water stress product is that it tracks water availability in terms of volumetric water requirements for human (domestic) demands. Meanwhile, the streamflow anomaly maps contextualize current conditions in terms of the historic mean (1982–2016), which is a more traditional approach to drought monitoring.

To generate these maps, FLDAS total runoff drives the HYMAP2 routing scheme (Getirana et al., 2017) to produce streamflow (m^3/s). The average of the routed streamflow is calculated for each Pfafstetter basin level 6 from the USGS Hydrologic Derivatives for Modeling Applications database (Verdin, 2017) and this average is converted to a volume of water per month (m^3). The given month's anomalies are computed, as a percent of that month's historic mean, and shown in the "Runoff Anomaly" map (**Figure 4A**). Next, streamflow per capita is computed using WorldPop Africa 2015 population estimates (Linard et al., 2012), aggregated to the Pfafstetter basin level 6. Basin level monthly streamflow is then divided by basin level population estimates to derive streamflow per capita. Using the current and 11-months previous accumulation, streamflow per capita is classified per Falkenmark (1989) water supply thresholds. Finally, the difference from average class is computed for a given month and mapped (**Figure 4B**), highlighting locations where current and previous 11-months streamflow conditions depart from a basin's average water stress classification. Together these maps provide shorter and longer-term perspectives on water availability.

In general, these products are best used for bi-monthly monitoring and situational awareness, examples of which are in FEWS NET special reports (FEWS NET, 2015, 2016, 2017) to illustrate the severity and extent of recent droughts in sub-Saharan Africa. FLDAS outputs are well-correlated with remotely sensed ET and soil moisture ($R > 0.7$) (McNally et al., 2016, 2017) and accurately represented the water balance in the Blue Nile Basin, Ethiopia (Jung et al., 2017) in terms of remotely sensed ET ($R = 0.9$), total water storage ($R = 0.86$), and streamflow ($R = 0.9$). Given that these data are publicly available a growing body of literature is utilizing and evaluating the data (e.g., Philip et al., 2017). It should be noted that in evaluations and applications, a basin's water availability estimates may be limited by constraints related to the remotely sensed inputs and the hydrologic models. Currently, abstractions (e.g., irrigation) are not modeled which would influence the accuracy of soil moisture, ET, and streamflow estimates. The quality of the meteorological inputs is also a factor. CHIRPS precipitation, input to FLDAS, has been shown to perform well in Africa (Funk et al., 2015), but some locations that lack rain gauges may have large errors. Moreover, the operational FLDAS models (Noah36 and VIC412) represent naturalized streamflow and do not represent impoundments (e.g., dams), or groundwater, which may be important water sources for some communities. That said, adjusting the time scale of analysis does compensate for some of these shortcomings. For example, water stress based on a 12-month accumulation can capture deficits to groundwater and reservoirs.

The water stress and streamflow anomaly maps provide an example application that highlights the relationship between food and water in Southern Africa. The 1-month streamflow anomaly (**Figure 4A**) shows "short term" positive anomalies across much of the domain. The 12-month Stress Anomaly maps (**Figure 4B**) shows that these positive anomalies have increased water availability in Zimbabwe, Tanzania, and Kenya. However, this short term wetness was not enough to positively impact longer-term water availability across much of the region, particularly Southern Madagascar, the Western Cape, and Namibia, that were 1–3 classes more stressed than normal.

Well before 2018 below-average cumulative rainfall during the 2014–2015 rainy season in Southern Africa set the stage for water deficits with below average monthly rainfall and streamflow. The following year, the 2015–2016 El Niño and associated drought had a severe negative impact on agricultural outcomes across much of Southern Africa (FEWS NET, 2016), including Botswana, Swaziland, Southern Madagascar, Southern Mozambique, and the maize-triangle region of South Africa (see section Crop Monitors for AMIS and Early Warning). While more localized, the 2016–2017 rainy season registered below average rainfall for the Western Cape region (see section Improving the USDA-FAS Soil Water Information), and Southern Madagascar. The 2017–2018 season also registered below average rainfall across the region (see section Crop Monitors for AMIS and Early Warning). By June 2018, FEWS NET reported that consecutive years of below average rainfall had reduced agricultural production and incomes in several Southern Africa countries, and a Water Aid (2018) warned that water scarcity in Southern Madagascar and Southern Mozambique could reach Cape Town's feared, "Day Zero" proportions (i.e., taps run dry and people are required to queue for water).

A time series from the FLDAS archive (**Figure 5**) confirms that 2015–2016 was Southern Madagascar's second-worst season in the 35-year record in terms of rainfall and that annual runoff has been trending downward since 2010–2011. It is useful to look at both rainfall and runoff, given their non-linear relationship, when assessing water availability. The FEWS NET (2018a) reports "stressed" and "crisis" conditions in Southern Madagascar for the June-September 2018 and October-January 2019 period, highlighting lack of water availability for people and livestock (FEWS NET, 2018b). Contributing to this dire outlook was that as early as July 2018, El Niño conditions were forecasted for late 2018 and early 2019, increasing the likelihood for a delayed start of the rainy season (delaying crop planting), and below average rainfall totals (exacerbating water availability deficits). Working with the FEWS NET Southern Africa field scientist, these data will be used to monitor the situation and communicate in the Food Security Outlooks how local water availability relates to regional food security.

Improving the USDA-FAS Soil Water Information

The main objective of US Department of Agriculture Foreign Agricultural Service (USDA-FAS) is to provide timely information on current and expected agricultural supply and demand estimates. The water-food nexus approach is inherent, as they utilize and publicly provide information on the environmental conditions that influence agricultural supply, and combine this with other economic and policy information to produce estimates, that ultimately feedback into policy making. The USDA World Agricultural Outlook Board (WAOB) produces monthly forecasts of the global monthly crop condition assessments carefully compiled by USDA-FAS and posts to the public-facing Crop Explorer website (https://ipad.fas.usda.gov/cropexplorer/). The agency's regional and global crop yield forecasts are based on a large variety of agro-meteorological parameters and physically-based models compiled in the Crop Condition Data Retrieval and Evaluation (CADRE) Data Base Management System (DBMS). CADRE is a comprehensive geospatial database that utilizes remote sensing imagery, meteorological data, and *in situ* observations to produce preliminary crop condition and yield production estimates. Proper crop growth and development is largely dependent on the amount of water present in the root-zone. Therefore, a critical concern for the USDA-FAS analysts is to capture the impact of agricultural drought on crop development and health, and the resulting yield production. Since soil moisture is known to be a leading indicator of future crop conditions, the value of a robust soil moisture-based assessment within the historical climate context has proven to be critically important for the CADRE database (Bolten and Crow, 2012; Mladenova et al., 2017). The baseline soil moisture estimates in CADRE are developed using the modified two-layer Palmer model (PM), which is a water balance-based hydrologic model driven by daily precipitation data and minimum and maximum temperature observations (Palmer, 1965). PM produces global daily soil moisture estimates, whose accuracy is primarily driven by the quality of the precipitation data. This has been problematic over areas with limited gauge or poor-quality precipitation data that may not detect weather extremes. Agricultural drought, associated with the lack of water or soil saturation and floods (i.e., abundance of water), can have detrimental impact on crop growth and yield production.

To improve CADRE root-zone soil moisture estimates where there are precipitation-related errors, NASA has been working with USDA-FAS on the integration of surface soil moisture retrievals obtained using satellite-based remote sensing. The approach has been applied to the USDA-FAS Palmer model and the CADRE root-zone soil moisture information has been enhanced by the integration of soil moisture retrievals derived using observations acquired by NASA's Soil Moisture Active Passive (SMAP) mission (Entekhabi et al., 2010; Crow et al., 2012; Chan et al., 2016). SMAP's passive only retrievals are ingested into the PM using the Enhanced Kalman Filter (EnKF) technique, where the satellite-based surface soil moisture information is transferred into the models' sub-surface (i.e., root-zone) layer through a sampled error covariance matrix that reflects the error characteristics of both the model estimates and the satellite observations (Bolten et al., 2010; Han et al., 2014). The USDA-FAS crop analysts extract timely and essential information on changes in soil moisture conditions from root-zone soil moisture anomaly maps. It should be noted that in evaluations and applications, soil moisture estimates might be

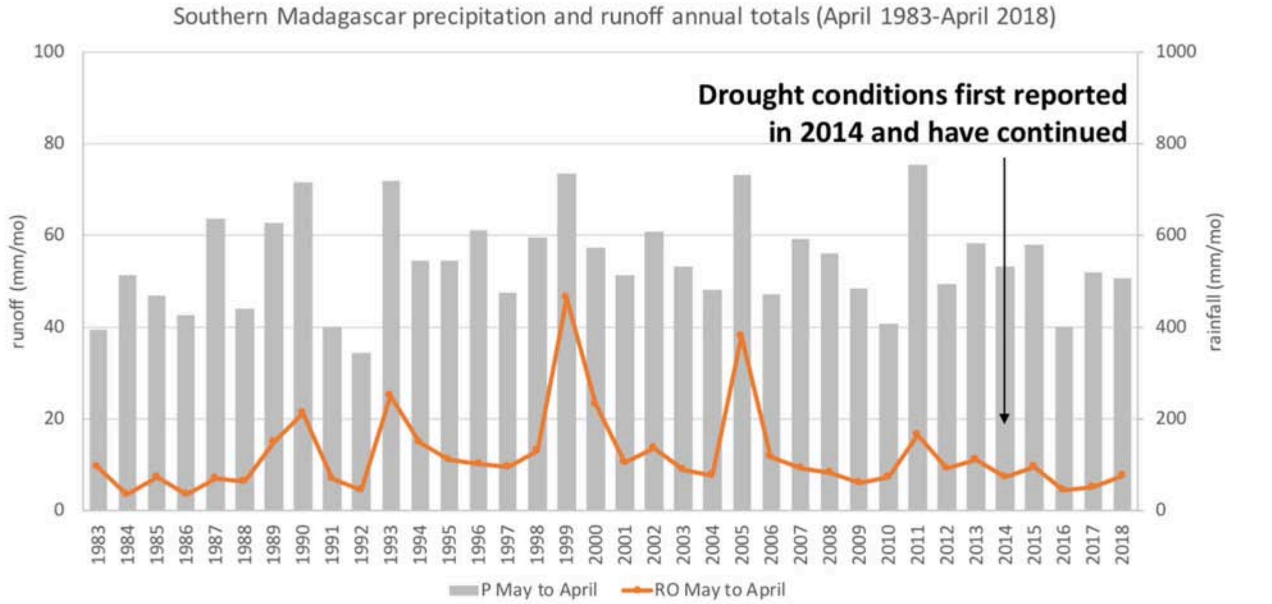

FIGURE 5 | Twelve-month precipitation and runoff spatially averaged over the Tsihombe basin, Southern Madagascar. 2016 was the second-worst year in the 35-year record. FEWS NET reports consecutive years of below average rainfall, and water availability deficits have reduced agricultural production and incomes.

limited by constraints related to the remotely sensed inputs and the hydrologic model. In addition to the shortcomings in satellite precipitation mentioned earlier, microwave soil moisture retrievals have larger errors when dense vegetation is present. Meanwhile, the Palmer model is a simple water balance model that may not represent local hydrologic complexity. Despite these limitations this system has been demonstrating its utility in an operational setting.

An example of root-zone soil moisture maps developed by the SMAP-enhanced PM over South Africa are shown in **Figure 6**. The Western Cape, a province located in the southern part of South Africa is the country's largest wheat-growing region. Winter cereals in the area are typically planted in May and harvested in October. The Western Cape has suffered a critical drought that impacted the 2017 growing season, which has been associated with record low rainfall, high temperatures, and high evaporation rates. The decline in moisture conditions during 2017 (**Figure 6**) would cause 29% reduction in wheat yield relative to the previous year based on the USDA-FAS reported estimates published in February 2018 (U. S. Department of Agriculture - Foreign Agricultural Service, 2018) This would consequently have a large impact on food security, social well-being, and loss of income in the area, the management of which would require financial investments and socio-economic support.

Throughout the process, USDA-FAS has worked with NASA to identify the problem (rainfall errors), and develop a solution to meet analyst needs. The careful integration of near real-time satellite-based soil moisture observations into the USDA decision support system allows USDA-FAS analysts to compare current soil moisture and crop conditions and develop a more comprehensive assessment of expected agricultural yield in many areas of the world that currently lack adequate ground-based observations. The continued partnership allows NASA remotely sensed soil moisture to be transformed into useable knowledge while USDA-FAS will continue to benefit from ongoing improvements related to NASA EO.

Modeling Agricultural Impacts Across Time Horizons

In addition to providing estimates of water availability and soil moisture, EO can be linked with biophysical and socioeconomic agricultural modeling frameworks that elucidate historical, current, and future challenges in the water-food nexus. To accomplish this, NASA scientists launched the Agricultural Model Intercomparison and Improvement Project (AgMIP) in 2010 to provide enhanced community organization around systematic intercomparison and stakeholder-driven applications of agricultural models to address food security (Rosenzweig et al., 2013). AgMIP's global community utilizes climate, crop, livestock, economics, and nutrition models to understand interactions between biophysical and socioeconomic systems, dependencies across local and global markets, and the shifting nature of impacts and risk across time horizons. The result is a series of models and tools that may be applied individually or as part of AgMIP's Coordinated Global and Regional Assessments (CGRA), a multi-discipline, multi-scale, multi-model, and multi-institution framework to address major challenges in adaptation, mitigation, food security, and food policy.

NASA observational products provide a critical foundation for modeling agricultural systems, as these assessments are rooted in the distillation of historical climate information and the creation of future climate change projections. The need for a consistent historical climate record led to the

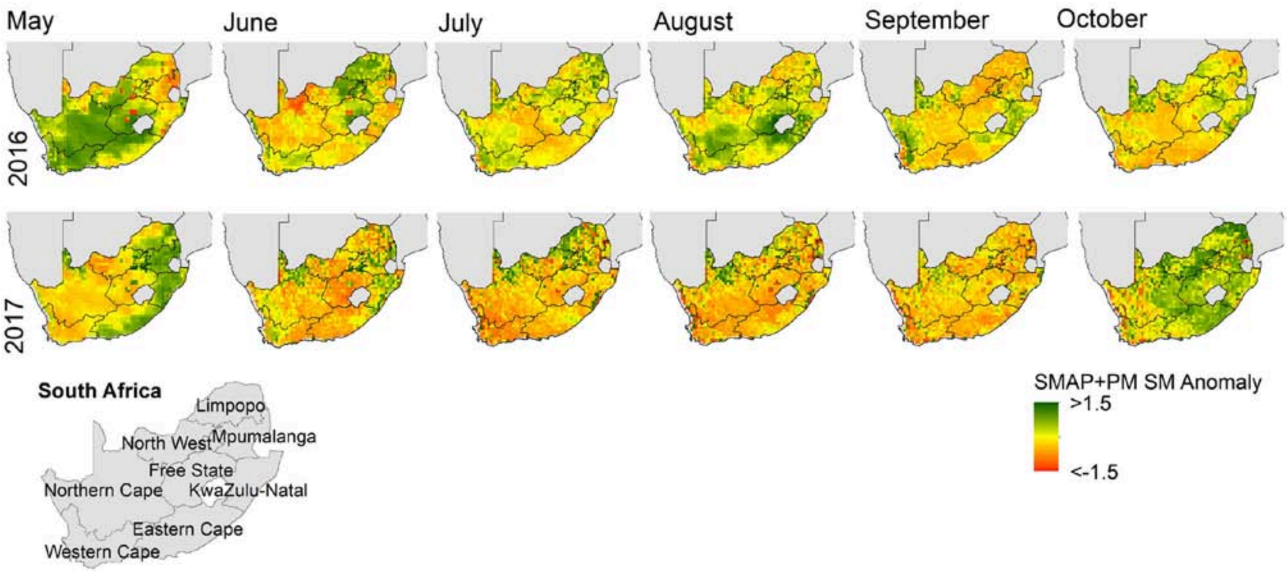

FIGURE 6 | Monthly root-zone soil moisture anomaly conditions over South Africa during the 2016 and 2017 growing seasons (May–October). Each value shows the deviation of the current conditions relative to the long-term average standardized by the climatological standard deviation. Negative values indicate that the current conditions are below average, while positive indicate surplus of water.

development of an agricultural modeling-oriented version of the NASA Modern Era Retrospective-analysis for Research and Applications (AgMERRA; Ruane et al., 2015). And to assess future conditions AgMIP models utilizes climate scenarios derived from the ensemble of Earth system models (ESMs) contributed to the Coupled Model Intercomparison Project with CMIP (Taylor et al., 2011; Eyring et al., 2015) and the NASA Goddard Institute for Space Studies Model-E (Schmidt et al., 2014). The application of global process-based crop models sheds light on strong differences in crop production and vulnerability across regions and farming systems. For example, the parallel Decision Support System for Agrotechnology Transfer (pDSSAT) model (Elliott et al., 2014) was used to simulate global, spatially distributed yield response to a 20% reduction in precipitation (**Figure 7**). A majority of pixels, with at least 10 hectares of rainfall maize, experience 0–30% loss in yields with 20% reduction in precipitation (brown colors, **Figure 7**). There are however, some areas with positive response to rainfall reduction, particularly in the wettest portions of the humid tropics (portions of the Brazilian interior, Bangladesh, and parts of the Congo Basin). These locations have plentiful water and therefore have sufficient amounts even with a substantial (20%) reduction, and the lower precipitation levels also have reduced runoff, fertilizer leaching, and soil erosion, which can have a slight benefit for yields. This type of information, generated as part of AgMIP's Global Gridded Crop Model Intercomparison (GGCMI phase 2; Elliott et al., 2015), motivates stakeholder interventions to increase resilience and reduce food security risks. Similar to previous case studies, we acknowledge there are sources of uncertainty from remotely sensed inputs or hydrologic parameters. Additional uncertainty is introduced in the modeling of crop yields, which requires information on crop parameters and farm management practices. Over time, and with partner cooperation, accuracy of these inputs will improve, but some error will remain. That said, water-food nexus stakeholders can still benefit from the exploration of future scenarios.

The process-based crop modeling community fostered by AgMIP provides an important perspective to stakeholder-oriented applications for food security and the water-food nexus. Stakeholders need information and understanding of agricultural systems across a continuum of time horizons (**Table 1**). Agricultural sector stakeholders are under high pressure to maintain high awareness of present field conditions and seek an improved understanding of past years' crops (e.g., farmers, disaster risk reduction community, commodities traders). Near term outlooks are important for an early indication of seasonal production and water consumption and the long-term outlooks help to manage complex risks, anticipate emerging opportunities, and ensure the viability of current resources and long-term investments.

Two cases exemplify the utility of AgMIP approaches for stakeholders. First, AgMIP partnered with the UK Department for International Development to assess the intertwining influences of socioeconomic development, climate change, and technological adaptation for vulnerable farming systems across 15 countries in sub-Saharan Africa and South Asia (Rosenzweig and Hillel, 2015). AgMIP partners worked closely with local stakeholders (regional and national ministries, development agencies, non-governmental organizations, farmers groups, and farm supply companies) to co-develop representative agricultural pathways (RAPs; Valdivia et al., 2015) indicating

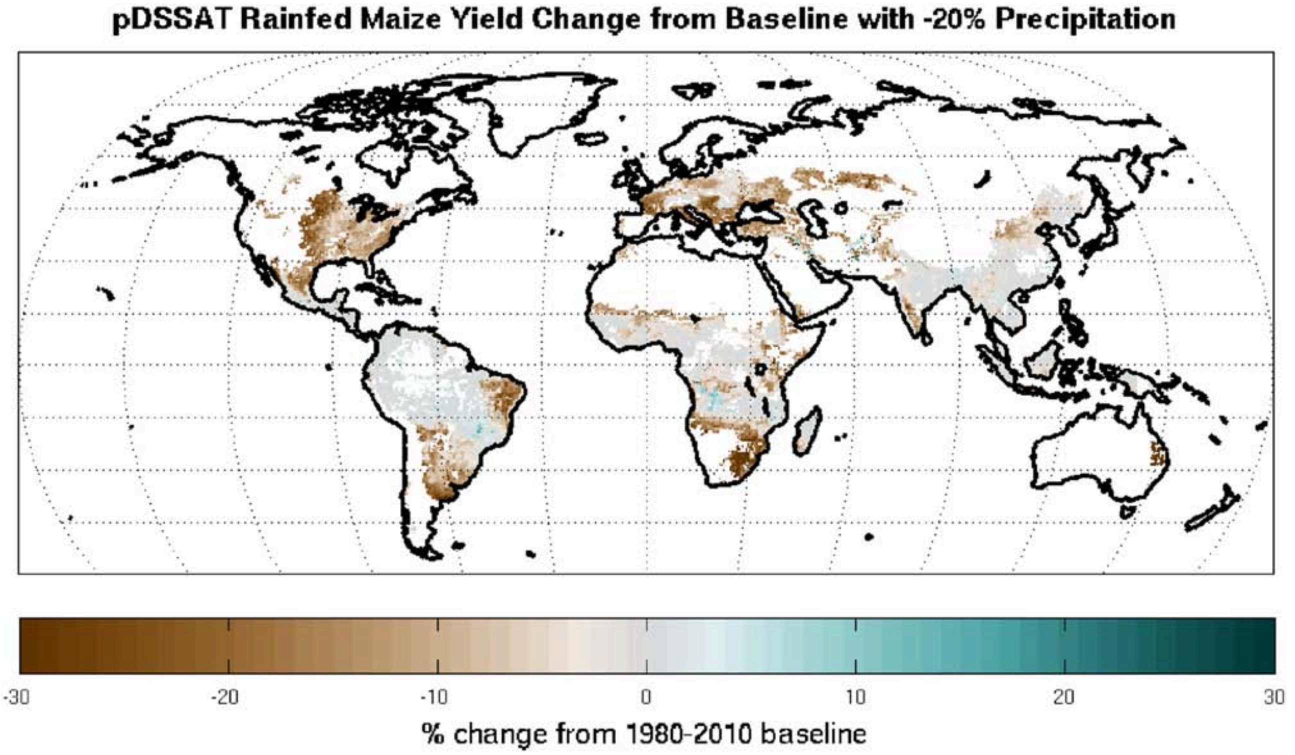

FIGURE 7 | Example of process-based crop model response map that motivates global and regional interventions. Rainfed maize yield response to a 20% reduction in precipitation, as simulated by the pDSSAT crop model as part of AgMIP's Global Gridded Crop Model Intercomparison. Note that only grid cells are shown where current rainfed maize production is at least 10 hectares according to the Spatial Production Allocation Model (SPAM2005) database (You et al., 2014).

TABLE 1 | Observational and physical model sources of information to drive crop models across a continuum of stakeholder-relevant time horizons.

Time horizon category	Weather/Climate data	Remote sensing data (~1970s-present)	Crop model simulation modes	Stakeholder needs
Past years	Historical observations and processed products	Vegetation and field environment observations and processed products	Historical simulations, retrospective analyses, and counterfactual/attribution studies	Attribution of anomalous yields and water use, identification of more resilient farming strategies
Present	Current observations and available products	Vegetation and field environment observations and available products	In-season simulations based on observations and available products	Early-warning systems and intervention triggers
Forecast	Weather and climate model forecasts	None	Crop yield forecasts from current state to end-of-season	Anticipate production shocks and their socioeconomic ramifications from local to global markets
Projection	Climate model projections	None	Crop yield impacts according to future/alternative farming systems, land use, and/or environmental conditions	Understand the shifting nature of impacts and risk, evaluate interventions to maximize economic and food security utility of land and water resources, identify and prioritize adaptation and mitigation policies and technologies

likely socioeconomic conditions that would shape future farming systems. While RAPs varied by location common themes included decreasing water availability, degradation of soils, and increasing use of fertilizers. Next, RAPs were evaluated for how global price changes and local climate shifts would create divergent impacts on regional households. In the case of Bethlehem, South Africa (Beletse et al., 2014) climate change scenarios predicted yield losses and associated revenue losses of 3–27% per farm. However, adaptation scenarios that included advancements in agricultural technology (e.g., improved seeds and fertilizers) increased yields 13–22% and decreased poverty 12–22%.

These results elucidate the potential for different adaptation and policy decisions to increase resilience and the likelihood of positive outcomes. The identification of agricultural technology advancement may lead to prioritization for further investment (often as elements of ongoing development investment or national adaptation and mitigation planning).

Second, AgMIP applied its CGRA process in response to the UN Framework Convention on Climate Change's request for information on the adaptation and mitigation costs related to global warming of 1.5 or 2.0°C above pre-industrial conditions (Rosenzweig et al., 2018). Results from 31 CMIP5 climate models, 5 additional GCMs that performed new 1.5 and 2.0°C stabilization simulations, 3 global crop models, 2 economic models, and regional case studies utilizing local crop and regional economics models elucidated the biophysical and socioeconomic impacts across farming systems and global markets (Ruane et al., 2018a,b). While results varied by region, in general, tropical maize yields declined and prices increased while soy yields increased, and prices decreased. Both maize and wheat cropping areas expanded while soy area planted decreased.

Results also quantified potential opportunities for farmers from mitigation-oriented subsidies (Antle et al., 2018). In one scenario, US Pacific Northwest wheat farmers could receive compensation for greenhouse gas mitigation via reducing soil emissions of greenhouse gasses and increasing production of biofuel crops. This policy strategy would offset the loss of income related to climate change and contribute to reduction in greenhouse gases. Consistently-linked simulations and scenarios also allowed for an unprecedented examination of uncertainty in projected impacts on local and global food systems (Ruane et al., 2018b), the shifting nature of extreme events (Schleussner et al., 2018), and effects on small-holder systems in West Africa (Faye et al., 2018).

SUMMARY AND CONCLUSIONS

These case studies demonstrate how EO are being used to assess water and food security outcomes, and designed to meet needs of analysts who work within larger decision-making contexts related to the water-food nexus. These projects work closely with stakeholders to ensure that current and future products support relevant decision-making. To summarize:

(1) GEOGLAM formed in response to a demand from G20 to provide agricultural relevant information from EO. Within this broader context, national and regional experts convene to reach consensus regarding the interpretation of EO and agricultural outcomes. Evaluations of requirements and EO's capability to meet them is an ongoing process undertaken in the broader GEOGLAM context (Whitcraft et al., 2015b). From initial success and lessons learned, this framework has been adapted to meet new demands from new partners including the Crop Monitor for Early Warning and National Level monitors. For example, new efforts will incorporate new EO that better represent irrigation, which is a requirement for addressing the food-water-energy nexus.

(2) The FEWS NET Land Data Assimilation System (FLDAS) and associated water stress products were developed in response to demand from USAID and FEWS NET to address the linkage between food security and water availability. These data are used within the broader context of food access, utilization, and stability. There is ongoing feedback and learning from partner scientists regarding how to best communicate the relationship between water availability, food security, and the water-food nexus.

(3) USDA-FAS soil water modeling was developed in response to demand from USDA-FAS to address errors in near real-time satellite derived precipitation products. These data are used in the broader context improving US agriculture export opportunities and global food security. Success can be attributed to, and lesson's learned from NASA scientist's willingness to work within the USDA system to easily meet FAS analysts' needs, as well as providing support as technology advances (e.g., SMOS to SMAP, and SMAP improvements in spatial resolution and latency). This partnership allows for the co-production of state-of-the-art, usable soil moisture information.

(4) AgMIP developed an assessment of vulnerable farming systems to meet the needs of the UK Department for International Development and UN Framework Convention on Climate Change's request for information on the adaptation and mitigation costs related to global warming. These cases fit within AgMIP's broader context of providing enhanced community organization around systematic intercomparison and stakeholder-driven applications of agricultural models to address food security. Moreover, AgMIP's global network of agricultural specialists that inform modeling efforts improve the quality and legitimacy of project results.

A commonality across these case studies is that they are all constrained by EO capabilities and uncertainties. With these constraints, EO data producers are transparent about what the models represent (e.g., natural streamflow vs. streamflow subject to impoundments and abstractions), model uncertainties (from model physics, parameters, and quality of inputs) and accuracy of remotely sensed products. For example, the accuracy of rainfall estimates may be contingent upon the extent to which satellite products have been calibrated to ground-based observations and the spatial distribution of these observations. Additional uncertainty is introduced when future climate scenarios are coupled with hydrologic and crop models.

Even with continuous improvements in EO to reduce these uncertainties, decision support is constrained by end-users' ability to recognize shortcomings in the data products and apply the information appropriately. What is an analyst's capacity for understanding of EO uncertainty, rather than accepting outputs from a "black-box"? And how well can analysts incorporate additional sources of information to answer lingering questions? For example, the USDA and FEWS NET hydrologic models do not include dynamic representation of cropping systems that would both depend on and determine water supplies, which are important considerations in the water-food nexus. Nor do these models represent irrigation or inter-basin water transfers, which can be energy intensive water supply mechanisms. GEOGLAM and FEWS NET analysts address some these limitations by incorporating additional sources of information via a convergence of evidence approach that considers information from remotely sensed soil moisture, evapotranspiration, and vegetation products that have been shown to detect the presence of irrigated agriculture (Senay et al., 2007; Lawston et al., 2017). In all instances, strong relationships and trust between EO data producers and end-users, described in this paper, are essential to compensate for uncertainties in EO and devise strategies to provide the best possible decision support.

Actionable Recommendations

These case studies demonstrate the value of NASA Earth science data through applications activities and are key examples of translating satellite data into actionable information and knowledge used to inform policy and enhance decision-making. One of the key lessons learned from these case studies is that given the complexity of problems that span the water-food nexus the partnerships between EO producers and end-users is critical for ensuring that EO data is applied appropriately to maximize its utility for decision support. Given these experiences we make the following actionable recommendations for other researchers (or applied science managers) interested in producing information for addressing the water-food nexus, and sustainable development policy guided by the literature on the co-development of useable knowledge for sustainability. We frame these recommendations in the context of NASA applied science programs; however, they are relevant to any organization and program that provides strategic guidance on food-water-energy projects.

First, during the "proof-of-concept" phase, specific applications need to be matched with methods and models that are appropriate given data availability, application time scale, delivery schedule, and requirement for precision (i.e., different approaches used to monitor global market impacts vs. identify field adaptation vs. assess long-term agricultural outlooks). NASA coordination can help more rapidly match science and decision context. Also during this phase, facilitated collaboration across NASA models, missions, and methods will build more robust applications, more rapidly characterize uncertainties, and ensure consistency in the downstream use of NASA products. For example, AgMIP is on the cutting edge of mechanistic modeling of both the biophysical and socioeconomic system that is a fertile ground of innovation for the case studies mentioned here, as well as other agricultural applications. NASA applied sciences could facilitate the integration of these systems to demonstrate proof-of-concept to existing and new end-users.

Second, stakeholder demand and engagement is key. Repeated interaction and iterative co-development of tools and information products build trust, understanding, and utility in application. If you have successfully moved from the "proof-of-concept" stage to engaging an end-user, listening and responding to their needs is critical: answer their specific questions, accept input from their experts, use their models/indices, provide products that analysts are familiar with, or can easily interpret, and provide trainings on new, potentially less intuitive products. This will ensure that you are producing "usable knowledge."

Finally, products (data, images, reports) need to be publicly available and follow guidelines for data sharing. Interactive user interfaces and web-pages that provide both graphics and data (e.g., PNG and GeoTIFF) can primarily support project needs as well provided content for the broader water-food nexus community. Following these guidelines has resulted in collaboration between FEWS NET, USDA-FAS, GEOGLAM, and AgMIP. Moreover, publicly available FLDAS estimates of the full water and energy balance (1982-present), being used by academic researchers (e.g., Philip et al., 2017) can provide important, useable insights to climate change, trends, and extremes. In addition to data and maps these projects provide a variety of reports online that can help others examine different facets of historic droughts. The strength of the data and products comes from close collaboration with specific end-users, while sharing the results in a useable way meets the important task of producing information for addressing the water-food nexus, and sustainable development policy.

These recommendations are directly applicable to better incorporate the role of energy availability and sustainability into water and food security applications, and better address the food-water-energy nexus. Additional research and "proof of concept" development that is led by or includes water-food applications scientists will need to devote effort to presenting new products and communicating research to potential end-users. Communicating these new efforts in a way that resonates with end-users may be an iterative process. Ultimately, moving "proof-of-concept" products into active decision support will require demand from end-users, and their commitment to a nexus approach to food-water-energy security and sustainability.

AUTHOR CONTRIBUTIONS

AM, SM, and AR contributed the concept and writing. AW and IM contributed to writing. JB, IM, CR, AR, IB-R, AW, CP-L, and AM designed respective projects in the case studies. SU reviewed the manuscript.

FUNDING

NASA Applied Sciences, FEWS NET's Participating Agency Program Agreement for NASA Water Availability Monitoring (AID-FFP-T-17-00001). NASA Harvest food security consortium (NASA NNH16ZDA001N-FSAC Grant No: 80NSSC17K0625).

ACKNOWLEDGMENTS

We appreciate the assistance of Amanda Evengaard and Meridel Phillips in figure creation (NASA GISS); Brian Barker for provision of figures (UMD); Kristine Verdin (NASA GSFC) for figure creation and Tamuka Magadzire (FEWS NET) for feedback.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Environmental Science

ORIGINAL RESEARCH
published: 08 March 2019
doi: 10.3389/fenvs.2019.00028

Recovery of Lost Nexus Synergy via Payment for Environmental Services in Kumamoto, Japan

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The objective of this study is to characterize and quantify the "trans-spatial nexus synergy" benefit of subsidized water ponding in the water-energy-food nexus in Kumamoto, Japan. After years of decreased rice production in upstream areas and associated declines in groundwater levels, the Kumamoto city government implemented a subsidy program whereby farmers in the Shira River basin receive payments to water their fields, which provides valuable groundwater recharge to downstream Kumamoto city. We quantify the economic benefits of this subsidy program, which include avoided additional energy costs to obtain scarcer levels of groundwater, as well as net revenue from the crops in the Shira River basin that would otherwise not be grown in the absence of the subsidy. These annual benefits can be combined and compared to the annual cost of the government subsidy. We also calculate potential historical losses that may have occurred in the region as a result of land use transitions from rice farming to urban use, which disrupted the nexus synergy between the watered fields and the groundwater table.

Keywords: water-energy-food nexus, synergy, Kumamoto, groundwater recharge, water ponding

OPEN ACCESS

Edited by:
Richard George Lawford, Morgan State University, United States

Reviewed by:
Carlo Giupponi, Università Ca' Foscari, Italy
Karen Grothe Villholth, International Water Management Institute, Sri Lanka
Steve Kopp, Environmental Systems Research Institute, United States

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Specialty section:
This article was submitted to Freshwater Science, a section of the journal Frontiers in Environmental Science

Received: *30 August 2018*
Accepted: *15 February 2019*
Published: *08 March 2019*

Citation:
Taniguchi M, Burnett KM, Shimada J, Hosono T, Wada CA and Ide K (2019) Recovery of Lost Nexus Synergy via Payment for Environmental Services in Kumamoto, Japan. Front. Environ. Sci. 7:28. doi: 10.3389/fenvs.2019.00028

INTRODUCTION

Water, energy, and food are fundamental resources, management of which are key for sustainable societies. Increases in population and changes in lifestyle put pressure on demand for water, energy, and food, which are expected to increase worldwide by 55, 80, and 60% in 2050, respectively (IRENA, 2015). These linked and interdependent resources make up the water-energy-food nexus, one of the most important global environmental and sustainability issues threatened by climate and societal changes (Hoff, 2011; Future Earth, 2014; Daher and Mohtar, 2015; Mohtar, 2015; Taniguchi et al., 2015; Mohtar and Lawford, 2016; Van Vliet et al., 2016). According to the Global Risks 2015 report (World Economic Forum, 2015), water, energy, and food have high global risks in terms of both likelihood (>4.5 on a scale from 1 not likely to 7 very likely) and magnitude of impact (>4.75). Therefore, analyses of the three resources to better understand the synergies and tradeoffs among the water-energy-food nexus are key to a sustainable society given increasing demand for these resources.

Connections between production and consumption within the water-energy-food nexus typically fall into one of three distinct categories. The first type involves the consumption of one resource to produce other resources. This is sometimes referred to as a direct "tradeoff" within the nexus. For instance, shale gas extraction requires fracking water, which cannot be reused (Taniguchi et al., 2017). Similarly, agriculture requires water, which also cannot be reused after food production. The second type of relationship can be described as an "alteration/interaction," wherein resources interact with each other, but each resource is changed, rather than consumed, after producing other resources. Water use for cooling power generation is one example of this second relationship. Water (volume) itself is not consumed but water temperature is changed after cooling. Another example is hot spring power generation (Taniguchi et al., 2017), in which only water quality (temperature) is changed after water use for energy production. The third type of relationship is the "linkage" between water, energy, and/or food, which is defined here as the "synergy" of the nexus. In this case, each resource is not necessarily consumed nor changed after producing other resources.

Within the "linkage" relationship, there are conceptually also three different types of ideal "synergies" of the water-energy-food nexus. The first one is contemporaneous place-specific synergy including efficiency increases via the nexus, such as the cascade use of water for energy and food production (reuse of geothermal energy water discharge for the production of greenhouse agriculture, for example). The second one is trans-spatial synergy which creates synergy of the nexus using connectivity of different spatial scales, such as trans-boundary resources management. The third one is trans-temporal synergy of the nexus, which creates synergy related to the trans-temporal scale of past-current-future connectivity, where future generations' preferences are considered. This study focuses on the second type of synergy of the nexus, "trans-spatial synergy," in Kumamoto, Japan (see **Figure 1**), where groundwater is the primary source of drinking water. Historically, rice farmers in the region upgradient of the city's most heavily used aquifer, have contributed to recharge via surface water irrigation. However, after years of decreased rice production in the upstream areas and increased urbanization and industrialization, concerns about mounting groundwater scarcity have led to the development of a multi-municipality trans-spatial collaboration.

Rather than developing expensive groundwater alternatives to combat growing freshwater scarcity, the Kumamoto city government, through collaboration with numerous stakeholders, determined that a managed aquifer recharge (MAR) program would likely be more cost-effective. In addition to increasing the volume of stored groundwater to support sustained resource use, MAR can provide numerous benefits including drought resilience (Scanlon et al., 2016) and water quality improvement (Maliva, 2014). MAR programs can sometimes be hampered by a clear economic case for implementation, however, especially when construction and operation of costly infrastructure is required (Arshad et al., 2014; Maliva, 2014). The case of MAR in Kumamoto is unique in that it is particularly suitable for financing using a payment for environmental services (PES) mechanism; a PES scheme is generally defined as a voluntary, conditional agreement between at least one seller and one buyer over a well-defined environmental service (Wunder, 2006; Engel et al., 2008). Ultimately a potentially win-win offsetting scheme was devised, wherein large groundwater users in Kumamoto City agreed to pay farmers in the Shira river basin to flood their fields (Shivakoti et al., 2018).

Ongoing since 2004, the Kumamoto program is touted as one of the few successful PES schemes for groundwater recharge-based natural infrastructure solutions worldwide (Shivakoti et al., 2018). Thus, there is no need to assess the sustainability of the already proven approach. Rather, the main goal of the current study is to characterize the synergistic implications of the subsidized water ponding program in the water-energy-food nexus in Kumamoto. To that end, we quantify the economic benefits of this subsidy program, which include avoided additional energy costs to pump scarcer levels of groundwater, as well as net revenue from the crops in the Shira River basin that might otherwise not be grown in the absence of the payments received by farmers. These annual benefits can be combined and compared to the annual sum of payments made by groundwater users. We also calculate historical nexus synergy losses that occurred in the region prior to the implementation of the subsidy program, where total annual

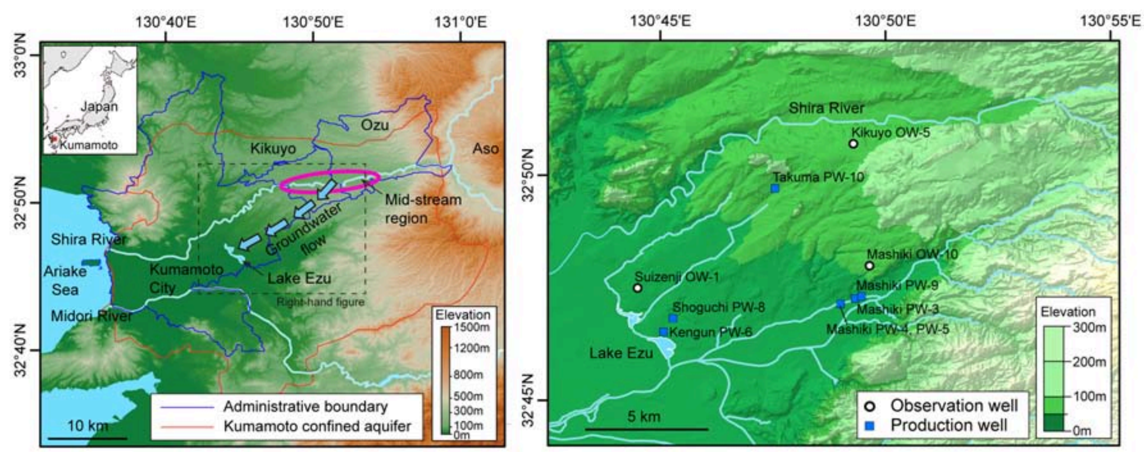

FIGURE 1 | Map of Kumamoto City and its primary underlying confined aquifer. **(Left)** Map showing research setting. **(Right)** Map showing well locations.

synergy loss is defined as the sum of farmer synergy loss and pumping synergy loss, farmer synergy loss is calculated in each year as the difference between maximum farm income observed during the study period and contemporaneous income, and pumping synergy loss is calculated in each year as the difference between minimum pumping cost observed during the study period and contemporaneous cost. All data and calculations are available in **Supplementary Table 1**.

MATERIALS AND METHODS

History of Groundwater in Kumamoto City

Kumamoto City (**Figure 1**) is the capital of Kumamoto Prefecture on Kyushu Island, Japan. Freshwater needs of the city's 730,000 inhabitants are met entirely by groundwater. Therefore, residents are mindful of the need to protect the underlying aquifer system for current and future generations.

The Kumamoto groundwater area (indicated by the red line in **Figure 1**) is bounded by the Shira River watershed to the north, the Midori River to the south, the Ariake Sea to the west, and the outer mountains of Aso caldera to the east (Hosono et al., 2013). The aquifer system consists mainly of volcanic pyroclastic deposits, porous lavas, and alluvial deposits that overlie the hydrogeological basement of Palaeozoic meta-sedimentary rocks and Pliocene to Quaternary volcanic rocks (Hosono et al., 2013). Highly permeable volcanic pyroclastic deposits form highlands (elevation ∼200 m above sea level) around the plain area (elevation ∼10 m above sea level), creating a region of high recharge potential for the entire aquifer system (Taniguchi et al., 2003). There are two major aquifers, an unconfined aquifer (ca. <60 m in depth) and underlying confined aquifer (ca. 70–200 m), separated by an impermeable lacustrine aquitard. However, this aquitard layer becomes discontinuous under the mid-stream region of the Shira River (see its location in **Figure 1**), allowing surface water to directly recharge the deep confined aquifer (Shimada et al., 2012) in that area. In general, groundwater in both aquifers flows following the topographical slope (**Figure 1**), recharging in the highlands and mid-stream region of the Shira River, then flowing laterally south- and westward (main flows are shown by the blue arrows in **Figure 1**), and mostly discharging within 40 years as springs in Lake Ezu (Taniguchi et al., 2003; Hosono et al., 2013; Ono et al., 2013; Kagabu et al., 2017; Okumura et al., 2018). Hydrochemical evolutions and issues regarding contaminations are reported in previous papers (Hosono et al., 2013, 2014; Hossain et al., 2016a,b). Groundwater from the confined aquifer is the major source of drinking water for the citizens of Kumamoto City (**Figure 1**). Paddies for artificial water ponding are allocated within the mid-stream region of the Shira River in administrative boundaries of Ozu and Kikuyo towns (within the pink circle in **Figure 1**) as the recharge rates have been documented to be very high (Hosono et al., 2013), and most groundwater users are concentrated in central Kumamoto City, (**Figure 1** and see Hosono et al., 2013 for detailed land-use pattern) downslope of the groundwater flow systems.

Groundwater levels have declined in the decades leading up to the early 2000s (**Figure 2**), due largely to a shift from agricultural to urban land use in key recharge areas (Shimada, 2010). As a result, the Kumamoto prefecture and city governments have worked together in recent years to develop policies aimed at enhancing recharge, including setting aside a proportion of urban zones as "green" to allow for recharge in areas that would otherwise be developed, mandating installation of rainwater infiltration tanks and equipment in certain buildings and greenhouses, and providing water ponding subsidies to local farmers in areas upgradient of the Kumamoto City aquifer system. While there are rivers in the area, groundwater is the preferred water source due to the high permeability in the study area, groundwater's seasonal stability (against drought, etc.), groundwater's superior water quality (Hosono et al., 2018), and the prohibitive infrastructure costs associated with capturing surface water. In this study, we focus on the potential benefits and costs of the water ponding subsidy program.

History of the Kumamoto Water Ponding Subsidy Program

By tracing stable oxygen isotopic compositions, Shimada (2010) identified the mid-stream region of the Shira River as a key recharge area for Kumamoto City's primary aquifer (**Figure 1**), located at the intersection of Ozu and Kikuyo town boundaries, and northeast of Kumamoto City Proper. Given the transboundary nature of the groundwater system, effective water management strategies for the region require coordination and cooperation between local and prefectural governments. In 2004, Kumamoto City government introduced a financial assistance program to encourage farmers in the mid-stream recharge area, including Kumamoto, Ozu, and Kikuyo to flood fallow rice paddies with river water in order to recharge the groundwater system underlying Kumamoto City.

Over the period 2004–2017, an average of 456 farmers participated in the program annually, 4.6 million m^2 of paddy field area was watered per year, 48.6 million JPY (427,921 USD) was paid in subsidies per year, and an estimated 13.7 million m^3 of recharge was captured annually (**Figure 3**). Recharge was estimated assuming that 100 mm of river water is applied daily for 30–90 days per year over the total paddy field area, which translates to an effective recharge rate of 3–9 m^3 per year for every 1 m^2 of paddy field area watered. Note that the sudden drop in all subsidy program-related indicators (number of farmers, subsidy level, watered area, and recharge gain) in **Figure 3** are due to the Kumamoto inland earthquakes which started by a large foreshock of M_w 6.2 on April 14 2016, followed by the main shock of M_w 7.0 the next day (e.g., Hosono et al., 2018). These earthquakes caused serious damage to infrastructures and surface- and subsurface lands including agricultural farm land and its irrigation system. Administrative functions including water ponding activates were not effective in 2016. Today, the water ponding program is now an important component in meeting total water demand in the area. Flooded fallow paddies have offset around 2 million m^3 and 12 million m^3 of the annual groundwater demand for industries and the Kumamoto City water supply, respectively, totaling ∼13% of total water demand in Kumamoto (Shivakoti et al., 2018).

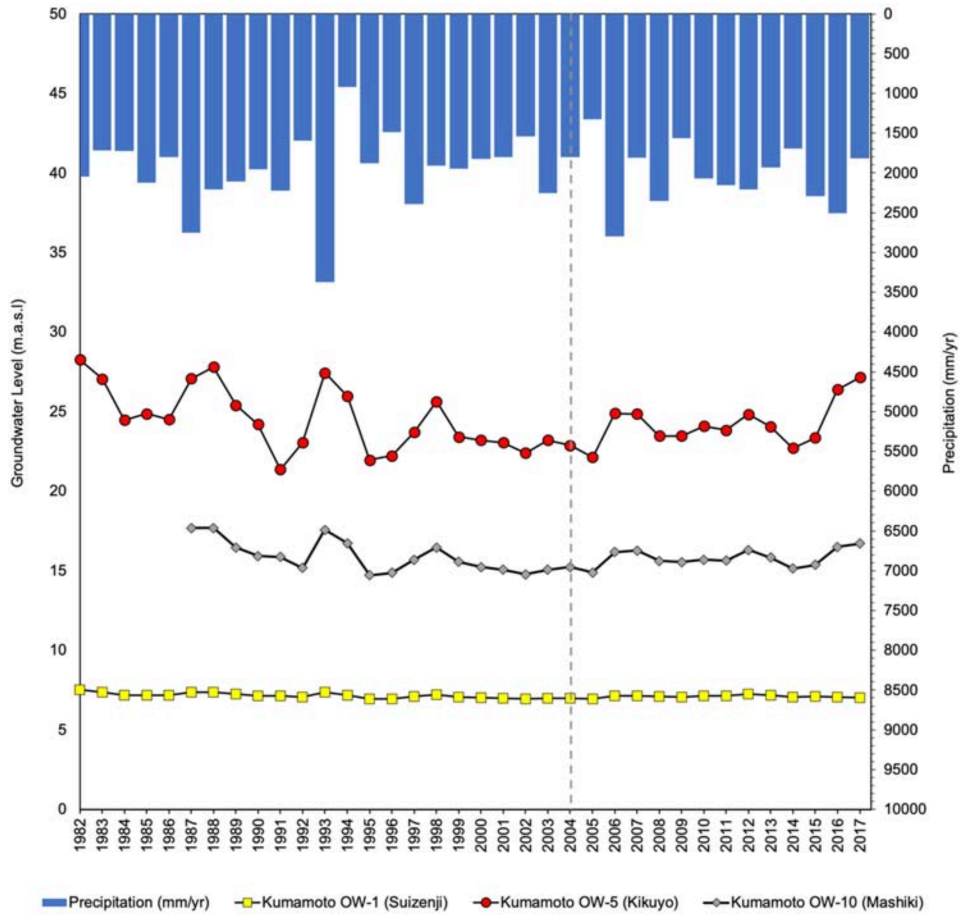

FIGURE 2 | Groundwater levels (m.a.s.l.) and precipitation (mm/year) over the period 1982–2017 at three observation wells in Kumamoto (see **Figure 1** for well locations). The vertical dashed line denotes the start of the subsidy program.

Pumping Cost Benefit of the Water Ponding Subsidy Program

In resource economics, groundwater pumping costs are typically modeled as an increasing function of lift, that is, the greater the distance between the ground surface and the water table, the more expensive to pump (Gisser and Sanchez, 1980; Feinerman and Knapp, 1983; Brill and Burness, 1994; Krulce et al., 1997). Under this assumption, the cost to raise a given volume of water from the aquifer to users at the surface is lower when the water level is higher. Therefore, if the Kumamoto water ponding subsidy program increases water levels over time, or at least avoids reductions in water levels that might otherwise occur without the subsidy, then the program generates a benefit equal to future pumping cost savings. While we have estimates of recharge gained as a result of the subsidy program (**Figure 3D**), translating that volumetric change to spatially distributed changes in lift is challenging for a number of reasons. Although much of the Kumamoto aquifer recharge comes from the mid-stream area, the exact proportion is uncertain. Moreover, while groundwater travel time from the unsaturated zone in the upgradient recharge area to the downgradient pumping wells in Kumamoto city is not well understood but somewhere in the range of 40 years (Kagabu et al., 2017), the significant pressure due to the volume of groundwater allows us to consider this connection directly as the pressure-driven hydrological response occurs spontaneously in the saturated zone and within 1 year in the unsaturated zone. Bearing in mind these substantial uncertainties, we elected to estimate the pumping cost benefit of the subsidy for a range of hypothetical changes in groundwater levels over the next 20 years. While the numbers are meant to be illustrative, the range captures what we believe to be plausible aquifer responses, given the size of the subsidy program.

Over the period 1982–2004 (prior to the subsidy program), water levels declined on average by 0.02, 0.24, and 0.14 m/yr at Suizenji, Kikuyo, and Mashiki observation wells respectively. In the years following implementation of the program, water levels have steadily trended upward, which suggests that the program contributed toward offsetting the decline prior to 2004. We specified a baseline effect of the subsidy on water level of 0.1 m per year, based on the assumption that the program provided

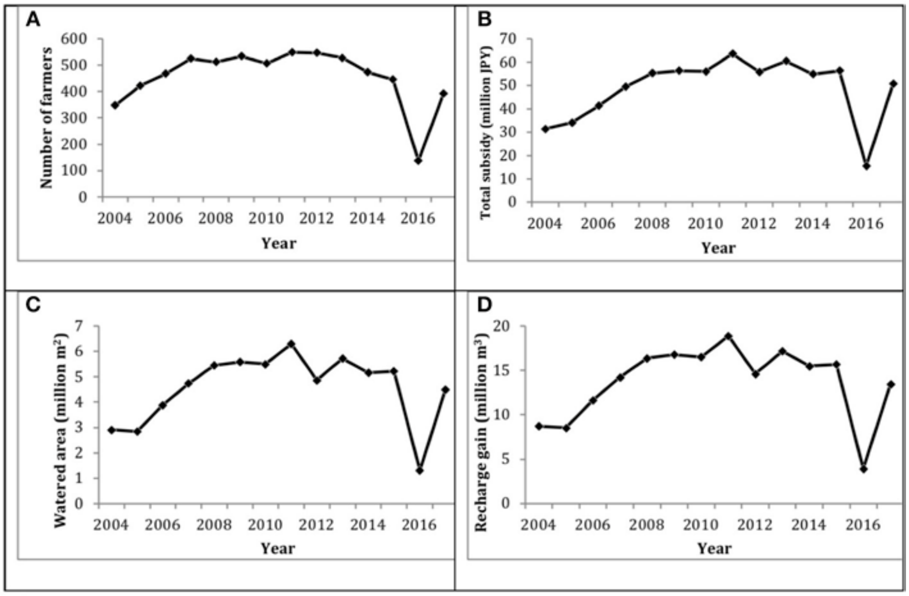

FIGURE 3 | Summary of Kumamoto water ponding subsidy program over the period 2004–2017: **(A)** number of farmers participating in the program, **(B)** total of all subsidy payments by year, **(C)** total paddy field area watered as a result of the program, **(D)** estimated recharge gain attributed to the program.

just enough recharge to counteract the average annual water level decline leading up to 2004. We also estimated pumping cost benefits for subsidy impacts of 0.2 and 0.3 m per year to consider the possibility that the program was more effective in contributing to the observed reversal of the water level trend. Pumping data from six wells (Muro, Okino, Horikawa, Hirakawa, Tsutsujidai, Takaono) from Ozu Waterworks were used to estimate a relationship between energy expenditure and lift (**Figure 4**). A linear fit ($R^2 = 0.8241$) generated a slope of 0.0044, which means that a 1-m increase in lift increases the total energy required for pumping groundwater to the surface by 0.0044 kWh/m^3. The annual change in energy demand for each of the three recharge scenarios was then multiplied by the average price of electricity across three pumping wells in Kumamoto City (Kengun PW-6, Shoguchi PW-8, and Takuma PW-10), inferred from electrical power consumption and electricity expenditure data. Because water levels are not measured in pumping wells at our study site, lift was calculated using observation well data matched to pumping wells based on proximity: Suizenji OW-1 was matched with Kengun PW-6 and Shoguchi PW-8, Kikuyo OW-5 was matched with Takuma PW-10, and Mashiki OW-10 was matched with Mashiki PW-3,4,5,9 (**Figure 1**). Pumping wells were selected based on current knowledge about the flow path of groundwater recharging from the mid-stream area (Shimada, 2010), where the subsidized ponding is occurring. Lastly, the unit change in energy cost was multiplied by the average (over the period 2012–2016) annual volume pumped, totaled across the seven pumping wells, to estimate the total annual pumping cost savings generated by the subsidy program. To test the sensitivity of the results, we also considered scenarios wherein pumping increased/decreased by 1 million m^3 and the price of electricity increased/decreased by 0.5 JPY/kWh (0.004 USD/kWh) annually over 20 years.

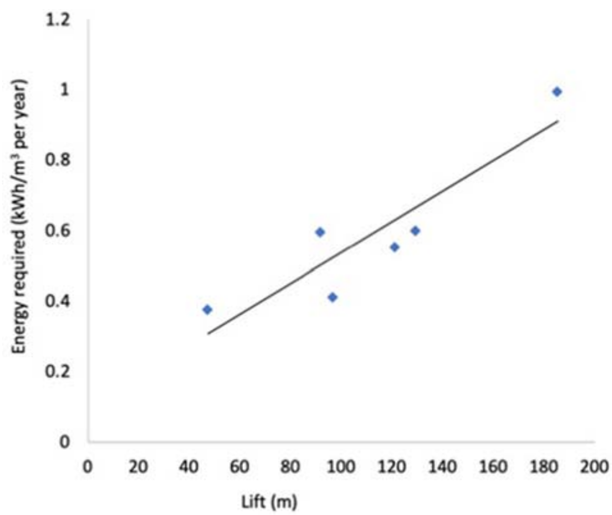

FIGURE 4 | Estimated relationship between energy for pumping groundwater and lift in Kumamoto ($R^2 = 0.8241$).

Farmer Income Benefit of the Water Ponding Subsidy Program

Farmers in Ozu and Kikuyo towns—in the mid-stream area of the Shira River where the largest volume of recharge occurs—who receive financial assistance through the artificial recharge program are required to water empty rice paddy fields 30–90 days out of the year. A condition of the water ponding assistance program is that the paddy is not producing rice at that time, in accordance with the national government's long-standing rice production control policy which has led to declining production since the 1960s (Lee et al., 2018). During the remainder of the year, however, farmlands can be used to grow crops, which support farm households. For some families, farming would be unsustainable without the financial assistance program, given increasing production input costs, a shift in the local economy toward other industries, and an aging population (Ministry of Environment Japan, 2015; Shivakoti et al., 2018). Because we do not know the specific dependency of farm income on this subsidy program, a range of avoided loss of farm income in Ozu and Kikuyo towns was included as a benefit of the subsidy program.

Over the period 2004–2014, the number of households that reported farm income ranged from 460–864 to 362–559 per year in Ozu Town and Kikuyo Town respectively. During that same period, the number of farmers participating in the subsidy program ranged from 138 to 549 per year, increasing annually from 2004 to 2007, remaining fairly constant through 2012, and declining thereafter (**Figure 3A**). Assuming that participating farmers were distributed in proportion to the total number of farmers who reported income in each town (likely an underestimate as most participating farmers come from these two towns), avoided farm income loss was calculated for Ozu and Kikuyo each year by multiplying the inferred number of participating farmers by average farm income per household. Total avoided income loss ranged from a low of 1.4 billion JPY (12.3 million USD) to a high of 3.2 billion JPY (28.2 million USD) per year. The average value of 2.4 billion JPY (21.1 million USD) was used to estimate the annual avoided income loss over 20 years in our baseline scenario. To test the sensitivity of the net benefit calculations to the farm income component, we also ran scenarios using 25 and 50% of the baseline value of avoided income loss. This allowed us to consider the possibility that some farmers would still be cultivating non-rice crops without the payment scheme, in which case 100% of farm income should not be attributed to the program.

Cost of the Water Ponding Subsidy Program

The water ponding subsidy program, which is operated by the Kumamoto City government, is funded from a combination of public tax revenue and private sources with interests in supporting the water resource, including for example Suntory, a Japanese brewing and distilling company. In general, the success of a PES program hinges on the development of an appropriate financing platform that generates a continuous flow of financial resources to fund payments over the long term (Mayrand and Paquin, 2004; Roumasset and Wada, 2013; Schomers and Matzdorf, 2013). This flow may be supported by direct payments from beneficiaries, government payments, and/or donations and grants from non-governmental organizations. In the case of Kumamoto, diversifying payment sources increases the ability of the program to sustain long-term financing, but it also potentially introduces some additional costs. For example, in addition to the direct cost to the public of supporting the payments, the program likely generates some excess tax burden—the welfare cost of raising extra revenue from an already existing distorting tax (Stuart, 1984; Ballard et al., 1985). The program also incurs some limited administrative costs (employs 1.5 FTE annually and <1 FTE between May and October to administer and monitor the program), as well as costs related to public outreach and education. Here we focus only on the direct revenue requirement, so our results underestimate the full cost of the program. The average value of subsidy payments over the period 2004–2017 (**Figure 3B**), estimated at 48.6 million JPY (427,921 USD) per year, was used to project the cost of the subsidy over 20 years.

Net Benefits of the Water Ponding Subsidy Program

Total benefits of the program were calculated as the sum of avoided pumping costs and avoided farm income losses, while total costs included the revenue required to fund the program payments. Annual net benefit—the difference between total benefits and costs—was then projected over 20 years for different combinations of model assumptions. The positive impact of recharge on water levels was varied from a 0.1 to 0.3 m/yr, based on the trend of declining water levels prior to program implementation. At the three observation wells, water level declined by an average rate of between 0.02 and 0.18 m annually over the period 1982–2003. Electricity costs may increase or decrease over time, particularly as renewable sources continue to become more cost-effective. Over the period 1982–2017, the unit cost of energy declined across the three Kumamoto pumping wells by between 0.18 JPY/kWh (0.0016 USD/kWh) and 0.25 JPY/kWh (0.0022 USD/kWh) annually. Thus, we considered the cases of electricity costs changing by ±0.5 JPY/kWh (0.0044 USD/kWh) per year. We also varied assumptions on future consumption needs (±1 million m^3 pumping/yr), and avoided farm income losses equal to 25 and 50% of the baseline value of 2.4 billion JPY (21.1 million USD) per year.

The water ponding program also allows farmers to continue production of local crops in the area, which has additional benefits in terms of energy offsets from avoided transportation and energy expenditures from outside the region. The region's local production of rice, watermelon, melons, tomatoes, etc. is highly valued and is another beneficial component of the nexus synergy between the water ponding program and Kumamoto's groundwater supply.

Historical Nexus Synergy Losses Prior to the Subsidy Program

In addition to projecting net benefits of the subsidy program into the future, we calculated total synergy losses over the period 1982–2016 in terms of both pumping costs and farm income. Note that groundwater levels may have started to decline prior to 1982, but due to limited data availability, our calculated synergy losses are likely conservative estimates. Pumping cost losses were estimated by first taking the difference between contemporaneous head level and maximum attained head level over the period 1982–2016. That difference was then converted to a change in energy via the energy requirement function (**Figure 4**) and multiplied by the contemporaneous unit cost of electricity and pumping volume. The resulting change in nominal pumping cost was then converted to 2018 JPY values and aggregated across years. Farm income losses were calculated by first converting nominal income to 2018 JPY values and identifying the maximum inflation-adjusted income value over the period 1982–2016. Annual synergy losses were then estimated as the difference between current year income and

TABLE 1 | Net benefit of Kumamoto water ponding subsidy program over 20 years under different assumptions about avoided pumping costs and farm income losses.

	Billion JPY (Million USD)		
	Baseline farmer benefit	**50% of baseline farmer benefit**	**25% of baseline farmer benefit**
Baseline pumping benefit	47.64 (419.43)	23.35 (205.62)	11.21 (98.71)
0.2 m/yr increase in head	47.68 (419.79)	23.39 (205.98)	11.25 (99.07)
0.3 m/yr increase in head	47.72 (420.15)	23.44 (206.34)	11.29 (99.43)
1 million m^3 increase in pumping/yr	47.65 (419.57)	23.37 (205.76)	11.23 (98.85)
1 million m^3 decrease in pumping/yr	47.62 (419.29)	23.34 (205.48)	11.20 (98.57)
0.5 JPY/kWh increase in energy price/yr	47.66 (419.60)	23.37 (205.79)	11.23 (98.88)
0.5 JPY/kWh decrease in energy price/yr	47.62 (419.26)	23.33 (205.45)	11.19 (98.54)

maximum income, and the total loss was calculated by summing annual losses.

RESULTS AND DISCUSSION

We find that total net benefit of the water ponding subsidy program, aggregated over a 20-year management period, ranges from 11.19 billion JPY (98.5 million USD) to 47.72 billion JPY (420.2 million USD) across 21 scenarios (**Table 1**)—seven sets of pumping benefit assumptions crossed with three sets of farmer benefit assumptions. The variation in outcomes is driven almost entirely by the assumptions underlying avoided farm income loss estimates. In other words, for a given farmer benefit level, net benefit remains relatively unchanged as pumping benefit assumptions (rows in **Table 1**) are varied. Whereas, for a given set of pumping benefit assumptions, net benefit varies substantially as farmer income benefits (columns in **Table 1**) are varied.

Our results suggest that the subsidy program is generally favorable, provided that the financial assistance continues to promote the generation of farm income in Ozu and Kikuyo towns in the future. If the payments are not enough to incentivize households to continue farming, then the net benefit of the program will decline, and possibly even become negative.

The nexus synergy losses in the years leading up to implementation of the subsidy program have been substantial. Increased pumping costs due to decreasing head levels were estimated at 61.4 million JPY (540,354 USD) over the period 1982–2003. Farm income losses (relative to the maximum observed income level) totaled 116.4 billion JPY (1.02 billion USD) over that same period. Although returning to historical synergy levels may not be realistic given additional external factors affecting head levels (e.g., changing rainfall patterns due to climate change or more impervious surfaces due to increased urbanization), the subsidy program will help to mitigate some of the synergy losses moving forward.

Aside from the direct benefits of the water ponding subsidy program measured here, there are several additional values of Kumamoto's groundwater supply that we do not attempt to quantify or monetize, but add to the social value of this system. First, the source of much of Kumamoto's groundwater discharge, Lake Ezu (see **Figure 1** for its location), is a symbol and icon for Kumamoto citizens and visitors. Without Lake Ezu's contribution to groundwater, aquifer head levels may be lower by almost 5 m, resulting in additional pumping costs of nearly 10 million JPY (86,140 USD) annually over our 20-year planning horizon. And as a cultural symbol of Kumamoto, 500,000 tourists visit Suizenji Gardens each year, bringing in roughly 7 billion JPY (61.6 million USD) to the Kumamoto visitor industry annually (Kumamoto City, 2017). Finally, without access to Kumamoto's groundwater supply in the future, alternative water sources such as dam systems built upstream of Shira River may be necessary (including additional water treatment), costing on the order of several trillion JPY. Ensuring the continued nexus synergy between upland farmers and downstream groundwater recharge also helps secure stable water availability into the future, avoided costs of which may be significantly higher than the avoided future pumping costs discussed here.

AUTHOR CONTRIBUTIONS

MT, KB, and JS: motivation and framing for the project; CW and KB: economic analysis and writing; MT, JS, and TH: environmental and hydrologic analysis and writing; CW, JS, TH, and KI: figure and table development; JS, TH, and KI: data collection, map development, background research, and information.

ACKNOWLEDGMENTS

This research was supported by Research Institute for Humanity and Nature (RIHN: a constituent member of NIHU) Project No. 14200097, entitled Human-Environmental Security in Asia-Pacific Ring of Fire: Water-Energy-Food Nexus. We thank the government offices of Ozu-Kikuyo Waterworks, the Ozu and Kikuyo branch of the National Federation of Land Improvement Association, Kumamoto City, and Kumamoto Prefecture for kindly providing water level and pumping cost data.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2019.00028/full#supplementary-material

Supplementary Table 1 | All data used in the analyses (head levels, precipitation, pumping rates and costs, subsidy information, recharge, and farmer income), net benefit scenarios, and synergy loss calculations.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Environmental Science

HYPOTHESIS AND THEORY
published: 21 March 2019
doi: 10.3389/fenvs.2019.00032

One Swallow Does Not Make a Summer: Siloes, Trade-Offs and Synergies in the Water-Energy-Food Nexus

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OPEN ACCESS

Edited by:
Rabi Mohtar,
Texas A&M University, United States

Reviewed by:
Richard George Lawford,
Morgan State University, United States
Nadim Khouri,
World Bank, United States

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Specialty section:
This article was submitted to Freshwater Science, a section of the journal Frontiers in Environmental Science

Received: *30 January 2018*
Accepted: *22 February 2019*
Published: *21 March 2019*

Citation:
Kurian M, Scott C, Reddy VR, Alabaster G, Nardocci A, Portney K, Boer R and Hannibal B (2019) One Swallow Does Not Make a Summer: Siloes, Trade-Offs and Synergies in the Water-Energy-Food Nexus. Front. Environ. Sci. 7:32. doi: 10.3389/fenvs.2019.00032

Synergies are required to ensure coordination between UN agencies (on norms and indicators), Member States (on coherence of policy instruments) and consumers (on perceptions of safety and affordability of services) to advance the achievement of Sustainable Development Goal (SDG) target 6.3 which focusses on reuse of wastewater. In this paper we employ theoretical insights derived from an agent-based modeling approach to undertake a critical examination of the recent UN-WATER directive on SDG target 6.3 and advocate for an improved understanding of factors that determine whether and how effective wastewater reuse will be possible while accommodating for regional variation and institutional change. We demonstrate that by applying the Nexus approach it is feasible to overcome siloes by forging concepts of trade-offs and synergies to draw out coupled perspectives of bio-physical and institutional dimensions of water-energy-food interactions. By employing this proposition, the paper advocates for place-based observatories as a mechanism that can support valorization of data and methodological assumptions as a precursor to robust monitoring of the SDG's. The systematic use of literature reviews and expert opinion to develop and pilot-test composite indices via place-based observatories raises the prospect of a data light approach to monitoring SDGs; specifically, what are the merits of relying on extensive survey data compared to composite indices that while being amenable to supporting benchmarking and scenario analysis can provide the insight needed to inform decision-making and robust monitoring of global goals?

Keywords: Water-Energy-Food Nexus, Sustainable Development Goals, trade-offs, siloes, synergies, agent-based modeling, Wastewater Reuse Effectiveness Index, place-based observatories

INTRODUCTION

The gulf between theory and practice in Global Public Goods Research[1] has become apparent in recent years. For instance, International organizations such as the Consultative Group on International Agriculture Research (CGIAR) have for their part placed a premium on adoptionrates for technical options that encourage resource recovery and reuse as an indicator of the effectiveness of international development assistance. However, a recent CGIAR Standing Panel on Impact Assessment synthesis report found adoption rates for full-fledged NRM technologies[2] to be remarkable and consistently low, ranging between 1 and 10% in areas where a variety of actors had been promoting these technologies (Stevenson and Vlek, 2018). Similarly, research on the merits of integrated billing for water supply and sanitation in the Netherlands showed that consumers stood to benefit in terms of less time and money spent on administration (Salome, 2010). However, despite the efficiency gains that could arise from overcoming administrative siloes combined billing has not succeeded because this would require the Water Boards (responsible for sanitation) and private companies (responsible for water supply) to give up some of their autonomy with regards to their sources of financing (see also Howarth and Monasterolo, 2016; Yang et al., 2016; Weitz et al., 2017).

These examples outlined above highlight a key issue that speaks to the question posed by this Special Issue: *Achieving Water-Energy-Food Nexus Sustainability- a Science and Data Need or a Need for Integrated Public Policy?:* there is a lack of understanding of the institutional pathways (mediated by state and market mechanisms) for adoption of the results of controlled experiments and case studies.

Recognizing the lack of understanding of (i) the institutional environment (i.e., property rights, legal and policy framework), (ii) the trade-offs involved in decision making and (iii) administrative culture and policy priorities, an agent-based modeling approach has emerged to emphasize the use of role games and experiments to collect data as well as having stakeholders involved in validation of multi-dimensional models (Barreteau et al., 2010; Poteete et al., 2010, p. 13). Agent-based modeling can potentially support analysis of the Sustainable Development Goals (SDGs) because it emphasizes the need to examine mechanisms for coordination and information sharing among networks of public agents, in the absence of which synergies in decision making fail to emerge.

Specifically, with reference to SDG target 6.3[3] synergies are required to ensure coordination between UN agencies (*on norms and indicators*), Member States (*on coherence of policy instruments*) and consumers (*on perceptions of safety and affordability of services*) to ensure effective reuse of wastewater. The failure to ensure coordinated action could exacerbate unintended consequences of policy action. In existing literature on public choice and New Institutional Economics (NIE), we can find some theoretical propositions that promote understanding of synergies in environmental planning and management. For instance, rational choice scholars imply that improved information could potentially overcome the effect of siloes through coordinated and evidence-based decision making (North, 1990; Ostrom, 1990). NIE scholarship, on the other hand focuses on the aspect of strategic interaction[4] in the decision- making process. This scholarship implies that decisions of officials within public agencies need not be made merely based on available information (i.e., data and evidence) but more on strategic considerations (Eggertsson, 1990; Harriss et al., 1995).

The analysis of the role of data and evidence in decision-making process would be enhanced by acknowledging historical specificities of the institutional environment. This is precisely because these historical specificities shape subsequent choices in environmental planning and management i.e., whether to prioritize infrastructure construction or service delivery, promote centralized or decentralized governance, and emphasize public or private service delivery models (Pollitt and Bouckeart, 2000; Abelson, 2003). It is pertinent to acknowledge in this context that the trajectory of Global Public Goods Research on Natural Resource Management (NRM) has itself undergone a shift in emphasis toward understanding the role of institutions in environmental planning and management. In the tradition of the "stages of growth" model of economic development, scholarship has iteratively emphasized the role of extension agencies such as forestry and irrigation departments in: (i) establishing infrastructure, (ii) enabling well-functioning markets for distribution of seeds and fertilizers, and (iii) disseminating information on management practices on the

[1]In the era of technological change, rise of emerging economies and global environmental challenges the potential of the private sector as a stakeholder in achieving the Sustainable Development Goals (SDG's) cannot be understated. But it is important to emphasize that from the point of view of monitoring the SDG's, UN think tanks have a mandate to improve the capacity of regional, national and local governments to support the design, implementation and monitoring of global goals. For an excellent discussion of the role of global think tanks in supporting evidence-based decision making (see Niblett, 2018).

[2]The five technologies that were reviewed included Conservation Agriculture (CA), Fertilizer Micro-dosing (MD), Alternate Wetting and Drying (AWD), Agro-Forestry (AF) and Integrated Soil Fertility Management (ISFM).

[3]The SDGs were agreed by UN member states at the High-Level Political Forum (HLPF) in September 2015. SDG target 6.3 states "by 2,030 improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally" (UN-Water, 2015). The Sustainable Development Goal (SDG) target 6.3 by methodologically implying "wastewater supplied to a user for further use with or without treatment and excludes water which is recycled within industrial sites" hints at the potential for wastewater reuse in agriculture (WHO UNICEF, 2015). The indicators for monitoring the SDGs were ratified by the HLPF in July 2018 for which the World Health Organization and UNHABITAT (*co-custodian agencies*) recommended the inclusion of a specific indicator on reuse for SDG 6.3.1 (UN-Water, 2018, pp. 57–58).

[4]Within agent-based models, agents are defined as autonomous decision-making algorithms. By focusing on interactions between agents who are boundedly rational and vary in their attributes within the agent population, agent-based modeling has the potential to generate a series of observed behavioral regularities that may be useful in clarifying the following issues: (a) how do agents make decisions? (b) how do they forecast future developments? (c) how do they remember the past? (d) what do they believe or ignore? (e) how do they exchange information? (Poteete et al., 2010, p. 211).

assumption that these interventions will boost agricultural yields and with the expectation of a positive effect of their adoption on levels of poverty and hunger (Brohman, 1996; Dorward et al., 2005; Shiva, 2010; Food Agriculture Organization, 2014).

Recent Nexus scholarship has begun to emphasize the importance of agent-based modeling to systematically analyse the role of social networks, institutional capacity and information sharing within and between departments responsible for management of water, energy and food (Harwood, 2018; Portney et al., 2018; Uden et al., 2018). However, formal models often work with unrealistic assumptions and without addressing the gap between theory and practice and thus do not explain the behavior of public agencies and agents in a comprehensive manner (Poteete et al., 2010, p. 4; Smajgl and Ward, 2013a). Against this background, it is feasible to overcome siloes by forging concepts of trade-offs and synergies to draw out a coupled perspective of bio-physical and institutional dimensions of water-energy-food interactions. By employing this proposition, the paper advocates for place-based observatories as a mechanism that can support valorization of data and methodological assumptions as a precursor to robust monitoring of the SDG's.

In this paper we employ theoretical insights derived from an agent-based modeling approach to undertake a critical examination of the recent UN-Water directive on SDG 6.3.1[5] and advocate for a multi-dimensional approach to monitoring global goals. Conventional unidimensional approaches emphasize: (1) a disproportionate focus on analysis of behavior of bio-physical resources; (2) efficiency of ecological systems; (3) statistical analysis of interactions between SDG goals and targets; and (4) case study research-data, models and approaches that have neither been pilot-tested nor valorized through engagement with governance structures and processes (see Cai et al., 2017; Bleischwitz et al., 2018; Dombrowsky and Hesengerth, 2018; Liu et al., 2018; Scott et al., 2018), and thus could promote siloes in environmental planning and management with potential to seriously undermine the credibility of the global monitoring regime.

Our proposed approach, on the other hand, advocates for improved understanding of the factors which determine whether and how effective wastewater reuse is possible while accommodating for regional variation and institutional change. As demonstrated in this paper, the proposed Wastewater Reuse Effectiveness Index (WREI) composed of both bio-physical and institutional components, relied upon data valorization, expert opinion and coupling of bio-physical and institutional perspectives of water-energy-food interactions with potential to effectively monitor SDG 6.3. Further, WREI showcases cutting edge applications of the Nexus approach[6] in managing trade-offs and fostering synergies in environmental planning and management (Kurian and Ardakanian, 2015; Scott et al., 2015).

[5]The directive notes "A sub-indicator on reuse would respond to the full aspirations of indicator 6.3.1, and would encourage better assessment of reuse potential, in support of target 6.4 on water scarcity" (UN-Water, 2018, p. 58).

[6]For purposes of our analysis we define the Nexus approach as a framework that enables integrative modeling of trade-offs with the objective of advancing synergies in decision making on water-energy-food interactions.

The subsequent sections of the paper are organized as follows. In section Governing the Nexus of Water, Energy and Food: The Case of Wastewater Reuse in Agriculture we discuss the implications of grounding the Nexus approach for management of environmental resources in discourses of planetary boundaries and the circular economy. Section Monitoring Sustainable Development Goal (SDG) Target 6.3 on Wastewater Reuse: Method, Data and Applications of Agent Based Modeling highlights the applications of trade-off analysis in delineating the role of financing, institutional capacity and information in fostering synergies in environmental planning and management. Section Political Economy of Public Decision Making in the Water-Energy-Food Nexus explores the role of composite indices in advancing monitoring of wastewater reuse and its implications for learning and capacity development via place-based observatories. The concluding section of the paper discusses the ramifications of monitoring wastewater reuse in agriculture for design of global public goods research.

GOVERNING THE NEXUS OF WATER, ENERGY AND FOOD: THE CASE OF WASTEWATER REUSE IN AGRICULTURE

Planetary vs. Administrative Scale Perspectives of Environmental Change

Agriculture has today become a key driver for four of the eight Planetary Boundaries (PB's) (identified by Rockstrom et al., 2009) that are at a critical stage of risk: freshwater use, biogeochemical flows, changes in biosphere integrity and climate change (Campbell et al., 2017). We could deduce from the arguments of "stages of growth" theorists that as economies grow infrastructure begins to play an important role in connecting populations to services in the form of irrigation, wastewater treatment or hydro-power. This is where planetary scale analysis of climate change, biogeochemical flows, biosphere integrity and land-system change need not necessarily align with decision making at administrative scale: plot, farm, local government or river basin authority. In other words, while results of planetary scale analysis may emphasize the finiteness of water, soil and waste resources and advocate for recharge of aquifers, restoration of soils, multiple uses of forest ecosystems, extended life-cycle management of infrastructure or tax rebates for adoption of renewable energy, administrative scale decisions need not necessarily support policies, projects or programs that emphasize circular economy pathways such as reuse, re-manufacture, replace, reduce and retrofit (Destouni et al., 2013; Jaramillo and Destouni, 2015). On the contrary political economy compulsions may drive decision makers to commit more resources toward exploitation of newer sources of water and energy without ensuring that established infrastructure is properly functioning. This may satisfy entrenched political interests but may exacerbate pressure on environmental resources (Agrawal, 2005).

Given the stark divergence between planetary and administrative scales of analysis, five contemporary trends within the agriculture sector necessitate particular attention to enable a transition from a narrow focus on crop systems toward food systems: (Tomich et al., 2018) (a) De-coupling of GDP growth from labor force participation in agriculture (Campbell et al., 2017), (b) increasing diversion of water from agriculture toward urban water supply reflecting a growth in secondary towns at the peri-urban interface, (c) changes in diets away from staples toward processed food reflecting changes in composition of labor force and changes in income and non-farm employment (**Annexure 1**), (d) Land sub-division with potential to affect the viability of farming operations especially in high-density tropics (Saith, 1992) and (e) the growing influence of transnational corporations for seeds, capital, pesticides, marketing and mechanization that has had the effect of exacerbating the separation of power from local politics and decision- making structures (Kurian, 2010).

Looking ahead to prospects for 2050 Hazell (2017) foresees growing differentiation within agricultural sectors in developing countries, with small farms becoming smaller and more numerous; more part time farmers, particularly among smallholders, for whom agriculture is a modest and diminishing share of household income and growing bifurcation between.....young and elderly farmers and geographically well-situated regions (urban and peri-urban) vs. isolated, marginal rural areas. He therefore argues that agricultural research that take consideration of contemporary conditions with the goal of advancing poverty reduction, must consider a *typology* of different smallholder types with different resources, connections to markets and hence economic prospects and agriculture for development needs. To these categories he adds, we must also add important differences in household structure and intra-household differences across farms, even within the same communities, and the culturally mediated roles of gender in access to land, irrigation water, forests affecting labor market participation and wages, which may systematically disadvantage women and girls and make them more directly experience poverty (Agarwal, 2001).

Trade-Off Analysis and Rebound Effects of Water-Energy-Food Interactions

When integrative analysis of interventions is weak, we fail to account for rebound effects in development practice (**Annexure 2**). For example, a recent CGIAR assessment found that high levels of fertilizer subsidies (energy) in Zambia adversely affected rates of adoption of Integrated Soil Fertility Management (ISFM) (Stevenson and Vlek, 2018). This is where trade-off analysis can prove to be important in untangling the individual elements of the ISFM technology package into costs and negative externalities that are involved covering water, energy and food. The subsidies on fertilizer make their application more likely than in other countries, but farmers stop after applying fertilizer and don't do the other things that will build up soil fertility in the long-run. These reasons could be prohibitive effective labor costs of applying the other component practices; farmers not perceiving a benefit from the package as a whole; farmers not caring about long-term fertility (*high discount rate*) or that it is just not on their radar (*short planning horizon*).

Trade-off analysis may reveal the priorities and accompanying logic guiding decision makers within a given administrative jurisdiction as to which set of actions to prioritize. For example, who are the beneficiaries of energy subsidies and how does this compare with the interests of farmers with potential to benefit from adoption of ISFM? Further, are the equity concerns relating to increased women's workload under irrigated agriculture likely to override the interests of those benefitting from expanded urban water supply because of catchment protection interventions? Therefore, trade-off analysis can inform targeting of development interventions in line with locally defined norms of fairness. In situations where equity is prioritized for example, targeting may lead to design of subsidy schemes that focus attention on reducing income poverty among poorer households and increased investment of savings to improve productivity of livestock and agricultural assets (Standing, 2017). Cash Conditional Transfers (CCT's), for example in Sri Lanka's *Samruddhi* scheme resulted in improved child nutrition, while in other cases transfers that have increased productivity of agriculture and livestock have resulted in reduction in casual wage labor which tend to be lower paying among non-farm jobs.

Synergies: A Function of Legal and Policy Frameworks

Agent-based modeling emphasizes the importance of coordinated action to overcome siloes in decision making. Agent-based modeling of trade-offs will reflect the fact that policy and management choices that operate at global, national and local scales are guided by norms and agency and individual behavior that are focused on ensuring a balance between planetary scale imperatives of resource conservation/reuse and institutional priorities of effectively delivering critical public services at the appropriate administrative scale[7] (Thaler, 2015). The degree to which institutional synergies are forged will determine the success with ensuring a balance and mitigating rebound effects in environmental planning and management. When planning over-emphasizes either bio-physical or administrative imperatives rebound effects are bound to be amplified either in the form of environmental risks or institutional siloes. The level of divergence from the ideal, balanced scenario is depicted as the space between the blue continuous line and the blue broken line in **Figure 1**.

Historical institutionalist literature enables us to identify three components of robust synergies: (a) social networks that support information flows and knowledge exchange among different functionaries within and across departments, ministries and agencies, (b) deployment of complimentary skill sets (capacity) by key players and (c) a critical mass of financing and technology that can be appropriated by agencies and departments focused on achieving a particular policy goal (Gregory, 1997; Batley, 2004).

There are also several enabling factors for robust synergies, notably: (a) a clearly articulated legal and policy framework, (b)

[7]Administrative scale is defined here as the coverage area for delivery of specific public services. Depending on institutional context and type of service under consideration administrative scale could be defined by village, town or ward boundaries.

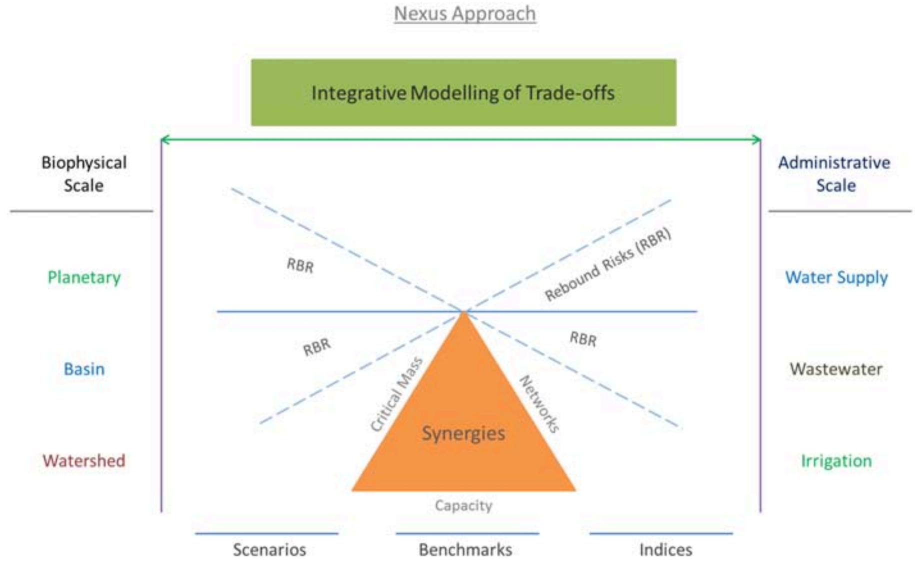

FIGURE 1 | Managing rebound effects in the water- energy-food nexus. Adapted from Kurian and Ardakanian (2015), Kurian (2017), and Kurian (2018).

clear set of policy instruments for implementation of legal and policy framework that includes directives, guidelines, circulars, standards and notifications stipulating how choices regarding technology and financing options may be arrived at, (c) data and evidence on distribution of bio-physical and institutional risks, (d) manageable levels of administrative discretion with regards to interpreting and implementing policy instruments and (e) incentive structure (penalties and rewards) for compliance with policy instruments (Pollitt and Bouckeart, 2000; World Bank, 2009; Kurian et al., 2018).

In terms of a parsimonious model, co-provision offers insights on how one may examine the effect of synergies in environmental planning and management. The following are some elements of a co-provision model that merit consideration (Kurian and Dietz, 2013):

- Variability in climatic, soil and groundwater conditions that influence system performance in terms of biophysical processes and infrastructure operation
- Accountability in fiscal relations involving multiple levels of government with potential to impact on infrastructure design and incentives for effective delivery of public services
- Levels of discretion by public officials in enforcement of rules relating to infrastructure financing and Natural Resource Management (NRM)
- Uncertainty in factor and product markets with potential to influence synergies in environmental management
- Heterogeneous social relations that offer opportunities for local leadership to emerge for management of natural resources.

Coupling Bio-Physical and Institutional Models of Water-Energy-Food Interactions

Agent-based modeling while highlighting tensions between the application of Nexus principles in research and development practice has the potential to identify pathways that can overcome silos in environmental planning and management. Firstly, Nexus research implies transdisciplinary dialogue involving experts and non-experts to develop, pilot-test and validate models (Gilbert and Bullock, 2014). Further, the process of validating models may require that data and methodological assumptions be valorized to meet both the tests of scientific rigor and policy relevance. Secondly, Nexus research also implies the necessity of translating scientific results to inform design, monitoring and evaluation of programs and projects that adopt Nexus principles in development practice (Stirling, 2014). A pathway of how Nexus principles could be applied in development practice is offered by multiple use water services of which a prime example, one may argue is that of wastewater reuse.

The tensions between application of Nexus principles in research and development practice suggests an urgency for coupling global models of bio-physical change with models of institutional change at appropriate administrative scale. This would emphasize the fact that social rules relating to tariff setting, design of public subsidies or delivery of water, energy and food services are determined in the political arena typically involving strategic interactions and interdependence of officials within public agencies (Bates, 1995; Barreteau et al., 2010). Expert opinion would be required to calibrate model prototypes because they can help explain how equity can sometimes trump efficiency arguments in decision making and why despite the availability of data and monetary resources inaction may become the norm in the face of well- established risks such as droughts and deteriorating water quality (Howarth and Monasterolo, 2016; Weitz et al., 2017; Uden et al., 2018). In subsequent sections of this paper we make a case that the study of dynamic socio-ecological systems is best supported by recourse to place-based observatories that can develop and validate composite indices as a mechanism for monitoring global goals (Larson and Smajgl, 2006; Tian et al., 2018).

Methodologies for Evaluating Nexus Typologies of Resource Recovery and Reuse

Wastewater reuse assumes significance from the perspective of examining both policy orientation of research and the role of feedback loops in governance systems. Wastewater reuse in agriculture assumes importance since it has been estimated that approximately 20 million hectares of land is currently under cultivation worldwide using wastewater Kurian et al., 2013. When wastewater is better managed, significant economic benefits can be derived in developing countries through reuse for productive purposes like agriculture, kitchen gardens and poultry rearing (Jimenez and Asano, 2008). Some of the direct benefits of wastewater collection and reuse could include double cropping and lower input costs for agriculture (Rijsberman, 2004). There may also be important economy-wide trade-offs of encouraging freshwater swaps through use of treated domestic wastewater in agriculture. While these trade-offs could involve enhanced source sustainability of the urban water supply, lower energy pumping costs and improved food security arising from increased farm incomes (Kurian et al., 2013), linearity of outcomes cannot be assumed (Miller-Robbie et al., 2017).

The idea of working with typologies to better understand agrarian change that we alluded to earlier has been accompanied by discussions within the Impact Evaluations (IE) community of practice on the need to improve upon our approach to design of Randomized Control Trials (RCT's). The standard approach adopted by IE has been to choose a control area like the area where the intervention is being introduced, and compare outcomes in both areas (Craig, 2015). Several iterations of the approach including "difference-in-difference" method, however, cannot consider area-specific trends, that is, changes other than those attributable to the intervention that occur in one or other of the areas. This is like the energy subsidy example in Zambia and its adverse impact on adoption of ISFM technology. The synthetic control method attempts to overcome this problem by comparing the trend in the outcome of interest in the intervention area with the trend in the synthetic composite area[8]. Both the discussions on typologies and the use of synthetic controls in IE hold the potential to contribute toward the holy grail in NRM innovation; namely a tool that has a degree of scale and context neutrality and thereby has a recommendation domain that encompasses a range of ecologies and socio-economic contexts (Stevenson and Vlek, 2018).

The discussion emphasizes the need for going beyond conventional RCT design (see Dhehibi et al., 2018) and for a re-examination of the role of extension agencies in supporting uptake of the outputs of NRM research based on robust typologies of trade-offs in development (**Table 1**). This means that while there have been many RCTs looking at the performance of these technologies where the unit of randomization is the plot, there is a serious dearth of RCTs looking at randomization at the village or individual level– the only research designs capable of rigorously uncovering the exact causal pathways between adoption of technical options and impact on water, energy and food security. Qualitative and descriptive impact evaluation studies of adoption pathways in the real world may be useful for generating hypotheses, but there has been insufficient attention to putting these hypotheses to a rigorous test.[9]

TABLE 1 | The use of typologies in impact evaluation studies.

CGIAR technology option	Example of trade-offs	Typology considerations
Fertilizer micro-dosing	Food production vs. food safety	Rural-urban/agro-ecology/water endowed/bounded energy systems/climate stressed
Integrated soil fertility management	Soil erosion control vs. urban water supplies	Rural-urban/agro-ecology/water endowed/bounded energy systems/climate stressed
Conservation agriculture	Agricultural productivity vs. diversification of income	Rural-urban/agro-ecology/water endowed/bounded energy systems/climate stressed
Agro-forestry	Food production vs. sustainable sources of energy	Rural-urban/agro-ecology/water endowed/bounded energy systems/climate stressed
Alternate Wet-drying	Environmental sustainability vs. stabilization of demand for farm labor	Rural-urban/agro-ecology/water endowed/bounded energy systems/climate stressed

MONITORING SUSTAINABLE DEVELOPMENT GOAL (SDG) TARGET 6.3 ON WASTEWATER REUSE: METHOD, DATA AND APPLICATIONS OF AGENT BASED MODELING

Empirically grounded agent-based models make it possible to evaluate whether hypothesized processes are consistent with empirically observed patterns of behavior (Poteete et al., 2010, p. 211). Therefore, in contexts characterized by complex feedback loops between resource use, agricultural productivity and considerations of distributional equity (for example, favoring well to do vs. poor consumers), posing the relevant question can be a major challenge in devising a methodology for monitoring a global goal on wastewater reuse. In this section we discuss the approach to developing, validating and pilot-testing the Wastewater Reuse Effectiveness Index (WREI)- an integrative

[8]It is important to clarify that small-scale RCT's could be run with a control area and a treatment area but to be cost-effective such comparisons need not be limited to making a single 1 to 1 comparison. In village-level randomization, eligible villages would be spread out across the landscape and enrolled into a study–often many 100 s of villages. For interventions at the level of larger administrative units (i.e., regions/countries) there are almost never enough of them to randomize across, hence RCTs cannot used in this way. Synthetic control methods can be applied in the contexts of these "small N" cases but they come with several restrictive assumptions, even if they relax the parallel trends assumption that is central to difference in differences (see White, 2009).

[9]The agriculture technology adoption initiative has begun addressing some of the shortcomings of conventional RCT led approaches (see http://atai-research.org).

modeling tool that supports data valorization and expert opinion to elaborate upon the role of institutions in environmental planning and management. At the outset it must be clarified that an index is defined as an aggregate measure to monitor change. The aggregate measure consists of indicators and variables. While variables are directly measurable, an indicator while based on a conceptual framework, can be converted into a variable.

Translating a Policy Concern Into a Researchable Question

Three distinct circumstances[10] defined the process by which research on wastewater monitoring via a composite index were framed. First, as part of a regional workshop on SDG monitoring methodologies that was organized by the United Nations, practitioners and scientists debated the state of the art on indicators for target 6.3 of the SDG's (Meyer and Kurian, 2016)? Second, participants queried whether the objective of global monitoring is to benchmark country performance on reuse or to ultimately identify the incentives required that would make reuse possible and build capacity to enable institutional change. Third, during a field visit to a wastewater treatment plant in Hanoi, workshop participants from five countries identified a common policy concern. Our approach to the subsequent research was influenced by the common policy concern that was articulated as follows: which sewer system- combined vs. simplified was better placed to facilitate wastewater reuse in the context of rapid urbanization? (Kurian et al., 2016b).

Inter-operability of Monitoring Instruments

The workshop revealed that the indicators currently being used by the UN to monitor SDG target 6.3 were focussed on bio-physical aspects of wastewater use. Second, the indicators did not explicitly consider the issue of wastewater reuse. Third, the monitoring methodology was biased toward reporting status on wastewater use and not toward understanding the incentives that would facilitate wastewater reuse. For this reason, a global monitoring methodology that purports to improve the situation must be interoperable. Inter-operability could mean: (a) the methodology enables comparisons based on typologies of indicators in response to a policy concern that has been validated at appropriate regional/local scale and (b) the methodology engages scientists and non-experts to construct composite indices and facilitate data transformation and visualization to enable knowledge translation that supports evidence-based decision making (Endo et al., 2015). To do so the Hanoi workshop resolved to construct a *Wastewater Reuse Effectiveness Index* (WREI) based on a field visit to Indonesia (OECD, 2008; Kurian et al., 2016b).

[10]Trans-disciplinary scholarship has emphasized that framing a policy relevant research question usually results from a combination of factors: (a) circumstances of research question framing, (b) priority accorded to different forms of evidence and (c) consistency of language used by disciplines represented in a research project (Harriss and Lyon, 2014).

Wastewater Reuse and Associated Trade-Offs

Reused wastewater has an economic value and the establishment of a reliable price is necessary to guarantee an efficient allocation. Determining the *Willingness-to-Use* (WTU) and the *Willingness-to-Pay* (WTP) for wastewater therefore highlights several potential trade-offs. For example, while recycled water, desalination and rainwater collection may contribute to water security, they may increase energy requirements or mitigate the risks of contamination of potable water through improved treatment. Hernandez-Sancho and Sala-Garrido (2008) emphasize that to encourage the use of recycled water, its tariffs should be significantly smaller than those of drinking water. They claim that the principle of cost recovery should not be strictly applied on water reuse projects while drinking water is being subsidized, as low drinking water rates make reused water uncompetitive. Additionally, when setting the price of recycled water, the cost of producing positive externalities should be considered namely those related to the regeneration of ecosystem service functions such as aquifer recharge[11]. Educational campaigns to increase public awareness about the advantages of reused water and to promote communities' involvement in water management issues may reduce the reluctance to use reclaimed water and increase the WTP for it.

Lessons From Pilot-Testing a Composite Index for SDG 6.3

In Kurian (2017) we reported on a prototype composite index that was constructed based on a field visit to Indonesia. The prototype Wastewater Reuse Effectiveness Index (WREI) relied on review of documentation provided by UNHABITAT on SDG 6.3, discussions with academics and policy makers and a review of secondary literature. Expert opinion was sought through discussions with a panel drawn from academia and government agencies. Weights were subsequently accorded to governance parameters with potential to explain effective reuse of wastewater. The expert opinion revealed that governance and political stability as measured by indicators such as levels of corruption, fragmentation of water and sanitation sectors and existence of a legal and policy framework was critical to sustaining effective reuse of wastewater. Surprisingly, income and charges as reflected in indicators such as average cost of per cubic meter of wastewater to consumers relative to average income of the country and recycled water charges relative to those of drinking water were rated as having less influence on effective reuse.

The overall approach used to construct WREI was validated at a workshop involving eleven countries in the Arab region (in

[11]In situations where municipalities must meet advanced treatment standards extra costs are not incurred on treatment of wastewater since the municipality has this sunk cost to incur and there is no need to charge the user an "additional cost" for treating water. Wastewater reuse therefore, becomes a convenient way for disposal of effluent that in any case needs to be treated but with no additional cost to the consumer.

addition to Indonesia and Brazil)[12]. Based on an invitation from the Ministry of Water Resources and Sanitation, data from the State of Sao Paulo was employed to test the predictive capacity of WREI. The pilot-testing revealed the importance of arriving at an appropriate set of indicators before weights are assigned based on expert opinion. Undertaken in the absence of expert opinion the capacity for WREI to predict scope for effective wastewater reuse in Sao Paulo was seriously curtailed[13]. WREI Expert panel data from India was subsequently used to revise the WREI model based on the comments received from Brazil[14]. In all the three cases- Indonesia, Brazil and India reuse of wastewater in agriculture was emerging as a policy and legislative priority, especially to address water scarcity in urban areas.

Aggregation and Synthesis of Bio-Physical and Institutional Data on Effective Reuse

Aggregation and synthesis of data from bio-physical and institutional and governance domains in the form of a composite index can be a useful tool for policy making. But existing wastewater indices only include biophysical indicators; the WREI index overcomes this limitation by analyzing how countries fare given their political, institutional, and socio-economic environment (OECD, 2008). The combination of bio-physical and governance dimensions in an index portrays the difference between theory and reality because conventional reuse indices by emphasizing the bio-physical dimension fail to explain the institutional conditions that would enable translation of reuse potential into effective reuse of wastewater. To measure effectiveness in wastewater reuse, the bio-physical component is calculated by referring to the institutional and socio-economic component of the index. In developing the Wastewater Reuse Effectiveness Index (WREI) the following two approaches were combined. The first, and most preferred, is to use regression analysis. The second approach relies on experts to attribute weights to each component of the institutional and socio-economic framework. For this reason, we deliberately included two components in construction of WREI. The first component deals with the bio-physical aspects of wastewater, which has three variables gleaned partly from the SDG 6.3 indicator list which includes only two variables namely wastewater safely treated and ambient water quality. To this we added a third variable namely, wastewater reused to create the first component-(WRI-BCI) $_{\text{it}}$. The second component deals with socioeconomic, environment and governance aspects (WRI-GSE)$_{\text{it}}$. A normal or weighted index can be constructed depending on the context. The finalized WREI composed of biophysical and governance indicators was constructed using India data that is mainly drawn from secondary sources[15] to develop a typology of variables to model effective wastewater reuse for India.

As mentioned variables of bio-physical component of the index include: (i) proportion of wastewater treated; (ii) proportion of water bodies with good ambient water quality; and (iii) proportion of wastewater reused of the total. These variables are taken on Zero to 100 scale after normalizing i.e., by converting the absolute numbers into percentages. A simple average of the three variables provides the bio-physical component WRI (BCI)$_{\text{it}}$. Similarly, a total of eleven variables is included in constructing the WRI (GSE)$_{\text{it}}$ component. The composite waste water reuse effectiveness index (WREI)$_{\text{it}}$ is then constructed using the two component indices and can be expressed mathematically as follows:

$$WREI_{\text{jt}} = I_{\text{jt}} = \sum I_{\text{kjt}} W_{\text{kjt}} + \sum I_{\text{ljt}} W_{\text{ljt}} \quad (1)$$

Where WREIjt is the wastewater reuse effectiveness index for country '*j*' in time '*t*'.

I_{kjt} is the index of component '*k*' *(BCI)* of country '*J*' in time '*t*' and I_{ljt} Index of component '*l*' *(GSE)* of country '*j*' in time '*t*'. The weighted summation of the BCI and GSE components are estimated separately for each country for a specific reference year. Summation of the countries can provide the basis for regional estimates and benchmarking of performance with reference to the SDGs. Similarly, summation over the years can support scenario analysis and inform discussions on incentive structures and monitoring methodologies to achieve the SDGs. Using the real time data (presented in **Tables 2**, **3**) for India for the year 2015 the index is prepared using the equation 1 outlined above.

TABLE 2 | Biophysical component index of wastewater reuse effectiveness index developed based on data for India (WRI-BCI).

Indicator	Measure	Actual value %	Weights %	Weighted value
Waste water safely treated	%	25	25	6.25
Water bodies with good ambient quality	%	37	25	9.25
Wastewater Reuse/total wastewater#	%	20	50	10
WRI (BCI)$_{it}$		27.3*	100	25.5+

**BCI with equal weights (simple average). + BCI with differential weights. # Estimate based on the studies of various locations.*

[12]The validation was in the form of a joint communique issued by the United Nations in Amman, Jordan dated March 23, 2017 and endorsed by 11 countries from the Arab region including Indonesia and Brazil.

[13]The pilot-testing of WREI also revealed that as per the original formula the bio-physical and institutional and socio-economic components did not complement each other. Rather, both dimensions of the index tended to move upwards toward a ratio of 100. But from the point of view of SDG monitoring the scope for decision makers to rely on WREI to prioritize protection of bio-physical resources or delivery of public services is limited since the original formula was set up to show a movement for bio-physical and institutional and socio-economic components of the index- moving upwards but in parallel.

[14]Feedback from the State Secretariat of Water Resources and Sanitation, Sao Paulo was received in the form of an official communication dated 16 February 2018.

[15]Secondary sources are mainly data published by government agencies. In the case of India, macro-economic variables like per capita income and literacy are available from the annual economic survey published by the Ministry of Finance, Government of India; information on wastewater is published by the Central Pollution Control Board, Government of India; and the information on governance variables is published by the Ministry of Panchayati Raj, Government of India. The details about data sources are available in (CPCB, 2015; GoI, 2016).

TABLE 3 | Governance and socioeconomic component index of wastewater reuse effectiveness index developed based on data for India (WRI-GSE).

Component	Indicator	Measure	Actual value %	Weight %	Weighted value
Socioeconomic	Per Capita GDP (PPP)	%	24	10	0.2
	People depending on Waste water	%	02	10	0.2
	Awareness about waste water	%	47	05	2.35
Environment and sustainability	Population affected by water borne and water wash diseases	%	0.3	20	0.06
	Extent of soil degradation	%	29	05	1.45
	Area irrigated by waste water (potential)	%	3	20	0.6
	Crops grown under Wastewater (subsistence or high value)	% of subsistence crops	75	02	1.5
Governance	Area under water / waste water management institutions	%	22	05	1.1
	Policy environment (including water/waste water policy)	%	50	10	5
	Cost recovery	%	10	03	0.3
	Effectiveness of decentralized governance	%	31	10	3.1
WRI $(GSE)_{it}$			26.7	100	15.9

Assigning Weights for Index Components: The Role of Expert Opinion[16]

BCI measures the actual bio-physical situation of countries in terms of target 6.3 of SDGs. The conceptual model is presented in **Figure 2**. It was estimated that sewage generation in India in 2015 was 61, 754 million liters per day (MLD) the sewage treatment capacity was only 22, 963 MLD (CPCB, 2015). Moreover, it was observed that 40% of the STPs do not function and the remaining function at 72% capacity. While some estimates indicate that 62.8% of the total sewage is discharged directly into nearby water bodies, given the poor functioning of STPs the actual proportion of total sewage discharged directly into water bodies was revised to 75% i.e., 25% of the wastewater generated is *effectively* treated (Kurian et al., 2013; CPCB, 2015).

Regarding wastewater reuse, the available estimates are based on selected class I and class II cities (893 in all)[17] and do not consider the smaller towns and hence the estimate is revised accordingly (20%). All these data are available readily and in near real-time. WREI can be estimated in two ways i. e, one by assuming that all the variables are equally important and carry the same weight and another that assumes that some variables are more important than others and hence carry different weights. In the case of equal weights, a simple average would generate the WREI. But when weights are accorded to each variable a weighted average is used to arrive at WREI. The weights are determined either with the help of regression analysis or expert opinion. Here, the weights are determined using the expert opinion. Weights reflect the relative importance of each variable in a country or regional context (**Figure 2**).

Following equation (1) above the normal WRI $(BCI)_{it}$ index with equal weights for India is 27.3 (**Table 2**). When differential weights are used for each component the index is estimated at 25.5. The indicator waste water reuse is given a weight of 50% while the other two are given 25% each to reflect the fact that reuse is the major component of total wastewater that is used. It is no surprise, therefore, that like in the case of Indonesia and Brazil reuse of wastewater in agriculture was emerging as a policy and legislative priority in India too, especially to address water scarcity in urban areas.

Expert opinion is also crucial in allocation of weights for the institutional component of the index (GSE). A total of 11 indicators are included in constructing the WRI $(GSE)_{it}$ component. Different weights are given to each indicator (**Table 3**). The socioeconomic sub-component is given a 25% weight, while environment and sustainability component are given 47% weight and Governance sub-component is given a 28% weight. In fact, weights are fixed for each indicator first and then summed up by sub-component. These weights are fixed based on a thorough review of literature on the subject and expert opinion. For instance, per capita GDP and people depending on waste water are given 10% weight and awareness is given a 5% weight. We can deduce that higher GDP per capita can positively influence wastewater reuse. But India is yet to acquire comparable levels of per capita GDP and hence a modest weight is given. Awareness about water quality risks are expected to put pressure on policy makers to improve the situation. But at the same time, given the multiple and competing developmental priorities such as income and employment generation, wastewater reuse receives low priority at the policy level given lower levels of per capita GDP.

In the case of environment and sustainability sub-component the population effected by waste water and area irrigated by waste water are given a 20% weight. The reason being that both these indicators directly affect the economy, viz., irrigated agriculture contributes to food security and livelihoods and health impacts of poor water quality can impose a burden on the economy. In the case of Governance sub-component the policy environment and decentralization are each given 10% weights. This is because despite a conducive policy environment in India [i.e., *'swatch bharat'* (clean India) initiative], which focuses on waste management, the mechanisms for policy enforcement remain weak. Furthermore, while political decentralization is theoretically known to play an important role in creating the right set of incentives for effective wastewater reuse, the process

[16]Professor V. Ratna Reddy in his capacity as Alexander von Humboldt Fellow at United Nations University Was invited to provide expert opinion on wastewater management in India.

[17]Based on the CPCB (2015). It is important to note that classification of cities is based on population size and periodically updated based on census reports.

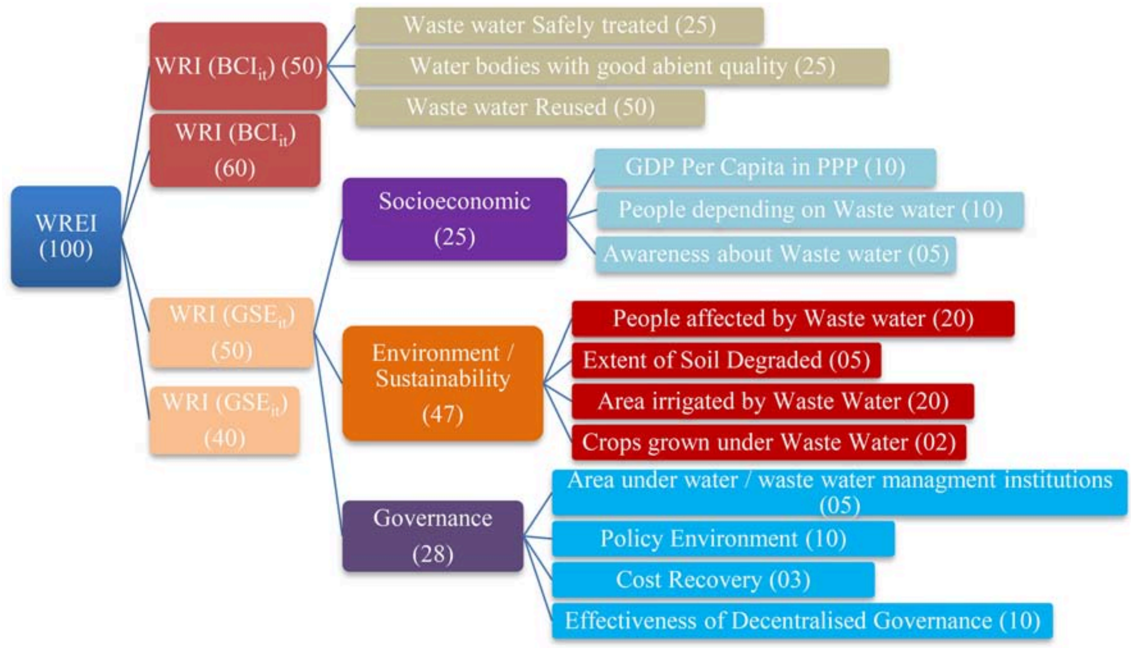

FIGURE 2 | Typology of indicators used to model effective wastewater reuse in India. Figures in Brackets are the Weights based on the experience from India.

TABLE 4 | Wastewater reuse effectiveness index developed based on data for India (WREI).

Scenarios	WRI (BCI) $_{it}$		WRI (GSE) $_{it}$		$WREI_{it}$	
	Normal	Weighted	Normal	Weighted	Normal	Weighted
Without weights (50:50)	13.7	12.8	13.4	8.0	27.1	20.8
With weights (SI: 60:40)	16.4	15.3	10.7	6.4	27.1	21.7
With weights (SII: 70:30)	19.1	17.9	8.0	4.8	27.1	22.7

SI, Scenario one; S-II, Scenario two.

of decentralization and devolution of powers in India has been slow (GoI, 2016).

The estimated normal WRI $(GSE)_{it}$ index component with equal weights is 26.7 and the weighted index is 15.9 for India (**Table 4**). The composite wastewater reuse effectiveness index ($WREI_{it}$) is then constructed using the component wise indices. Two scenarios are developed: one with normal (equal weights) and another with differentiating weights for each index. While the normal index is estimated at 27.1, the weighted indices range between 20.8 and 22.7 depending on weights i.e., 60:40/70:30 (**Table 4**). These indices can be compared across countries and ranked. In the case of cross- country comparisons, the use of a unified methodological framework and normalization of indicators can prove to be critical.

Integrative modeling of trade-offs that incorporates perspectives from both bio-physical and institutional domains will highlight the role of the political economy in decision making. Trade-off analysis will reflect the fact that policy and management choices that operate at global, national and local scales are guided by norms and agency and individual behavior with regards to allocation of financial and human resources and institutional capacity that can have an impact on the goal of balancing bio-physical risks with institutional ones. The systematic use of literature reviews and expert opinion to develop and pilot-test composite indices raises the prospect of a data light approach to monitoring SDGs; specifically, what are the merits of relying on extensive survey data compared to composite indices that are amenable to supporting benchmarking and scenario analysis and can provide the insight needed to inform decision-making and robust monitoring of global goals? (Kurian, 2017).

Global Monitoring Methodology That Incorporates Benchmarking and Scenarios

Plotting the hypothetical component wise scores of WREI for different countries/regions helps in understanding the role of governance/institutions in mobilizing public action in the form of finances, technology and skill sets to support an effective response to challenges posed by the fact that planetary boundaries are being reached. Such an approach to global monitoring can present a clear picture of the constraints various counties face and can serve as a basis for capacity building in support of normative change. **Figure 3** presents the hypothetical scores categorizing countries into one of the four quadrants (H:H); (L: L); (H: L) and (L:H). Quadrant one (Q_1) represents low BCI and GSE scores. The blue dots in this quadrant (Q_1) hypothetically represent countries (for example India: BCI: 17.9; GSE: 4.8). Quadrant four (Q_4) represents high BCI and

GSE scores where most developed countries are placed (H:H). The arrows indicate the desired direction of movement of the countries located in Q_1; Q_2 and Q_3. From a monitoring perspective it is desirable that countries move toward Q_4 i.e., toward achieving effective reuse (SDG 6.3). It may be noted that the countries in Q_1 could achieve the goal (moving to Q_4) either through Q_2 or Q_3 depending on their socioeconomic and policy environment. This hypothetical representation offers insights on how important it is to understand local context to explain the divergence between planetary scale imperatives of promoting reuse of resources and the administrative scale opportunities and constraints that would determine the scale and intensity of the institutional response that will ultimately drive the achievement of the SDGs.

We contend that the goal of global monitoring ultimately is not to prescribe institutional change in the form of budget allocations and staff reorganization but to consolidate the normative basis for effective wastewater reuse that incorporates a balanced view of both bio-physical dimensions associated with planetary boundaries and institutional ones of effectively delivering public services. The quadrants Q_2 or Q_3 as displayed in **Figure 3** could serve as a benchmark to predict effective wastewater reuse within individual countries. WREI can help to structure the discussion relating to the choice of norms, indicators and methodologies for data collection, analysis and synthesis and highlight the pressure this place on country nodal agencies[18] in terms of required capacities and skill sets for monitoring effective reuse of wastewater. This is especially the case in countries where data is not collected even for critical indicators like the quantity of waste water generated. While the Delphi technique could help in identifying the indicators, especially qualitative ones, skills and capacities are required to design and conduct Delphi studies at country level. Setting up the panel of experts, building consensus and organizing and validating the results prior to their use requires innovation in didactics and pedagogy which can become an additional focus of global public goods research undertaken by international organizations (Hsu and Sandford, 2007).

POLITICAL ECONOMY OF PUBLIC DECISION MAKING IN THE WATER-ENERGY-FOOD NEXUS

In the introduction of this paper we referred to the urgency for coupling global models of bio-physical change with models of institutional change at appropriate administrative scale. In this regard we pointed to the role of expert opinion in calibration of model prototypes with the objective of promoting analyses of dynamic socio-ecological systems. For this purpose, we would like to argue that place-based observatories can play an important role in developing and validating composite indices as a mechanism for monitoring global goals. The continuous back and forth that is required between theory, method and active engagement with considerations of revenue and expenditure that pre-occupy policy makers can be supported by online learning platforms, co-curation of data and models[19] and co-design of research questions (Kurian et al., 2016a). In the ensuing discussion we highlight some of the key insights of transdisciplinary scholarship that characterized our search for a robust monitoring methodology for SDG 6.3.

Interdependencies Based on Characteristics of Public Infrastructure

Water services may take the form of water supply, irrigation or wastewater treatment. Energy in the form of hydro-power or bio-energy is required to pump water supplies or treat wastewater. The costs of setting up "demand-driven"[20] infrastructure depends upon extent of local tariff collection and the type of technology that is chosen to provide the service. Cereal or pulses is produced using water that is pumped over long distances increasing both the risks and economies of scale of serving a larger population. Nevertheless, it is important to distinguish here between extension services and public services that play enabling roles in food production. Extension services are limited to information on crop varieties, fallow techniques or plant operations in the case of wastewater. Extension agencies also build "supply-driven" infrastructure to deal with specific environmental challenges like soil erosion. The durability of "supply-driven" infrastructure can have an impact on the reliability and quality of public services such as for example, hydro-power generation, water supply and irrigation that have the potential to influence levels of food security. In closed bounded[21] contexts it is relatively easier to make decisions based on a mapping of water, energy and food resources and infrastructure. However, in rapidly urbanizing regions where water, energy or food services may be procured from outside an administrative jurisdiction, the institutional risks are heightened because of increased uncertainties.

Differential Outcomes of Policy and Legal Instruments; The Role of Administrative Culture and Incentives

When decisions are made regarding water, energy and food services, especially in unbounded contexts, laws and policies must be implemented through recourse to instruments such as notifications, directives, guidelines, standards and circulars.

[18]From a monitoring perspective, nodal agencies could refer to entities that are responsible for collection and synthesis of data at country level such as for example, the bureau of statistics.

[19]Bousquet et al. (2002) advanced the idea of companion modeling which interactively combines agent-based modeling and role-playing games, and employs the latter to acquire knowledge, build and validate the agent-based model and use the model in the decision-making process.

[20]Demand driven infrastructure is infrastructure that is created to provide a service delivery function- eg. transport water from treatment facility or dam to end user. By contrast supply driven infrastructure refers to infrastructure that is created to respond to a challenge such as soil erosion- eg. a catchment forestry plantation.

[21] Bounded systems are where it is possible to procure resources such as water, energy or food to meet demands for public services locally. By contrast, systems for which resources such as water, energy or food have to be procured from outside a pre-defined physical or administrative boundary (eg. river basin or municipality) to meet demands for public services may be referred to as unbounded systems (Gregersen et al., 1989).

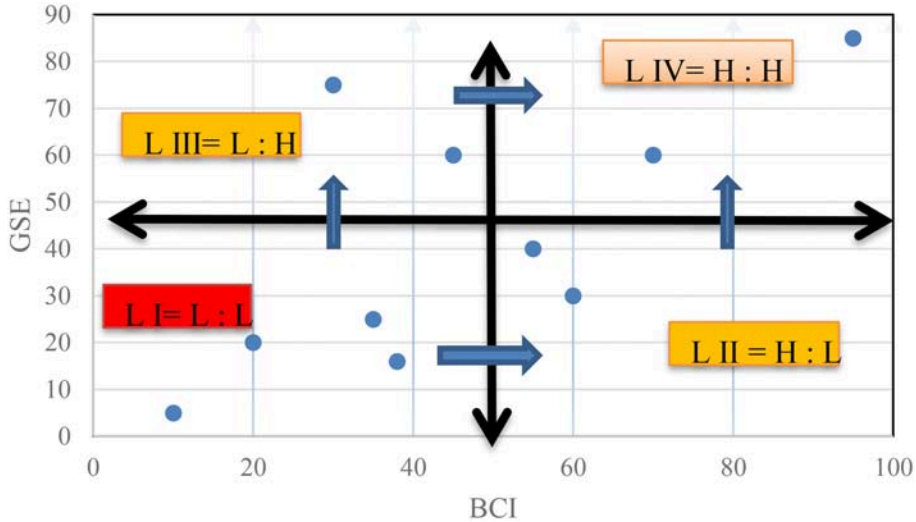

FIGURE 3 | A hypothetical ladder for monitoring effective wastewater reuse globally. $Q_{1...4}$, Quadrant; L, Low; H, High; Arrows indicate direction of movement.

These instruments that could be developed for a range of issues from technology choices to financing options could be interpreted and executed differently in different locations of a watershed, province or water user association (Agrawal, 2005). There could for instance, be perverse incentives that encourage public servants to construct water supply plants and wastewater treatment facilities without following guidelines with regards to operation and maintenance. In many instances administrative culture may differ and discretion may be exercised to larger or smaller degrees affecting program or project outcomes such as public health or food security. Optimization principles of reuse and recycle may be theoretically appealing but their actual realization at administrative scale is determined by "allocative" decisions, alignment of rules and existence of a critical mass of networked functionaries within line departments responsible for delivery of water, energy and food services (World Bank, 2004). This could produce differential results in terms of enhancing water, energy and food security (Dasgupta et al., 2005).

Financing Decisions and Institutional Risk Thresholds

The concept of a Nexus trade-off purports not to eliminate risks altogether be they institutional or bio-physical. Rather, the concept emphasizes the need to manage a balance between bio-physical and institutional risks. In other words, how to balance the risk of extreme water scarcity with the risk of extreme inequity in distribution of public services? By implication institutional thresholds of risk are shaped by two factors: (a) the quantum of environmental resources (e.g., Water or energy) required to produce potable/treated wastewater and (b) acceptable levels of distributional equity among consumers required to produce a given level of public services. A larger affected population could potentially lower institutional risk through the effect that economies of scale can have on lower costs of treating and transporting water (World Bank, 2006). On the other hand, a larger affected population could necessitate higher sunk costs for infrastructure which once created cannot be easily be altered without generating higher levels of institutional risk in the form of decaying infrastructure due to inability to allocate revenues toward Operation and Maintenance (O&M) (Savedoff and Spiller, 1999). In the absence of well-designed central transfers and subsidy schemes institutional risk may become pronounced (**Annexure 3**). The exact thresholds of institutional risk would, however be influenced by local context. For example, region specific rainfall patterns and locally acceptable levels of water use given the nature of agro-ecological conditions can define exact thresholds of institutional risk (Weckenbrock and Alabaster, 2015).

Design of Field Trials for Impact Evaluations of Food Production

At present NRM research is dominated by bio-physical perspectives of environmental change. We concur with (Albrecht et al., 2018) and others who have argued that the absence of integrative analysis incorporating perspectives on constraints and opportunities from the institutional domain leaves us with an incomplete understanding of prospects for environmental management. This incomplete view can lead us to over-emphasize environmental risk and be overly optimistic about the role of technology and financing in advancing sustainability. Our analysis leads us to believe in the need for a renewed theory of change focussed on adapting hypothesis and explanation to insights gleaned from data and without being over ambitious about fitting data to dominant models of environmental change (see also Pearl and Mackanzie, 2018). Such a renewal in scientific approach has implications broadly for how we structure learning and capacity development to inform feedback into governance structures and processes. One of the specific ways in which feedback into governance processes can be beneficial is to improve design of Randomized Control Trials (RCT's) to support the validation of composite indices in policy making.

Inaction and Siloes in Public Decision Making

When coordination results in inaction with regards to responding to well-established institutional or bio-physical risks, the prospects of achieving water, energy and food security are undermined. The recourse to food aid or extensive subsidies will not improve the prospects of sustainable development since they can undermine the development of local institutions (Ostrom, 1990). When there is a tendency to invest in human resource development at the cost of creating incentives for individuals to cooperate across departmental silos then even the largest expenditure programs will not result in sustainable improvements in water, energy and food security (see Wichelns, 2017). Instead they are more likely to produce rebound effects that entrench siloes in agricultural development and exacerbate certain risks such as the depletion of organic carbon or nitrogen in soils because of intensified agricultural practices.

Enabling the Development and Validation of Coupled Models of Water-Energy- Food Interactions via Place-Based Observatories[22]

Experiments repeatedly find that communication bolsters cooperation, but do not explain why (Poteete et al., 2010, p. 211). Stakeholder engagement is key to developing models that can explain and possibly predict the behavior of agents within a complex and changing political economy. Therefore, a prerequisite for the development, calibration and validation of coupled models of effective wastewater reuse is the documentation of protocols in agent- based modeling so that scholars can check and build upon each other's work (Poteete et al., 2010, p. 177). Place-based observatories by supporting the development of such protocols could enable the scaling up of results of research for use by decision makers (**Figure 4**). In this connection, the development, validation and pilot-testing of the WREI emphasized the importance of organizing data and models related on water resources, water quality, water reuse, administrative decentralization, risk assessments and climate variability. The exercise emphasized the imperative of downscaling global environmental models to support local decision making through provision of site-specific information (e.g., rainfall and temperature) from regional networks of independent researchers and institutes[23]. Second, place-based observatories can foster cooperation among networks of researchers and institutes to co-create a research question based on a unified interpretation of a policy challenge. Third, place-based observatories can support the development of typologies based for a given development challenge: example, salinization or soil erosion. Fourth, place-based observatories can structure data sets, analytical methods[24] and results in a practical manner through use of knowledge translation tools such as scenario analysis, agent-based modeling, composite indices and performance benchmarking (Kanter et al., 2018; Kurian et al., 2018). Finally, place-based observatories can facilitate valorisation of data and models aimed at the design, implementation, monitoring and evaluation of case studies that pilot-test and validate Nexus typologies and thresholds in development practice.

IMPLICATIONS FOR GLOBAL PUBLIC GOODS RESEARCH

This paper by undertaking a critical examination of the recent UN-WATER directive on SDG target 6.3 shows that synergies are required to ensure coordination between UN agencies (*on norms and indicators*), Member States (*on coherence of policy instruments*) and consumers (*on perceptions of safety and affordability of services*) to advance the achievement of the goal of reuse of wastewater. In this paper we demonstrate how the development, pilot-testing and validation of the Wastewater Reuse Effectiveness Index (WREI) relied upon data valorization, expert opinion and coupling of bio-physical and institutional models of water-energy-food interactions. In doing so we highlight the applications of the Nexus approach in managing trade-offs and fostering synergies in environmental planning and management. But, one *swallow does not make a summer* because in the absence of future analyses that adopts a multi-dimensional approach to monitoring of SDG's the credibility of the global monitoring framework itself can be undermined.

The WREI offers a refreshingly novel perspective on monitoring SDG target 6.3 by pointing out that *effective* reuse of wastewater can emerge only when a threshold of bio-physical risk (e.g., for water quality or precipitation) is crossed that is backed by governance / institutional resources in the form of financing, trained functionaries and networks for information sharing within public agencies. This makes the WREI not only effective but also sustainable in the long run, as technologies and policies may not sustain in

[22]Hall and (Hall Tiropanis, 2012) outline several key principles that can guide the management of place-based observatories: (a) access to distributed repositories of data, open data, online social network data and web-archive, (b) harmonized access to distributed repositories of visual/analytical tools to support quantitative and qualtitative research methods that Are inter-operable With either public and private data sets, (c) shared methodologies for facilitating the harvesting of additional data sources and development of novel analytical methods and visualization tools to address social challenges and promote innovation, (d) a forum for discussion about an ethics framework on the archiving and processing of web data and relevant policies and € a data-licensing framework for archived data and the results of processing of those data.

[23]Future research can clarify the role of observatories for global monitoring by pursuing the following questions: (a) what steps are involved in supporting data valorization through collection, sharing, analysis, decision making and coordinated action? (b) how can composite indices be developed to support interpolation between points of global/regional data and (c) how can interpolated fields be developed to support documentation of larger scale influences and enhance feedback into institutional and policy structures and processes? (see Schonberger and Cuker, 2013).

[24]For a recent example of methodological innovation with reference to use of multi-way modeling and self-organizing maps to study wastewater irrigation (see Jampani et al., 2018).

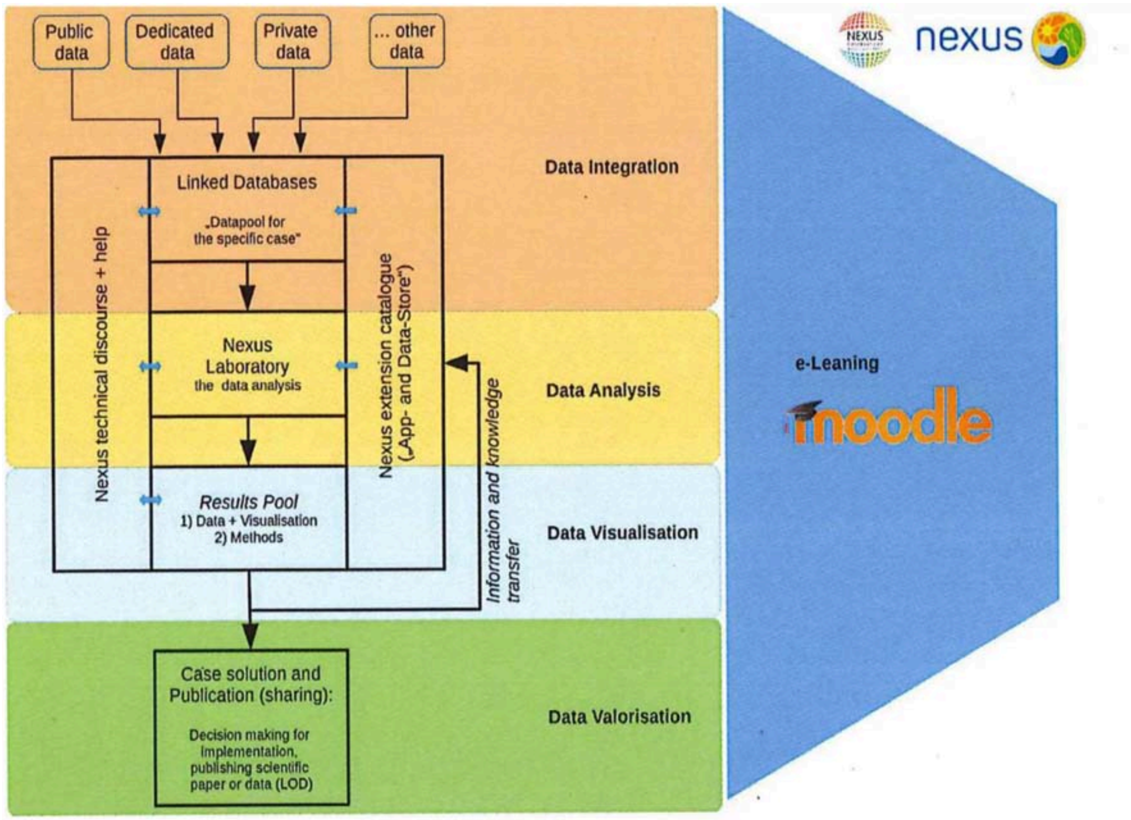

FIGURE 4 | A stylized computing workflow for an observatory. Adapted from Kurian et al. (2018).

the absence of good governance viz., appropriate institutions and enforcement mechanisms. To monitor effective reuse a composite index would leave the selection of indicators for bio-physical and institutional components to entities at appropriate administrative scale but ensure that the indicators/variables once identified through rigorous local vetting and discussions would support comparative analysis. An iterative process of designing, validating and pilot-testing of composite indices can overcome the challenge of attributing research results to policy outcomes which has proved to be the bane of global public goods research (see Renkow, 2018).

In this paper we argue that robust monitoring must encourage discussions of indicators, variables, data gathering and incentives that have the potential to generate sustainable improvements on-the-ground. The construction of the Wastewater Reuse Effectiveness Index (WREI) was guided by the goal of clarifying the basis for normative change- in other words how can wastewater reuse be effectively promoted to respond to global concerns of water scarcity, poverty and climate change? The adoption of a Nexus framework for the analysis highlighted crucial trade-offs both among environmental resources (for example- water, soil and waste) and delivery of public services (for example- irrigation, water supply, wastewater treatment) with potential to address the challenge of water, energy and food security. For example, while recycled water, desalination and rainwater collection may contribute to water security, they may increase energy requirements and the risks of contamination of potable water with consequences for public health. Furthermore, the predicted reduction in demand for potable water due to the implementation of alternative solutions may be smaller than expected precisely because for example, cost savings may drive up demand for services by consumers. The fact that all these effects are highly context specific in turn makes them difficult to predict. It is in this connection that place-based observatories can play an important role in supporting trans-disciplinary research by downscaling global environmental models, developing nexus typologies of a developmental challenge and supporting data valorization and knowledge translation.

Our analysis makes us skeptical about the prospects of global public goods research when it comes to advocating for institutional in contrast to normative change. This is because the effect of proposals for reform of budgetary strategies, plans for staff retrenchment and organizational re-structuring on policy outcomes can be multi-dimensional, recursive and non-monotonic (Bardhan and Dayton-Johnson, 2002). Therefore, taking a different approach we return to two questions that were raised on page 5 of this paper: how do decision makers forecast future developments? and (b) what do decision makers believe or ignore? Both these questions have implications for the political economy of public-decision making and future Nexus research is underway or being proposed to more rigorously test the hypotheses outlined below:

Hypothesis 1: Focussing on Norms and Intention of Agents with reference to Resource Reuse & Recovery

- Countries/regions that are successful with effective reuse of wastewater are more likely to be *already* successful with delivering public services; the quantum of available financing, skills and technology need not *a-priori* be a constraint and,

Hypothesis 2: Focussing on Observatories as Mechanisms for Knowledge Translation with reference to Wastewater Reuse in Agriculture

- Countries/regions that do not pursue effective reuse of wastewater in agriculture despite compelling environmental pressures in the form of for example, water scarcity or declining water quality may benefit from impact evaluations that support the development and pilot-testing of policy instruments (guidelines, notifications, standards, circulars, and directives) with the potential to aid uptake of technical options (for example, conservation agriculture, integrated soil fertility management, alternate wet-drying, micro-dosing or agro-forestry) based on a robust typology of wastewater management and integrative Nexus thresholds to public action.

AUTHOR'S NOTE

This hypothesis and theory article is the culmination of 6 years of multi-country and trans-disciplinary collaboration on the Water-Energy-Food (WEF) Nexus involving partners at the United Nations University (UNU-FLORES), United Nations Human Settlements Programme (UNHABITAT), University of Arizona, USA, Livelihoods and Natural Resources Management Institute, India, University of São Paulo, Brazil, Texas A&M University, USA and Bogor Agricultural University, Indonesia.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

FUNDING

Core budget of UNU-FLORES, Dresden, Germany for Capacity Development and Governance (CDG) Unit, 2013-18 (project numbers: 2389 and 9371).

ACKNOWLEDGMENTS

The preparation of this paper was funded by the UNU-FLORES projects titled development, validation and pilot-testing of monitoring methodology for SDG 6.3 (project code: 9371) and Nexus Observatory- data, monitoring and governance (project code: 2389). The corresponding author acknowledges the support of Reza Ardakanian (founding Director of UNU-FLORES), UNU-FLORES Ph.D. Cohorts, Manfred Buchroithner and Christian Bernhofer (TuD), Andrew Noble (SEI), Claudia Ringler (IFPRI), Stephan Huelsmann, Lulu Zhang, Rachel Ahrens, Mahesh Jampani, Andrea Mueller, Sekela Twisa, Solomon Gebrechorkos, Kristin Meyer, Yohannas Subhagadis, Ministry of Construction, Vietnam, Institute of Global Environmental Strategies, Japan, Arab Countries Water Utilities Association, Jordan, Ministry of Environment, Indonesia, Ministry of Water Resources and Sanitation, Sao Paulo, Brazil, Linda Veiga (University of Minho), GIZ, Belmont/H2020 Nexus Consortium and the Alexander von Humboldt Foundation, Bonn in developing some of the ideas contained in this paper. Earlier iterations of this paper also benefitted from discussions at the Chapel Hill Nexus Conference at University of North Carolina and the Consultative Group on International Agriculture Research (CGIAR) Science Forum 2018 organized by the Independent Science Partnership Council (ISPC), FAO, Rome for which the authors are grateful to Leslie Lipper and Preet Lidder. Three reviewers and Yu Kojima offered critical comments on an earlier draft of the paper.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2019.00032/full#supplementary-material

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The handling editor and reviewer RGL declared their involvement as co-editors in the Research Topic, and confirm the absence of any other collaboration.

frontiers in Environmental Science

ORIGINAL RESEARCH
published: 12 April 2019
doi: 10.3389/fenvs.2019.00037

How Methods for Navigating Uncertainty Connect Science and Policy at the Water-Energy-Food Nexus

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Specialty section:
This article was submitted to Freshwater Science, a section of the journal Frontiers in Environmental Science

Received: 11 September 2018
Accepted: 01 March 2019
Published: 12 April 2019

Citation:
Yung L, Louder E, Gallagher LA, Jones K and Wyborn C (2019) How Methods for Navigating Uncertainty Connect Science and Policy at the Water-Energy-Food Nexus. Front. Environ. Sci. 7:37. doi: 10.3389/fenvs.2019.00037

As the water-energy-food (WEF) nexus becomes an increasingly common framework for bridging science and policy, there is a growing need to unpack and make explicit many of the methods and assumptions being used to operationalize the nexus. In this paper, we focus on two common approaches to nexus research, quantitative modeling and futures thinking, and the ways that each set of methodological tools address uncertainty. We first review the underlying assumptions of each approach with a focus on sources of and ability to measure uncertainty, and potential complementarities. Quantitative modeling takes a probabilistic approach to predicting the likelihood of a specific outcome or future state based on estimates of current system dynamics. In contrast, futures thinking approaches, such as scenario processes, explore novel changes that cannot be fully predicted or even anticipated based on current understandings of the nexus. We then examine a set of applied nexus projects that bridge science and policy-making contexts to better understand practitioner experiences with different methodological tools and how they are utilized to navigate uncertainty. We explore one nexus case study, LIVES Cambodia, in-depth, to better understand the opportunities and challenges associated with participatory modeling and stakeholder engagement with uncertainty in a policy-making context. Across the cases, practitioners identify the complementarity between modeling and futures thinking approaches, and those projects that integrated both into the planning process experienced benefits from having multiple angles on uncertainty within the nexus. In particular, stakeholder engagement provided critical opportunities to address some types of uncertainties (e.g., data gaps) through the use of local knowledge. Explicit discussions of model uncertainty and use of scenario processes also enabled stakeholders to deepen their understandings of uncertainties and envision policy pathways that would be robust to uncertainty. In many senses, models became boundary objects that encouraged critical thinking and questioning of assumptions across diverse stakeholders. And, for some nexus projects, confronting uncertainty in explicit and transparent ways build capacity for policy flexibility and adaptiveness. We conclude with a discussion of when and how these benefits can be fully realized through the strategic use of appropriate approaches to characterizing and navigating nexus uncertainty.

Keywords: water-energy-food, nexus, governance, modeling, futures thinking, scenario planning, stakeholder engagement

INTRODUCTION

In the context of global environmental change and efforts to achieve the United Nations Sustainable Development Goals, the water-energy-food (WEF) nexus framework is increasingly promoted as a means to integrate across systems and solution, identify and address risks, and ultimately contribute to sustainability (Bazilian et al., 2011; Hoff, 2011; Hussey and Pittock, 2012; Boas et al., 2016; Benson et al., 2017; Weitz et al., 2017a; Simpson and Jewitt, 2019). Nexus research explicitly connects human and natural systems, in order to provide a more complete picture about the causes and consequences of change. Realizing the potential of the nexus framework requires making decisions with the future in mind. But future nexus interactions are uncertain, and both research and practice must effectively account for a range of uncertainties.

One of the core assumptions articulated in nexus literature is that improved integration across water, energy, and food will contribute to sustainability (Bazilian et al., 2011; Hoff, 2011; Weitz et al., 2017a). However, while the concept of "the nexus" helps identify cross-cutting research questions, truly integrated analytical approaches that can be readily translated into coherent cross-sectoral and scale policy have been lacking (for recent critiques of the nexus, see Bazilian et al., 2011; Allan et al., 2015; Nature, 2016; Endo et al., 2017; Weitz et al., 2017b). While nexus research is often framed by social-ecological systems questions, and therefore requiring interdisciplinary approaches, much of this research applies engineering approaches to specific technical problems, investing in additional data sets and modeling techniques relevant to those problems (Dai et al., 2018). Oftentimes, the narrow focus on technical problems and engineering solutions are inadequate for policy makers who need to assess risks, trade-offs, and synergies across a broader suite of nexus interactions (Benson et al., 2017) and address uncertainty about how systems will change in the future (Peronne and Hornberger, 2014).

While uncertainty may not always be at the forefront in nexus publications, nexus work is fundamentally concerned with future uncertainty, through its engagement with complex systems, non-linearity, and interlinkages, as well as its concern with climate change and the trajectories of human communities and the natural resources they depend on. There is inherent uncertainty in how we might maintain ecological integrity and water, energy and food securities given the complex interplay of global earth systems and localized drivers of change. In the context of unprecedented global environmental change, scholars, policy makers, and practitioners increasingly call for greater attention to uncertainty in social-ecological systems (Gallopin, 2006; Binder et al., 2013; D'Odorico et al., 2018). There is growing attention to the ways in which systems exhibit non-linear behavior, and the limits to which past conditions can inform our understanding of the future. Over the past decade, scholars have increasingly problematize the idea of "stationarity," or the notion that natural systems function within a known envelope of variability (Milly et al., 2008; Gober, 2014; Poff et al., 2016). Problems that reflect cross-system dynamics are sometimes conceptualized as "wicked," where the nature of the problem is novel, not fully understood, and solutions are neither obvious nor agreed upon (Head, 2018). At the nexus, the scale and complexity of wicked problems make management and planning difficult, as decision-makers cannot observe all the ways in which one sector impacts another and what ripple effects this causes across different populations, scales, geographies, and time periods.

The following three challenges need to be addressed for the nexus framework to effectively characterize and address the uncertainties inherent in real-world WEF problems: (1) Resolving the technical challenge of analyses across sectors (e.g., water, energy, food) in a way that is robust, transparent, and credible to diverse stakeholders (Shannak et al., 2018); (2) Recognizing the governance challenge in building the legitimacy and salience of these various analytic tools so that they enable inclusive decision making that acknowledges contested views and values (Weitz et al., 2017b); and (3) Recognizing and addressing deep uncertainty about the future to identify robust policy choices likely to perform as intended over multiple possible futures (Herman et al., 2014).

Although the nexus framework inherently engages with future uncertainty, we argue that nexus work would benefit from more deliberate and in-depth attention to how various analytic tools, from quantitative modeling to qualitative futures thinking, fit into the nexus "toolbox" and nexus policy-making. This paper builds upon recent work calling for a pragmatic and integrated approach to addressing uncertainty in complex systems research and adaptive management (Chaffin and Gunderson, 2016; Memarzadeh and Boettiger, 2018). We first review and synthesize the ways that uncertainty is conceptualized in different analytic tools commonly used in nexus projects. We then present an analysis of applied nexus projects and how they integrate future uncertainty into analyses and decision-making. We provide an in-depth review of the LIVES (Linked Indicators for Vital Ecosystem Services) Cambodia project. This project conducted both qualitative and quantitative nexus modeling through a participatory process that integrated stakeholder knowledge of situated uncertainties into system dynamics model building and scenario development in support of sustainable development planning in the Mekong river basin.

Based on analysis of these nexus projects, this paper examines the barriers and opportunities for integrating quantitative modeling and qualitative futures thinking, and what that means for nexus governance and policy-making.

LITERATURE REVIEW

With nexus efforts developing at pace, one of the frontiers for nexus research is assessing the value of the nexus to support policy and practice (Ringler et al., 2013; Howells and Rogner, 2014; Gain et al., 2015; Boas et al., 2016; de Strasser et al., 2016; Gallagher et al., 2016; Grafton et al., 2016; Benson et al., 2017; Hagemann and Kirschke, 2017; Pahl-Wostl, 2017; Scott, 2017; Weitz et al., 2017b). Recent reviews suggest that the majority of nexus research aims to understand or quantify nexus interactions as opposed to addressing the challenges of policy and governance (Endo et al., 2017; Albrecht et al., 2018; Dai et al., 2018; Shannak et al., 2018). Nexus research is often justified with neo-Malthusian statements and statistics about growing populations, imminent water shortages, and the need to increase energy and food production. For example, Endo et al. (2017:21) commence by stating that "demands for water, energy and food are estimated to increase by 40, 50, and 35%, respectively by 2030." Similarly, in characterizing South Asia, Rasul (2016:15) states that "land, water and vital ecosystem resources are dwindling, but the population is growing." Such precautions set the imperative for analyses that optimize resource systems and increase efficiency across sectors, but the underlying assumption is that improved knowledge of nexus interactions will improve policy-making.

Most nexus projects recognize the need to address future uncertainty in both analyses and decision-making. For example, some nexus projects discuss the ways in which climate change might alter model results (e.g., Khan et al., 2017; Warmink et al., 2017) or how uncertainty about the accuracy and precision of particular data leads to instability in parameterization (e.g., Herman et al., 2014; Al-Ansari et al., 2015). However, very few nexus projects have well-developed, transparent processes for dealing with uncertainty, and assumptions about uncertainty vary greatly between quantitative modeling and qualitative futures thinking (Zinn, 2016). The diversity of definitions of, and assumptions about, uncertainty in nexus research and practice reflect more general characterizations of uncertainty across different disciplinary and epistemological traditions. An oft quoted typology comes from Donald Rumsfeld: known knowns (what we know we know), known unknowns (what we know we don't know), and unknown unknowns (what we don't even know we don't know). Perhaps the most important distinction within the literature is between risk, the probability of a particular outcome from a known distribution of outcomes (Beck, 1996; Polasky et al., 2011), and true uncertainty, which is fundamentally unquantifiable (Stirling, 2010; Pielke, 2012). First distinguished by economist Frank Knight, the latter is often referred to as Knightian uncertainty (e.g., Stirling, 2010), deep uncertainty (e.g., Maier et al., 2016), or ignorance (e.g., Rayner, 2012). In contrast, risk is often characterized as a relatively known unknown, especially in quantitative analyses. Statistical techniques are increasingly able to include unknown error terms in models, and to test the impacts of those errors (known unknowns) on the outputs of complex models [examples of these techniques include sensitivity analyses and mixed modeling with random effects (Bolker et al., 2009; Albrecht et al., 2018)]. In other words, the likelihood (risk) of, and difference in, outcomes associated with any particular future value of a given variable can be explored mathematically. However, quantification of risk cannot capture deep uncertainty, since by definition the likelihood, magnitude, and direction of those uncertainties is not fully or discretely known in the current moment. Thus, qualitative futures thinking, in particular scenario processes, are seen as a promising method that enables the integration of deep uncertainty into analyses and policy-making.

Uncertainty in Quantitative Modeling at Nexus

Currently, most nexus research utilizes quantitative modeling techniques to build knowledge of the dynamics and mechanisms within water-energy-food systems, to identify potential inflection points arising from interconnections and dependencies, and to project the possible outcomes of specific interactions and decisions (Endo et al., 2017; Kaddoura and El Khatib, 2017; Albrecht et al., 2018; Dai et al., 2018; Shannak et al., 2018). For example, coupled systems approaches highlight uncertainty and change, and focus on leveraging feedback processes to achieve improvement or difference across multiple components of systems (Carr et al., 2013; Antle, 2015; Fader et al., 2016). Gallopín et al. (2001:222) explain the orientating assumption of coupled systems analyses: "fundamental uncertainty is introduced both by our limited understanding of human ecological processes, by the intrinsic indeterminism of complex dynamic systems, and by myriad human goals." One key feature of the coupled systems approach is the need to incorporate spatial and temporal heterogeneity, but empirical analysis is often limited by data availability as well as by data quality. For example, until recently, the costs associated with gathering longitudinal data on natural systems precluded wide-scale coverage, and thus the historical record does not extend back very far at high temporal resolutions and broad spatial scales (Liu et al., 2007). Analyses therefore often use simulation approaches to model heterogeneity and probability of change in populations and systems, approaches that derive from both ecology (Holling, 2004) and theoretical economics (Antle et al., 2014).

Similarly, risk assessments characterizing relationships and potential feedbacks across system components often use simulations and statistical models that predict the likelihood of a specific risk or hazard and its impacts in a given place or on a given system (Healy et al., 2015; Roberts and Barton, 2015). Measuring risk often relies on financial valuation of the potential and actual negative impacts of natural and social phenomena to help make decisions about costs, benefits, and trade-offs associated with changes in a system (Daily et al., 2009; Poppy et al., 2014; Devineni et al., 2015). Another common quantitative approach in nexus research, life-cycle analysis (LCA) and associated flows research, incorporates uncertainty into macro or aggregate analyses of balance sheets and footprints (Ramaswami and Chavez, 2013; Blanchard and Fabrycky, 2014; Tilman and Clark, 2014). Heijungs and Huijbregts (2004) identify the statistical approaches used in LCA to address data gaps and data quality issues, which most commonly use frequentist statistics to determine confidence intervals and sensitivity analyses.

Advancements in various types of simulation and systems dynamics models have enabled uncertainty to be characterized in increasingly sophisticated ways. For example, agent-based modeling and Monte Carlo simulations can characterize impacts (or effects) of system dynamics even when the adequacy or accuracy of effect measurements are unknown. These techniques are able to communicate effect uncertainty not only as a single probability of occurrence, but also as a range of likelihoods (the potential risk) that an effect will occur. However, these models are more limited in their ability to integrate uncertainties that have not been measured with much precision or consistency, are inherently difficult to quantify, or are simply unknown. For example, if there are elements of the system that are qualitative in nature, such as future political will or technological innovation, attempts to quantify them in models may be meaningless. Further, if particular drivers, relationships, or outcomes are unknown, the very structure of the model produces uncertainty that cannot be dealt with mathematically. In short, contemporary and cutting-edge quantitative modeling approaches often used in nexus analyses are increasingly sophisticated at incorporating known unknowns, but by definition cannot capture parameters about which there is deep uncertainty.

Scholars and practitioners are increasingly calling for processes that engage stakeholders in thinking about the assumptions, strengths, and limitations of models and how conceptual and quantitative models fit into nexus governance and policy-making (see for example, Kumazawa et al., 2017; Pahl-Wostl, 2017; Bieber et al., 2018).

Uncertainty and Futures Thinking at the WEF Nexus

Futures thinking offers a distinctively different way of addressing uncertainty, as compared with the kinds of quantitative analyses typically used in nexus research. Futures thinking draws on a range of approaches that explicitly engage with deep uncertainty and attempt to integrate uncertainty into policy-making in ways that improve future outcomes. These approaches focus on current system dynamics and the multiple possible futures that could emerge from these. In preparing for multiple futures, futures thinking requires decision-makers to carefully consider the driving forces, key elements, assumptions, and even worldviews driving the system of interest, essentially, all the elements which could change in the future. This facilitates deep reflection on the current system structure, including transitions, thresholds, and tipping points, and the flexibility and capacity needed to deal with and manage (rather than mitigate and minimize) uncertainty. There is a growing call for adoption of future-oriented approaches to complex problems, such as those at the water-energy-food nexus (e.g., Kelly et al., 2004; Wyborn et al., 2016).

Futures thinking integrates a range of quantitative and qualitative approaches, including data mining (examining large data sets to identify trends), Delphi method (the questioning of expert panels), backcasting (where one future is envisioned and then traced backwards to the present (Boulding and Boulding, 1995), and visioning (imagining the ideal future). However, scenario planning is often regarded as the cornerstone of futures thinking due to its explicit focus on a range of plausible futures (Kelly et al., 2004). In scenario planning, a range of possible future situations are identified, highlighting the interactions between forces and elements in a system (Amer et al., 2013). In general, requirements for scenarios are that they are internally coherent, plausible, and fundamentally distinct from one another (Kelly et al., 2004). Typically the number of scenarios ranges from 2 to 6, and they can be normative (identifying a desired future) or descriptive (Bezold, 2009). A common approach is to consider archetypal scenarios, for example continued growth, collapse, steady state, and transformation (Dator, 2009).

A key theme of futures thinking is that the future is not deterministic; it takes as a central tenet that there is no one future that can be predicted, hence the focus on multiple futures (Kuosa, 2010). The goal of futures thinking is not to forecast the future, but to foster flexible and innovative thinking, or "stretch the strategist's imagination" (Bezold, 2009:86) by considering multiple possibilities. In this sense, it is more about stimulating a certain type of thinking and capacity than it is seeking concrete answers about what the future will look like. Thus, a key tenet of futures thinking is an engagement with and attention to uncertainty, including building mechanisms and capacities for adapting to change in the face of true surprises. For example, while scenario planning may integrate quantitative information, futures thinking does not ultimately quantify uncertainty or treated it as a risk or probability (Raskin et al., 2014). Instead, scenarios examine a range of plausible futures based on current science and on-the-ground knowledge, and then use those scenarios to develop actions that are robust to uncertainty. As Inayatullah (2008:6) says, "alternative futures thinking reminds us that while we cannot predict a particular future accurately, by focusing on a range of alternatives, we can better prepare for uncertainty, indeed to some extent, embrace uncertainty."

A key strength of futures thinking is that it brings uncertainty to the forefront. In futures thinking approaches, uncertainty is not minimized or ignored, or necessarily quantified, but rather used to foster new types of decision making, as well as new criteria for evaluating decisions. For example, a decision may be judged based on how reversible, how flexible, how adaptive, how robust it is, rather than how optimal it is based on limited existing knowledge (Stirling, 2010). At the same time, purely qualitative approaches do not realize some of the key benefits of quantitative modeling. Models and modern computing power can perform calculations about system linkages and dynamics that human brains are not capable of. Furthermore, the probabilistic approach to uncertainty taken by quantitative models can provide some estimate of the likelihood

TABLE 1 | A typology of sources of uncertainties and methods to include uncertainty in water-energy-food nexus research and application.

Sources of uncertainty	Description of uncertainty	Methods for including uncertainty
Conflicting science	Different studies or models point to different outcomes (e.g., whether precipitation will increase or decrease in the Northern Rockies as a result of climate change)	Scenario thinking Simulation models (multiple parameterizations)
Data gaps	Scientific research that could be pursued but has not yet been conducted (e.g., how replacing protein from fish with protein from agriculture will impact water pollution)	Mechanistic and simulation models Interpolation and inferential statistics
Biophysical relationships	Relationships between organisms and ecosystem processes (e.g., how new aquatic invasives will impact food webs)	System dynamics models Production function models? Species distribution models?
Extreme events	Uncertainty about the future likelihood, frequency, intensity, or duration of extreme events (e.g., flooding or drought)	Scenario thinking Simulation models of probability of risk Frequentist statistics
Solutions	The efficacy of particular solutions (e.g., how much will pump hydro help us smooth out variability in renewable energy)	Scenario thinking Simulation models of system dynamics
Long term impacts	The long-term consequences of actions being pursued now (e.g., long-term water pollution from hydraulic fracturing)	Life-cycle analysis Sensitivity analysis
Technological	What kinds of innovations will be available and when (e.g., advances in battery technology or sediment transport through dams)	Forecasting
Economic	Future prices, investments, and market conditions (e.g., the price of solar or coal)	Quantitative and qualitative forecasting models Sensitivity analysis
Political	What policies will be passed or eliminated (e.g., energy or agricultural subsidies, regulations on water pollution)	Stochastic and Bayesian statistics
Geopolitical	What policies and projects other nations will pursue (e.g., dam building in upstream nations)	Stochastic and Bayesian statistics
Social	What the public will think and do (e.g., voting behavior, consumer preferences)	Agent-based modeling Stakeholder analysis
Unknown unknowns	We do not even know which questions to ask	Accepting deep uncertainty

Portions of this typology were generated by graduate students in the UM BRIDGES Food-Energy-Water Nexus course at the University of Montana.

of specific future scenarios, which can help to focus discussion and possible investments of scarce resources. In some cases, models results are surprising and point to future trends or risks that would not otherwise be anticipated.

Integrating Quantitative Modeling and Futures Thinking to Support Nexus Governance

If, as Stirling (2015:5) argues, the nexus must "go beyond narrow risk-based methods of 'sound scientific' 'evidence based policy' to more fully address uncertainty, ambiguity, and ignorance," then nexus research and practice must expand the frameworks and methods on which it draws. Stirling's (2015) comparison of nexus studies analyzes how, within each study, the level of uncertainty was described as minimal, but comparing across studies, supposedly certain results differ dramatically. One way to address the limitations and partiality of most nexus analyses is to integrate the assumptions and approaches to dealing with uncertainty that are inherent in any single analytical approach, quantitative or qualitative. In **Table 1** below, we present a typology summarizing the main sources of uncertainty identified in the nexus literature, as well as the analytical techniques typically used to address these uncertainties.

There are three reasons why we argue that integrating multiple analytic techniques, such as quantitative modeling and qualitative futures thinking, might produce results that are more policy-relevant as compared with using any single approach.

Firstly, mixed methods approaches are needed for analysis of complex and uncertain social-ecological systems because these systems are subject to constant, non-linear change. Interestingly, the two approaches described above, quantitative modeling and qualitative futures thinking, are rarely used together in nexus analyses. The divide between quantitative and qualitative approaches to uncertainty is problematic because it limits our ability to draw on the different strengths and potential synergies of these different methods, and ultimately contribute to the science-policy integration required for effective WEF governance [as identified by Doll and Romero-Lankao (2016); Weitz et al. (2017b)]. The role that uncertainty plays in different epistemological and disciplinary approaches has long been the subject of discussion by both philosophers of science and applied researchers (Samuelson, 1963; Schwandt, 1989). Contemporary theory and research focused on addressing complex sustainability challenges has begun to address head-on the underpinnings and manifestations of different conceptualizations of risk, uncertainty, and future possibility (e.g., Zinn, 2016; Warmink et al., 2017). An explicit engagement with futures thinking and with deep uncertainty, which requires acknowledging the unknowns beyond those that can be dealt with quantitatively in a model, could begin to address concerns raised by some quantitative researchers who worry that discussing uncertainty will undermine the perceived legitimacy of complex systems modeling (Doll and Romero-Lankao, 2016). Identifying the types of uncertainty that can be dealt with in robust ways within quantitative modeling provides both clarity about the strengths and clear delineation of the limitations of such modeling (Uusitalo et al., 2015).

Second, science-policy activities that do not recognize or address deep uncertainty work against flexible and robust decision making and introduce new risks. Flexibility and adaptability are believed to enhance resilience in the face of change (Armitage et al., 2009). Despite the distinction between uncertainty and risk made by many scholars, approaches to uncertainty often blur the line between these two concepts. Commonly, attempts to incorporate uncertainty involve reducing it to a probability through quantitative methods like Bayesian calculus (Maier et al., 2016). As Maier et al. (2016) explain, approaches to uncertainty often involve considerations of model inputs, parameters, and structure, all according to probability distributions: essentially, they engage only with the known unknowns. However, although the quantitative modeling frameworks described above have been primarily operationalized using techniques with limited ability to capture deep uncertainty, they can be integrated with qualitative approaches that account for processes that cannot be quantified and unknown unknowns. For example, coupled systems analyses has engaged with work on adaptive capacity (Gallopin, 2006; Carpenter and Brock, 2008; Chaffin and Gunderson, 2016), as well as institutional analyses of collective decision-making (Ostrom, 2009; Koontz et al., 2015), both of which emphasize mechanisms to address future uncertainty.

Thirdly, more fully embracing uncertainty can lead to more democratic and transparent policy processes. The tendency to quantify, reduce, or ignore uncertainty promotes expert-driven, top-down, and technocratic solutions (Stirling, 2010) because of the assumption that uncertainty can be reduced sufficiently to justify a one-size-fits-all policy solution. At the same time, scientific uncertainty can be politicized in ways that stymie policy-making, as is the case in climate policy, which can increase reluctance to explicitly acknowledge uncertainties. Thus, the use of science in policy-making is often influenced by historical, biophysical, social and political uncertainties—and attitudes toward those uncertainties—more so than by any objective contribution that science may make to determine a rational choice (Jamieson, 1996; Cash et al., 2003; Posner et al., 2016). By keeping uncertainty transparent, political processes remain just that: deliberative, based on human judgments, and subject to democratic processes, rather than dictated by unproblematic "scientific facts" that ignore and conceal uncertainties.

To examine these assumptions in more depth, we explored the following research questions:

1. How is uncertainty navigated in applied nexus projects that work across research and policy-making?
2. How have quantitative modeling and qualitative futures thinking been integrated?
3. What are some benefits and drawbacks to integrating quantitative modeling and qualitative futures thinking, specifically for a policy-making context?

METHODS

We focused this research on applied nexus projects with an on-the-ground component or proposed policy intervention (and thus did not include projects that were purely research-oriented). This choice enabled us to explore how uncertainty and futures thinking are not just considered in nexus research, but how they are implemented and enacted (or not) in nexus policy-making.

To identify applied nexus projects, we conducted a Web of Science search for "water-energy-food nexus" and obtained ∼500 results. We then examined each project to identify applied projects that clearly linked research to management or policy interventions. Not surprisingly, most nexus projects research, theorize, and critique the nexus. We also utilized online searches to identify additional projects that were not yet in the publication stage. We identified 12 applied nexus projects and collated basic information available from project websites in a database. We contacted all 12 projects and conducted in-depth, semi-structured interviews with project leads from nine projects in October 2017. One project consisted of multiple sub-projects, so two individuals from the organization were interviewed, resulting in 10 total interviews. We also reviewed relevant project documents obtained from interviewees.

An interview guide was utilized to ensure comparability across the interviews. The guide contained specific probes to obtain additional detail related to how uncertainty was conceptualized and operationalized. Interviewees were asked about the overall approach of the project, strengths and weaknesses of their approach, how the project dealt with uncertainty in current conditions, how it dealt with future uncertainty, and then how these concepts were communicated to stakeholders or participants in decision making contexts (see **Appendix 1** for interview questions). Interviews were recorded and conducted with approval from the University of Montana Institutional Review Board. Interviews were then analyzed through an iterative constant comparative method to learn how different projects conceptualized and integrated uncertainty and futures thinking into their work. As part of this process, researchers compared across projects and engaged with relevant literature throughout the analysis to build a dialogue between theory and data, and to examine patterns across the dataset. To protect interviewee confidentiality, project names were removed and replaced with pseudonyms (P1–P9). All participants were then provided with the opportunity to review the results, make corrections, and identify their project by name if they desired. Thus, some projects are identified by name below while others remain anonymous. To provide a sense of the scope, scale, and nexus issues, a table of reviewed projects has been included (see **Appendix 2**).

We complement the nine projects examined through interviews and document analysis with an in-depth case study of LIVES Cambodia. LIVES Cambodia utilized participatory systems dynamics model building and scenario analysis to develop a nexus analysis of a transboundary landscape on the Mekong River. This case study contributes rich detail on beliefs and attitudes toward uncertainty within a project that blends quantitative modeling and qualitative futures thinking.

Similar to the nine projects describe above, the case study is examined from the perspective of the project lead (who is also an author on this paper), who served in the dual role of colleague-researcher on the project (Sandiford, 2015). The project lead draws on 15 interviews conducted in December 2017 with project partners using the Most Significant Change method (Dart and Davies, 2003). Interviewees were asked to reflect on critical outcomes—for themselves as individuals, for their organizations, and for the participants—and the barriers and enabling conditions related to achieving these outcomes. Using these interviews, project evaluations, and participant observation, the project lead reflects below on how local project partners and participants (1) changed their thinking on sources of uncertainty and how to address these in decision-making processes, and (2) the benefits and challenges of using both quantitative modeling and qualitative futures.

RESULTS

Below we examine the results from our research on applied nexus projects and our analysis of the LIVES Cambodia case study. We describe how the nine applied nexus projects envision and operationalize uncertainty, synthesizing findings from in-depth interviews, as well as project documents and peer-reviewed articles describing the projects. We then explore the LIVES Cambodia case study, delving into the opportunities and challenges that this project faced relative to uncertainty. In both sections, stakeholder engagement plays a critical role in navigating uncertainty.

Overview of Applied Nexus Projects

The nine projects we initially investigated are extremely heterogeneous in scope, scale, and location. Some well-established, large scale research institutes like the Stockholm Environment Institute (SEI) and P1 carry out many projects at the nexus, from transnational and national to basin and sub-basin scales. Many projects were framed in terms of a basin or region, but carried out through stakeholder workshops on smaller scales. For example, the IUCN's Wise-Up to Climate project (henceforth Wise-Up) works in the Tana basin in Kenya and the Volta basin in Ghana/Burkina, but often focuses on sites at the community level. Other younger or more exploratory projects, for example P8, P4, and the Kitchen Nexus, work only on the regional scale or only in one location.

The majority of projects dealt with water, energy, and food as the primary nexus elements of concern, although many privilege one element over others or take one element as a starting point to see how the other elements will be impacted. For example, P8 works on redistributed manufacturing of food- they investigated how re-localizing production of bread and tomato paste would impact water and energy consumption in food systems.

Some initiatives were framed explicitly in terms of transdisciplinary research (Ring of Fire, Wise-Up, Northern Ireland Nexus), or citizen science (P4), and with only one exception (P2), all had participatory elements wherein stakeholders helped identify research questions to varying extents. The initiatives also had variable relationships to decision-making contexts. For example, in the projects by SEI and P1, researchers were specifically contracted to help policy-makers develop national-level plans, and thus were well-positioned to have an impact on specific decisions. Other projects were at an earlier stage of the research process, trying to create a basis for future engagement with decision-makers (Northern Ireland Nexus, Kitchen Nexus, and P8).

The initiatives also displayed a range of attitudes and approaches toward modeling. On one end, some projects had no modeling component (Kitchen Nexus, Northern Ireland Nexus, P4), and some project leads expressed doubts about the utility of combining quantitative modeling with narrative scenarios. On the other end of the spectrum, P2 was based largely around innovative modeling techniques and integration of different models in novel ways to support decision making. However, the majority of initiatives fell somewhere in the middle, using a quantitative model (or models) as part of a larger process of engagement. In general, project leads described models as tools, and not necessarily the main focus of the project. Exemplifying a typical approach, one project lead explained that, *"the model becomes a boundary object- an object that people can discuss in more or less neutral terms in order to have discussions about hard trade-offs, but it's not the thing."* In general, project leads described the role of models in decision making in nuanced ways. As this person stated: *"We know that extra information may not necessarily change decision making. It's not like decision-makers around the world have just been waiting for that one amazing model that's going to blow everyone's mind!"* Throughout interviews, project leads described models as tools for creating dialogue, raising awareness, and bringing current challenges to the fore. For example, the project lead from SEI explained that, "They know that water scarcity will be an issue in the future, but the model shows that *one million* people will be without water under X development plan." In summary, interviewees argued that models can make general areas of concern more concrete and tangible.

How Applied Nexus Projects Integrated Uncertainty

These projects dealt with uncertainty in a variety of ways. For the projects using quantitative models, project leads spoke in detail about the different kinds of uncertainties in the model. One recurring challenge was finding sufficient data. For example, for projects working in the Mekong, Eastern Africa, and the Nile basin obtaining data was a continual struggle. Project leads repeatedly referred to the challenges of working in a "*data scarce environment.*" For some, lack of data seemed to be the only type of uncertainty. However, others suggested that lack of data was just one of the uncertainties at play. In other words, some projects engage primarily with the known unknowns (data gaps, etc.), whereas others described multiple sources of uncertainty, including unknown unknowns. For example, a

P1 project lead explained that he had worked with Bayesian analysis, Monte Carlo simulations, and other methods for dealing with uncertainty probabilistically, but that these methods were insufficient. As he put it:

> *One of the biggest mistakes people make, in every type of modelling too, is to assume that the past will continue under the same conditions. This is what you can call structural uncertainty... the relationship between different drivers is changing, their weight is changing, or there will be new drivers. So that's something you have to open up in people's brains.*

P1 uses various types of quantitative models which are incorporated into "*visioning*" processes carried out with stakeholders. In the P1 approach, stakeholders develop detailed visions, or pictures of an ideal future. P1 researchers then sit in on stakeholder discussions, and listen to causal statements- assumptions about what causes what that may not be directly related to the vision, yet underpin it. The model is then used to test these causal assumptions, or "*rattle the mental models*," as project lead explained. For example, if researchers hear stakeholders make statements like, "*irrigation schemes will result in less poverty*," the model will then be used to test this assumption. Once these causal assumptions have been tested, they are presented back to stakeholders who then alter their development plans to achieve their shared vision. The P1 project lead explained that, before presenting the model, researchers worked to set the stage for stakeholders that "*what you are about to see is not the truth*." In this project, the model is used as a tool to help stakeholders reflect on the assumptions that underpin their strategies. The project lead said that it was often challenging for the researchers who produced the model to be this explicit about the uncertainty.

The most common approach to dealing with uncertainty was through the use of scenarios. For some projects, the scenario approach was adopted specifically to highlight uncertainties. For example, the Northern Ireland Nexus project lead explained, "*I was deliberately trying to create a sense of uncertainty… to be subversive of anyone's sense of security*." Many projects work explicitly to help stakeholders think in terms of multiple futures. For example, the SEI project lead discussed how their approach deliberately disturbs the conventional notion that there is one impending future: "*The national plans suggest a single future world of wonderfulness, but what we're trying to argue is that that may get derailed. Your wonderful agricultural world may derail your wonderful energy world."*

One surprising finding from the interviews was that some projects take distinct approaches to uncertainty in different work streams. In Ring of Fire, an interviewee explained that uncertainty is dealt with by creating scenarios; however the project takes two distinct approaches to creating them. One is quantitative, based on integrated modeling and deals with uncertainty through probabilities. In a separate work stream, they create qualitative scenarios with local stakeholders, which grapple with all sorts of uncertainties that are difficult to quantify, for example uncertainties related to changing population demographics and future legislation. While the two types of scenarios had not been integrated at the time of the interview, Ring of Fire planned to incorporate the quantitative indicators into the qualitative scenarios and then use these integrated scenarios to engage local government.

Similarly, P8 and Wise-Up have distinct biophysical/economic modeling and socio-political work streams with distinct methods and treatments of uncertainty. For example, the project lead of P8 who is a modeler was able to speak to the ways that the model deals with uncertainty, while acknowledging all of the types of uncertainty that are unquantifiable, and dealt with more by his colleagues in the other work streams. Interviewees from P8, Wise-Up, and Ring of Fire all expressed that integration between work streams was sometimes constrained by time and finances, as well as differing visions and epistemological assumptions between research teams.

Two of the projects that did not use models utilized different understandings of uncertainty. In P4 where citizen science is the focus, the project lead was able to explain how uncertainty is understood in the community where he works. Community members talk about variable rainfall as a symptom of political corruption and changes in the social order in the community: it is a reflection of the health of the world which is out of balance. For these community members, uncertainty is a symptom of what is wrong with society. In this project, uncertainty is addressed through ethnographic methods- examining how it is understood by local residents.

How Applied Nexus Projects Engaged Stakeholders in Thinking About Uncertainty

Since these projects dealt with uncertainty to varying extents (both explicitly and implicitly), insights on how to communicate these ideas to stakeholders or use them to facilitate decision making were also uneven. However, when asked how projects communicate about uncertainty to stakeholders, a resounding answer from almost all projects was that this was a two-way process. Nearly all project leads emphasized that they learned from participants as much as the opposite. For example, in Northern Ireland Nexus, stakeholders brought up uncertainties precipitated by Brexit that had not been previously considered. P8 project staff learned that exorbitant rent prices in their study site were a major uncertainty for future local food manufacturing. In both cases, the project had not considered these sources of uncertainty before engaging with stakeholders.

Along this line, many project leads emphasized that working with stakeholders was a sort of ground-truthing for data, particularly in data-scarce, highly uncertain contexts. As a P1 lead explained, "*We ask, how valid do you think these findings are?*" Similarly, the project lead from P4 emphasized that their participatory iterative approach helps "*break down the assumption that you as an outside researcher make about both the way the landscape works, and also the aspirations the community has for it.*" Project leads repeatedly emphasized that they learned from stakeholders with extensive experience in a given context or sector.

Conversations with project leads also revealed specific, practical tips for getting stakeholders to think about uncertainty and communicating the results of complex models. In getting people to engage with multiple possible futures, a consistent concept (expressed in many different ways) was anchoring the future to something concrete that the participants can relate to. According to project leaders, anchoring is used to help stakeholders imagine the future by connecting it to something that has already happened (a past event) or already exists (a current policy). This helps futures become more relatable and tangible for stakeholders. For example, in Northern Ireland Nexus, the project lead began the scenarios with actual events that had occurred in the past.

Similarly, SEI sometimes reminds participants of an unexpected event from the past:

> *If [participants] are getting stuck on assuming something will happen that is in fact uncertain- remind about what has happened in the past there or elsewhere. Wherever they're stuck, try to give them an anchor in their own experience that gets them out of that stuck place.*

The project lead illustrated this process using the example of the fall of the Berlin wall, saying that *the day before it happened, the world was certain it wouldn't*. In other SEI nexus projects, they embed their scenarios within existing national plans. The concept is the same- begin with concrete ideas that are in the participants' realm of experience, and then gradually become more imaginative to illustrate multiple plausible futures through the scenarios.

One consistent recommendation was to be transparent about assumptions, uncertainties, and sources of data. However, accompanying this was an emphasis on being judicious and strategic with the amount of information shared with stakeholders. As one person explained,

> *You don't have to go into the detail. There are just some key things people need to know to feel comfortable with the model. . . .they don't necessarily need to know how it works, but they really want to know what's gone into it, and the key assumptions of that data going into it.*

As another project lead explained, "*the modeler gets up there, with scatter plots and everything, and people's eyes glaze over. Even within the research team!*" She accompanied this by emphasizing the importance of participation in workshops and having stakeholders "*present back*" to researchers.

Multiple project leads explained that representing uncertainty numerically or probabilistically was insufficient for most policy audiences, that those numbers would "*lose their nuance in policy circles*." As one person explained, a probabilistic representation of uncertainty (i.e., risk) may be well-understood by technical audiences, but amongst less technical audiences, the high levels of uncertainty represented in one number may be lost in translation. Said differently, a single, definitive representation of uncertainty is more vulnerable to political pressure than multiple, qualitative forms of uncertainty. This is not to say that uncertainties should never be represented quantitatively, but rather that the way uncertainty is communicated should be carefully tailored to the particular audience.

Conversations on communicating about future uncertainty also surfaced challenges. The most consistent challenge in getting stakeholders to engage with multiple futures was the mismatch between scales. Often, politicians think in terms of 5–10 years, whereas nexus research may be concerned with larger timescales. A project lead from Ring of Fire illustrated this challenge with a typical example. The researchers involved in the project wanted to discuss projections for the year 2100, stakeholders wanted to focus on 2040, and it was such a conflict, they ended up doing both.

Another consistent challenge in getting stakeholders to discuss the future and uncertainty was working in contexts with immediate, pressing issues. For example, for P2, trying to engage policymakers in turbulent, war-torn countries in conversations about the future was a challenge while immediate political unrest was so prevalent. Similarly, in the P4 project, electricity and population growth present immediate challenges to decision-makers: having conversations about long term future is not always a priority.

Case Study of LIVES Cambodia

The case study location is the Mekong Flooded Forest Landscape which covers two provinces in northeastern Cambodia, Kratie and Stung Treng, and Champasak province in Lao PDR (see **Figure 1**). Two major mainstem hydropower projects are underway in the landscape. Hydropower is one of few alternatives to improve national energy security (RGC, 2016) but the resulting changes in the Mekong river's flow, flood regime, fish migration patterns, and biodiversity from these developments is a risk to rural livelihoods and food security (MRC, 2017). These risks are compounded by anticipated changes to monsoon seasons, as well as changes to overall precipitation and temperature, as a result of climate change (Loo et al., 2015). Equitable solutions have been elusive due to differences in local and national priorities (Siciliano et al., 2015) and complex cultural, political, and historical factors (Milne and Mahanty, 2015). Most development planning to date has been sector-specific.

LIVES Cambodia was a 3 years transdisciplinary project collaboratively designed by a project team that included individuals from Cambodia's Ministry of Environment's National Council on Sustainable Development; World Wide Fund for Nature; KnowlEdge, a consultancy firm for participatory system dynamics modeling; the Royal University of Agriculture Cambodia, the Royal University of Phnom Penh, the University of Bergen, and the University of Maryland. The project sought to demonstrate the value of integrated, cross-sectoral, participatory nexus analyses and to co-produce new knowledge (Cash et al., 2006; Berkes, 2009) to support sustainable development decision making in this landscape using participatory system dynamics modeling (Antunes et al., 2015). Participants, including provincial departments of national ministries, civil society representatives, and members of local farming and fishing communities, were involved in participatory model building exercises as well as facilitated dialogue on qualitative and computer simulation scenario outputs (as per Vennix et al., 1996; Lane, 2008; Antunes et al., 2015) (see **Figure 2**).

FIGURE 1 | The LIVES Cambodia study site.

Navigating Uncertainty in a Data-Poor Environment

The LIVES Cambodia model was designed explicitly to produce descriptions of possible futures (scenarios) potentially stemming from the convergence of local water-energy-food conflict, global environmental change, and socioeconomic change in the Mekong Flooded Forest landscape. System dynamics modeling creates explanatory models of system structures and simulates the dynamic interplay between key variables to explore system behavior over time (Forrester, 1961). Systems dynamics models have been used extensively for planning under complexity and uncertainty and look promising for nexus assessments given their ability to integrate social, economic, and environmental dimensions into scenarios (Bassi and Gallagher, 2016). The process entails iterative problem identification, system conceptualization, computer model formulation and validation, and both qualitative and quantitative scenario analysis.

At the start of the process, team members and participants assumed the LIVES Cambodia model would fill current data gaps on mainstem hydropower development risks for national and local energy security, local fishery sustainability, local food

FIGURE 2 | LIVES Cambodia participatory modeling exercise.

security and agricultural livelihoods sustainability to predict future outcomes for policy solutions accurately. One civil society partner argued that reducing uncertainties through scientific evidence was *"required for policy change."* As the group built the model, many project team members and participants started "*to realize we don't have that data*" and that "*without the data, it's hard to make choices.*" LIVES Cambodia aimed to missing long-term data on such variables as fisheries and land productivity, dolphin birth rates and death rates, local market prices for rice and fish in part through the participatory stakeholder process. Dialogue processes helped to deepen participants understanding of uncertainties and key data gaps. Key uncertainties revolved around the relationships between developments (e.g., hydropower) and impacts (e.g., the availability of fish resources), which future changes to anticipate (e.g., how climate change might impact the monsoon), and the efficacy of specific mitigation and adaptation actions. As one research partner reflected: "*We don't know exactly yet what we will change...We don't know exactly what is the policy that will work.*"

Initially, uncertainty was not explicitly discussed in the stakeholder workshops beyond acknowledging these data gaps and issues. The main objective communicated to participants was to identify potential future risks in Kratie and Stung Treng provinces that could be monitored through 10–12 key indicators. These indicators would inform policy actions and investments in formal commune and national development planning processes. Project team members were reluctant to raise the question of uncertainty directly with provincial and community stakeholders. Some team members worried that an open discussion of uncertainty would further complicate an already complex project and method that was new to stakeholders. Others were concerned that final results would be appear less credible to participants if uncertainty was made explicit, potentially affecting the policy impact of the project. Some team members also had concerns about model robustness. However, uncertainty implicitly played a key role in the project design through the focus on building and questioning causal assumptions with the intention of identifying unforeseen risks due to interplay between WEF nexus elements.

The basic premise, based on previous applications in similar contexts (Voinov and Brown Gaddis, 2008; Videira et al., 2010; Kopainsky et al., 2017), was that (1) participatory system dynamics modeling could identify major structural elements in the social-ecological system and how these elements might interact and evolve over time, despite local data scarcity (Sterman, 2000); and (2) this would be useful to decision making under uncertainty because of the contribution of "crowdsourcing" (Backstrand, 2003; Bott and Young, 2012) accomplished through participatory processes that encouraged critical thinking about system linkages (Leys and Vanclay, 2011; Bodin, 2017).

The project focused on scenarios rather than specific policies because, in this context of multiple and heterogeneous actors, scenarios provide an aggregated analysis of the different governance responses that first must be negotiated and agreed upon before specific policies could be defined and implemented. Further, training and capacity building was provided to the project team to be transparent about the meaning of the model outcomes, with a specific focus on how the model did not predict future outcomes but rather produced results that represented one possible future. As one of the project modelers reflected:

> *People believe if they invest a lot of money in a model, they believe that it should accurately predict the future...The [LIVES] project raised awareness about the how hard it is to predict the future. I get frustrated with tools that say that they can predict the future and help policy makers...Donors and policy people want research to give certainty to policy making but in reality, it is very hard to prove that a particular intervention is going to work...it seems like anybody who suggests their data and models can give absolute certainty is lying..*

Thus, a key strategy to help participants engage with the model was understanding its strengths and limitations, and predictive abilities given that multiple futures were possible for the landscape.

Integrating Futures Thinking Into the Deliberative Process

A notable challenge was developing the scenarios in futures thinking procedures with provincial administration stakeholders. For some, the computer software was confusing. Others reported to local researchers that they felt they were not in a position to speculate about the future given "*the decision* [about hydropower infrastructure placement and design] *is not made by them.*"

This almost certainly reflects the politically sensitive nature of the forthcoming hydropower developments approved at central government level, rather than a lack of capacity to imagine the future. The project team implemented two strategies to overcome this barrier. A more intensive engagement with representatives from fishing and farming communities—both mixing these participants with provincial administrators and conducting separate sessions just for community-level actors. The latter enabled a more grounded, less overtly political discussion of future trends and potential responses as seen from the local-level perspective. Secondly, a more "hands on" group modeling protocol that allowed participants to engage in deeper ways with scenario development. Finally, the project team synthesized discussions across both the provincial and community sessions to develop draft scenarios which were then validated with stakeholders in final workshops. The final scenarios explored the ways that different development scenarios would impact food, water and livelihoods security. The four scenarios are summarized here:

1) Maintaining the status quo development pathway (no dams);
2) Introducing the two planned hydropower developments, modeling the impact of the Stung Treng dam and then subsequently adding the Sambor dam (in order of their likely completion and operation);
3) Implementing one adaptation strategy in local agricultural systems focused on intensification of rice production (based on Cambodia-specific data: Ly et al., 2012, 2016);
4) Implementing an environmental flows mitigation policy in the planned hydropower projects with the goal of maintaining flows on the mainstream of the Mekong river [as per specifications in Babel et al. (2012)].

A common reflection across project team members and participants points to one factor enabling this outcome. The participatory system dynamics modeling methodology used often gave voice and legitimacy to a range of interests, opening up space for deliberation and engendering a new sharing of information and perspectives. As one civil society team member claimed: *"participants dared to say anything, their voice is included."* Local participants initially expressed that they did not have the education or credentials of national level government and university participants. But as they engaged in the process, they "*challenged*" the assumptions of the model *"saying this variable shouldn't connect to that one."* As a result, some national government team members realized that they "*lack the knowledge of the reality*" of local communities and that local stakeholders *"know more about the landscape, they know with their own eyes."* The participatory process enabled the group to recognize the value of local knowledge and integrate that knowledge into the model to fill data gaps regarding the relationships between key variables. As one participant commented about the model building process, "*It's done with people. I think as a planner, this is really important.*"

By the end of the 3 years, there were signs that the project team and participants were shifting away from a focus on filling data gaps and waiting for model results toward asking how the LIVES Cambodia process of participatory model building and futures thinking itself might contribute to a "*better plan, better future.*" Project participants with responsibilities for local planning and expressed an interest in utilizing the participatory model building and scenario tools in Commune Investment Planning, a formal part of developing the next National Strategic Development Plan (2019–2023). Further, some project team members came to recognize that uncertainty is not always a result of lack of information or data gaps. Because data is politicized in Cambodia, some participants expressed concerns that others were deliberately withholding information during the model building process to create uncertainty about the impacts of hydropower developments on local communities: *"Data holders do not want to share data,"* one civil society project partner claimed. For other team members, the interest that government partners had displayed throughout the process provided evidence that policy influence was possible even in the face of ongoing uncertainties. For example, one civil society team member who initially expressed frustration at not having "*evidence for advocacy*" on hydropower from the model, reflected later that uncertainty about future actions and solutions could potentially be tackled in through stakeholder deliberation, saying "*If we introduce integrated planning based on the causal loop diagrams, all the people sit in the same room and discuss from one issue to another issue and get consensus for policy implementation. This way is very effective.*"

Ultimately, the deliberative process that drove the model building and scenario development enabled stakeholder recommendations to be crafted in the face of uncertainty. Looking back, some project team members who had initially opposed addressing uncertainty explicitly reflected that one of the key insights from LIVES Cambodia was that planning for the future often requires thinking about complexity and uncertainty. One civil society partner compared SWOT (strengths, weaknesses, opportunities, and threats) analysis (commonly used in planning processes in the case study location) to the group systems model building (Causal Loop Diagrams), saying: "*We have been trying to cope with limited local knowledge by using simple tools—but the CLD shows that even if it is complicated, it is better. People accepted that SWOT was simpler, but giving the wrong analysis. CLD is more complex but reflects the situation better.*" In effect, though the original plan had been to minimize discussions of uncertainty in stakeholder workshops, the choice of the system dynamics modeling methodology may have introduced uncertainty by default. New capacities for dealing with uncertainties were developed through the engaging with the modeling process, specifically critical analysis of feedback loops, the possibility of non-linear change, and the potential for delayed effects in a system's structure and evolution. The participatory process created conditions whereby deep uncertainty could be explored by stakeholders. Discussions about cause-effect linkages and future scenarios led to more agreement on where and how to intervene—including clarity on who has the capacity to intervene. This process also pointed to a range of possible solutions or development pathways. As this participant pointed out: "*That's the kind of planning you need. [...] Not just filling in the template. It gives you flexibility. Though you know your goal is sustainable development, there are many ways there. We can identify diverse ways to get there.*"

Summary of Results

The nexus case studies demonstrated a range of levels and a diversity of types of engagement with uncertainty and futures thinking. For some, uncertainty played a key role in the project and was intentionally brought into focus for stakeholders. In these projects, uncertainty was invoked to foster robust decision making, question causal assumptions, and surface unforeseen conflicts between nexus elements. In other projects, uncertainty was more incidental, implied in the research question or encountered as a challenge to the project as planned. LIVES Cambodia, a project in the latter category, demonstrates how projects mixing participatory research, quantitative modeling, and qualitative futures thinking will often be called to explicitly address uncertainty in some way. This kind of flexibility and reflection on development pathways builds the adaptive capacity needed in the face of deep uncertainty and potential surprises. We suggest that mixing participatory research, quantitative modeling, and qualitative futures thinking methods shows promise in developing such capacity.

DISCUSSION

We set out to understand how nexus projects envision, operationalize, and navigate uncertainty, specifically in those cases where nexus research is linked to policy-making contexts. Through in-depth interviews with project leads from nine applied nexus projects and a detailed examination of LIVES Cambodia, we discovered complex, nuanced understandings of the types of uncertainties that are important, as well as detailed insights into the opportunities and challenges of engaging stakeholders in thinking about uncertainty.

Interestingly, interviews with project leads led to more nuanced discussions of uncertainty than are currently present in the nexus literature. This may be a result of the focused nature of academic publishing and the barriers to reflecting in-depth on the limitations of a particular analyses (especially the analysis that was employed for the publication). This finding may also be an artifact of our sampling process, which focused specifically on nexus projects that bridge science and policy. For example, while LIVES Cambodia did not set out to explicitly integrate uncertainty into their project, workshops with stakeholders raised critical questions about uncertainty that became an important part of the process. Thus, it is possible that moving nexus science into policy-making requires confronting uncertainty in different ways as compared with nexus research that is more detached from applied contexts.

That said, engaging stakeholders in explicit conversations about uncertainty is challenging. This is due to the technical nature of how uncertainty is dealt with and represented in modeling computations and the challenge of communicating about that process to a broad audience. But conversations about uncertainty are also challenging because of a fear that acknowledging uncertainty will undermine the credibility and utility of a particular model.

One way out of this conundrum is to utilize qualitative futures thinking processes, such as scenario planning, to engage stakeholders in more deliberative, explicit discussions of uncertainty (either alongside quantitative modeling or as a separate exercise). Futures thinking processes require participants to confront uncertainty through a focus on a specific range of futures, and as a result they question assumptions, foster flexibility, gain insight into the present, and craft robust solutions. Of the nexus projects we examined, those with a clear focus on multiple possible futures discussed various types of uncertainty more explicitly and in more detail, and emphasized uncertainties with their stakeholders.

However, models were also utilized in stakeholder processes to enable critical thinking about uncertainty, system dynamics, and proposed policies. As models moved into stakeholder processes, they often played the role of boundary objects (Midgley, 1992), fostering dialogue about the assumptions about the system that underlie computations, as well as on the strengths and weaknesses of specific computational techniques. As was demonstrated by LIVES Cambodia, engaging stakeholders in the model building process can also help improve the model to the extent that local knowledge can be used to address data gaps and critically evaluate model assumptions. Further, many projects were using models in participatory processes in which hypotheses could be tested, evaluated, and revised, through a transparent and collaborative process. This process required modelers to develop the skills to engage in critical reflection with the models that they built (Senge and Sterman, 1992). Project leads found that while these conversations were challenging, they led to deeper discussions, more holistic framings of problems, and an acceptance of the different types of uncertainties, beyond simple data gaps, that plague nexus research and governance.

This is the process of knowledge co-production, where experts and non-experts collaborate to create new knowledge and catalyze change (Cash et al., 2006; Berkes, 2009; Miller and Wyborn, 2018). The negotiation, mediation, and deliberation that comprise co-production can play an important role in achieving new governance outcomes for collective action problems characterized by deep uncertainty (Innes and Booher, 2010; Wyborn, 2015). Howarth and Monasterolo (2017) justify a co-production approach to nexus research precisely because of complexity, non-linearity, and uncertainty inherent in such analysis.

Critically, when situated within a participatory process, quantitative models present a "jumping off" point from which to initiate discussions about the future. Breaking out of a focus on present day politics and challenges is one of the difficulties that needs to be addressed when facilitating conversations about the future. In such circumstances, a quantitative model that stretches out to 2030–2050 or beyond can present participants with a future that "destabilizes" their connection to the present, and confronts them with medium to long term outcomes that can be traced back to choices made historically. The model then provides a tangible boundary object around which to have a conversation about human agency within a system, and the various pathways that are available. In these circumstances, simulation models can be used to test the outcomes of proposed pathways, or a set of assumptions about how a given set of actions might lead to particular changes. When the simulations expose a set of unanticipated consequences or behaviors, the model does not need to be "right" to be useful, as it shows the possibility for unforeseen impacts, thereby explicitly demonstrating the nature of the uncertainties present within nexus governance.

Creating actionable knowledge in this way is an iterative process that requires diverse points of view at all stages of research (Pohl, 2005, 2010; Lang et al., 2012). If the goal of nexus work is to link science and policy, then producing science that engages in meaningful ways with policy-making requires more than integrating across quantitative modeling and qualitative futures thinking. It requires thinking carefully about how science and policy come together when projects engage stakeholders in model building and in scenario development, and through both processes build capacity for making decisions in the context of uncertainty.

RECOMMENDATIONS

Based on the research described above, we provide the following recommendations for applied nexus projects:

Embrace transparency—Be sure that all assumptions, key uncertainties, and data sources in a model or any kind of analyses are communicated clearly to stakeholders.

Be participatory—Create a process for mutual learning that values different kinds of knowledge, including expert and local knowledge. Stakeholders can help validate research findings, critique and support assumptions made by researchers, and present new uncertainties that hadn't been considered.

Envision models as a tool- Encourage participants to value the model as a boundary object that facilitates discussion about future possibilities, based on available data and current assumptions. Models are powerful tools to spark discussion and raise areas of concern. Discussions about model uncertainty and limitations can be balanced with an emphasis on the critical role that models can play in facilitating discussions about the future.

Use scenarios to raise awareness of uncertainty—Craft scenarios so as to highlight areas of uncertainty that stakeholders may not have fully considered. Techniques like wind-tunneling (seeing how a given policy will perform under various scenarios) can help to fortify a given policy or management plan against multiple uncertainties. Scenarios also help participants consider how to build adaptive capacity in the context of deep uncertainty.

Represent uncertainties in ways that work for your audience—With technical audiences, probabilistic treatments of uncertainty may be sufficient to communicate uncertainty within a model. However, with many policy-makers and practitioners, a probability, or risk, may not be adequate. Simplified, numeric representations of uncertainty may be more vulnerable to political pressure and may neglect deeper uncertainty. Instead, help stakeholders understand the sources and nature of uncertainty, and encourage critical thinking about the role of uncertainty in decision-making.

AUTHOR CONTRIBUTIONS

LY, EL, LG, KJ, and CW jointly contributed to manuscript development. LY, CW, LG, and EL designed the study of applied nexus projects. EL conducted interviews and analyzed interview data. LG conducted the case study analyses. KJ provided the examination of quantitative nexus analyses. CW and LY synthesized across project elements.

FUNDING

The research presented here is based on work supported by the Nomis Foundation, Luc Hoffmann Institute, the National Science Foundation (Grant No. 1633831), and the National Socio-Environmental Synthesis Center (under funding received from the National Science Foundation DBI-1639145).

ACKNOWLEDGMENTS

We also wish to thank the project leads from applied nexus projects who participated in interviews as well as the team members and participants from the LIVES Cambodia project.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2019.00037/full#supplementary-material

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Environmental Science

ORIGINAL RESEARCH
published: 24 April 2019
doi: 10.3389/fenvs.2019.00050

Understanding the Water–Food–Energy Nexus for Supporting Sustainable Food Production and Conserving Hydropower Potential in China

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OPEN ACCESS

Edited by:
Rabi Mohtar,
Texas A&M University, United States

Reviewed by:
Fouad H. Jaber,
Texas A&M University, United States
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Specialty section:
This article was submitted to Freshwater Science, a section of the journal Frontiers in Environmental Science

Received: 15 August 2018
Accepted: 01 April 2019
Published: 24 April 2019

Citation:
Liu W, Yang H, Tang Q and Liu X (2019) Understanding the Water–Food–Energy Nexus for Supporting Sustainable Food Production and Conserving Hydropower Potential in China. Front. Environ. Sci. 7:50. doi: 10.3389/fenvs.2019.00050

Optimizing water–food–energy (WFE) relations has been widely discussed in recent years as an effective approach for formulating pathways toward sustainable agricultural production and energy supply. However, knowledge regarding the WFE nexus is still largely lacking, particularly beyond the conceptual description. In this study, we combined a grid-based crop model (Python-based Environmental Policy Integrated Climate—PEPIC) with a hydropower scheme based on the Distributed Biosphere Hydrological (DBH) model to investigate the WFE interplays in China concerning irrigated agricultural production and hydropower potential. The PEPIC model was used to estimate crop yields and irrigation water requirements under various irrigated cropland scenarios, while the DBH model was applied to simulate hydrological processes and associated hydropower potential. Four major crops, i.e., maize, rice, soybean, and wheat, were included for the analyses. Results show that irrigation water requirements present high values (average about 400 mm yr^{-1}) in many regions of northern China, where crop yields are much higher on irrigated land than on rainfed land. However, agricultural irrigation has largely reduced hydropower potential up to 50% in some regions due to the substantial withdrawal of water from streams. The Yellow River basin, the Hai River basin, and the Liao River basin were identified as the hotspot regions concerning the WFE interactions and tradeoffs. Further expansion the irrigated cropland would increase the tradeoffs between supporting sustainable food production and conserving hydropower potential in many parts of China. The results provide some insights into the WFE nexus and the information derived is useful for supporting sustainable water management, food production while conserving the potential for hydropower generation in China.

Keywords: water–food–energy nexus, irrigation water requirements, crop yields, hydropower potential, PEPIC, DBH

INTRODUCTION

Water, food, and energy are the most important resources supporting the development of human society. Due to the highly intrinsic linkages between them, it is essential to manage the three sectors in an integrated way. The Water–Food–Energy (WFE) nexus was emerged as a concept to deal with the complex relations among the three sectors. The WFE nexus was firstly highlighted by the Bonn 2011 Nexus Conference through its background paper (Hoff, 2011). It is vital to optimize the WFE nexus for the purpose of achieving the ambitious Sustainable Development Goals (SDGs) ratified by the United Nations in September 2015, as 10 out of the 17 SDGs are related to the WFE nexus (Bieber et al., 2018). Our planet is facing great challenges to feed the growing and increasingly affluent population. Thinking and acting with a WFE concept is the key to improving overall resource use efficiency (Ringler et al., 2013). However, current research on the WFE nexus is still on the initial phase with a large number of review papers focusing on clarifying its definition and out looking the major research directions (Perrone and Hornberger George, 2014; Smajgl et al., 2016; Liu J. et al., 2017; Cai et al., 2018; D'odorico et al., 2018). Without detailed understanding of the WFE nexus and tradeoffs, it is difficult to use the WFE concept to facilitate the success of SDGs by 2030 (Galaitsi et al., 2018).

Water, especially that for irrigation, is recognized as the central position in framing the WFE nexus (Cai et al., 2018; D'odorico et al., 2018). As the largest water consumer, irrigation accounts for about 70% of global water withdrawal and is responsible for 40% of total grain production (Ringler et al., 2013). Hydropower is the most important renewable energy resources, which receive increasing attention worldwide (Stickler et al., 2013; Liu et al., 2016c). There is a conflict between irrigation water withdrawal and hydropower generation, especially in dry seasons. For instance, Zeng et al. (2017) found that 54% of global installed hydropower has competitive relationships with irrigation. On the other hand, irrigation pumping could be high energy consuming. Concerning resource use efficiency, optimizing the WFE nexus does not always correspond to maximum crop yields, with the potential to save water and energy (Zhang et al., 2017). Therefore, using the irrigation as a connection provides good case to demonstrate the WFE nexus and understand its complex interplays.

China is particularly facing great challenges associated with optimizing the WFE, as it has to use <10% of the global arable land to feed one fifth of the global population. Water resources distribute extremely unevenly in China, with very low water availability in the northern parts of the country. Furthermore, irrigation is important to increase crop yields there (Piao et al., 2010). The annual average of gross hydropower potential in mainland China was estimated as high as 650 GW (billion watt) over the period 1971–2000 (Liu et al., 2016c). However, it is still lacking in the literature that explores the extent to which the WFE nexus is interrelated and which regions are facing more challenges. In order to fill in this research gap, we used a unique approach by coupling a grid-based large-scale crop model (Python-based Environmental Policy Integrated Climate, PEPIC) with a hydrological model (Distributed Biosphere Hydrological, DBH) to estimate irrigation water requirements, crop yields, and hydropower potential in mainland China. The WFE interplays were investigated by considering various irrigation scenarios with respect to four major crops: maize, rice, soybean, and wheat. The study will identify the hotspot regions regarding the WFE nexus and provide a preliminary reference for the integrated resources management in China.

MATERIALS AND METHODS

The PEPIC Model

The PEPIC model (Liu et al., 2016a) was used to simulate irrigation water requirements and crop yields. PEPIC is a grid version of the EPIC (Environmental Policy Integrated Climate) model (Williams et al., 1984). The EPIC model was initially developed to estimate the effects of soil erosion on soil productivity in the mid-1980s. Since its inception, EPIC was continuously extended to simulate a wide range of complex processes related to crop growth, e.g., hydrology, soil erosion, soil temperature, carbon dynamics, and nutrient cycles (Williams, 1995; Izaurralde et al., 2006). EPIC has been widely used and validated around the world (Gassman et al., 2005). However, EPIC is a field level model. The grid-based PEPIC model facilitates the application of EPIC on large scales with high spatial resolutions. The PEPIC model has been used to simulate crop yields, crop water use, and irrigation water requirements (Liu et al., 2016a). It performed well on simulating national crop yields, which match the data reported by FAO around year 2000. The PEPIC model can also capture the interannual variability of crop yields caused by climate forcing (Müller et al., 2017). Beyond this, PEPIC was successfully used to simulate global nutrient cycling, e.g., nitrogen losses (Liu et al., 2016b), and phosphorus cycles (Liu et al., 2018) relating to production of major crops on a global scale. We used the calibrated PEPIC in this study.

PEPIC simulates crop growth at a daily scale. Daily potential biomass is simulated by considering an energy–biomass conversion approach. Potential biomass is reduced by a major plant stress (including temperature, water, nutrient, aeration, and salinity) to get the actual biomass. Crop yields are then estimated by multiplying a crop-specific harvest index and actual biomass accumulation when crop is mature. In this study, both rainfed and irrigated cultivations were simulated separately. For irrigated cropland, irrigation water requirements were estimated by using an automatic irrigation application approach. With this method, PEPIC applies water for irrigation automatically with sufficient amount of water when plant water stress limits potential biomass increases by a given threshold, e.g., 10% used in this study. This strategy can eliminate the plant water stress and is widely used in large scale crop modeling (Folberth et al., 2016; Liu et al., 2016b). The annual irrigation water requirements were calculated by summing up the applied water in each irrigation event during the whole growing season. An irrigation efficiency of 0.378 (Rost et al., 2008) was used for the whole of China in this study.

PEPIC requires digital elevation model (DEM), slope, climate, soil, fertilizer, and crop calendar as input data. Climate data, including precipitation, maximum and minimum daily temperature, wind speed, and relative humidity, were obtained from Weedon et al. (2014). Soil data were downloaded from the ISRIC-WISE dataset (Batjes, 2006). Fertilizer data, including nitrogen and phosphorus of mineral fertilizer and manure, were derived from the EarthStat dataset (Mueller et al., 2012; West et al., 2014). Crop calendar, including planting date and crop growth period, was based on the SAGE dataset (Sacks et al., 2010). The simulation period of this study is 1981–2010 with the first 20 years treating as spin-off period to phase out the impacts of unknown initial soil conditions. Four major crops, maize, rice, soybean and wheat, were simulated in the mainland of China with a spatial resolution of 0.5°.

The Hydropower Scheme Based on the DBH Model

A hydropower scheme (HPS) was developed based on the DBH model to estimate the gross hydropower potential (GHP) under different irrigation scenarios. The DBH model is a spatially distributed model integrating hydrological processes and soil-vegetation-atmosphere transfer processes (Tang et al., 2007, 2008). It incorporates a land surface model SiB2 (Sellers et al., 1996) and a distributed hydrological scheme. The hydrological scheme in the DBH model is based on geomorphological characteristics to estimate the surface and subsurface flow. Both saturated and unsaturated overland flows are considered in the model. The area-amount relationship for effective precipitation and the part of precipitation that becomes runoff, is used to estimate the overland flow. A linear reservoir routing model is used for large scale hydrological routing simulation (Liu et al., 2016d; Liu X. et al., 2017). The DBH model was initially developed and calibrated for large-scale hydrological simulations in the Yellow River basin (Tang et al., 2008) and showed fairly good performance. It was then improved for hydrological simulations taking human impact into account at a spatial resolution of half-degree and was verified in China (Liu et al., 2016c, 2019) and the globe (Liu et al., 2016d; Liu X. et al., 2017) with monthly and annual hydrological observations.

GHP is defined as the total energy of available runoff falling to the lowest level of a specific region. Based on the DBH model, flows for GHP estimation are considered from (1) cell-internal runoff (Q1) that falls from the mean to the minimum elevation (h1) of the considered cell and (2) inflow (Q2) that falls from the minimum elevation of the upstream cell to the minimum elevation (h2) of the considered cell (Liu et al., 2016c). In the HPS, GHP at each grid cell is estimated as:

$$\text{GHP} = Q1 \times h1 \times g + Q2 \times h2 \times g \tag{1}$$

where *Q1* and *Q2* are the cell-internal flow and the inflow (m^3 s^{-1}, cubic meter per second), respectively; *h1* and *h2* are the hydraulic head defined above (m); and *g* is gravitational acceleration (m s^{-2}).

The HPS was coupled with the PEPIC model to represent the links between hydropower and agricultural irrigation at large scale (**Figure 1**). To do this, HPS was fed with irrigation water requirements at the monthly scale, which were estimated by the PEPIC model. HPS runs at a daily time step; therefore, the monthly irrigation requirements were evenly disaggregated into daily values. The estimated irrigation water requirements by the PEPIC model were provided for the flow routing process in the DBH model. Discharge was withdrawn from the considered cell and then its adjacent grid cells (up to four adjacent grid cells) if necessary to fulfill the irrigation requirements before the GHP estimation. GHP was calculated based on the remaining discharge and the natural hydraulic head along the river network. At each grid cell, 20% of daily streamflow was arbitrarily reserved for environmental flows (Hanasaki et al., 2008; Pastor et al., 2014). The withdrawn water in HPS will be lower than the estimated irrigation water requirements if streamflow is not sufficient. Annual GHP was aggregated based on daily values at each grid cell. In this study, we focused on GHP and no reservoir regulation was applied in the HPS. The feedback of irrigation on runoff generation was not considered, from which uncertainty in discharge simulations may arise in some regions (Liu et al., 2019).

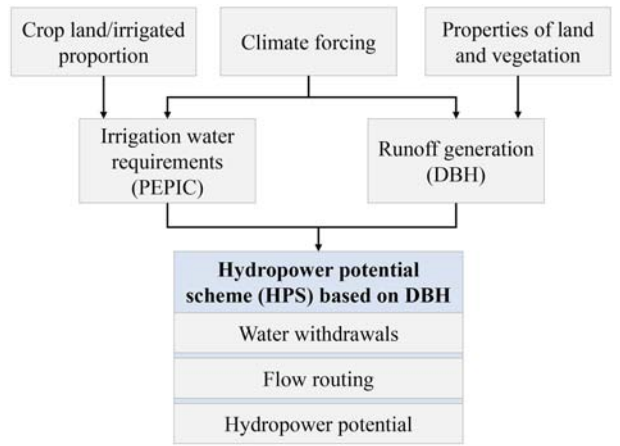

FIGURE 1 | Flow chart for the hydropower potential scheme (HPS).

Irrigated Cropland Scenarios

In this study, the MIRCA-2000 land use data (Portmann et al., 2010) were used as the benchmark of cropland for wheat, rice, maize, and soybean. The MIRCA-2000 dataset provides crop-specific irrigated and rainfed land use data for 26 crops throughout the whole world around the period 1997–2003. We considered 12 irrigated cropland scenarios on the basis of the MIRCA-2000 dataset: the baseline scenario (represents the reality around year 2000, then the national average irrigated cropland was about 70% of the total cropland, with substantial regional variations); the zero scenario (no irrigated land, that is, the whole cropland as rainfed land), and 10 incremental irrigated cropland (i.e., 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100%) scenarios, which take respective fractions of total cropland to irrigated land in each grid. It should be noted that the baseline scenario is different from the 70% incremental irrigated cropland scenario, as the later considers the equal percentage of cropland as irrigated land in all the river basins and grids. In the study, we kept the total cropland area unchanged, but adjusted the fraction of irrigated land to total cropland. These 12 irrigated cropland scenarios were used to examine the effects of varied irrigation water withdrawals on the hydropower potentials for mainland China and its 10 major river basins (**Figure 2A**).

RESULTS

Irrigation Water Requirements

Figure 2A shows the spatial distribution of area-weighted average of irrigation water requirements of the four crops, under the 100% irrigated cropland scenario, representing the max irrigation water requirements. Irrigation water requirements of the four major crops present very high values (400 mm yr^{-1}, millimeter per year) in the north parts of China, e.g., in the Hai River basin, the Liao River basin, the middle of the Yellow River basin, and the north part of the Huai River basin. The highest values are found in the northwest part of China with irrigation water requirements >500 mm yr^{-1}. On the other hand, the irrigation water requirements are small in the southern parts of China, with values generally below 100 mm yr^{-1}.

Irrigated cropland based on the MIRCA-2000 dataset (the baseline scenario) mainly located in the north parts of China, especially in the Hai River basin, the Huai River basin, and the Yellow River basin with high values over 200 kha (thousand hectares) in one grid (**Figure 2B**). Multiplying the irrigation water requirements with irrigated cropland of the four major crops, the Hai River basin required the largest amount of water up to 18 km^3 yr^{-1} (cubic kilometer per year), followed by the Yellow River basin (13 km^3 yr^{-1}), the Northwest River basins

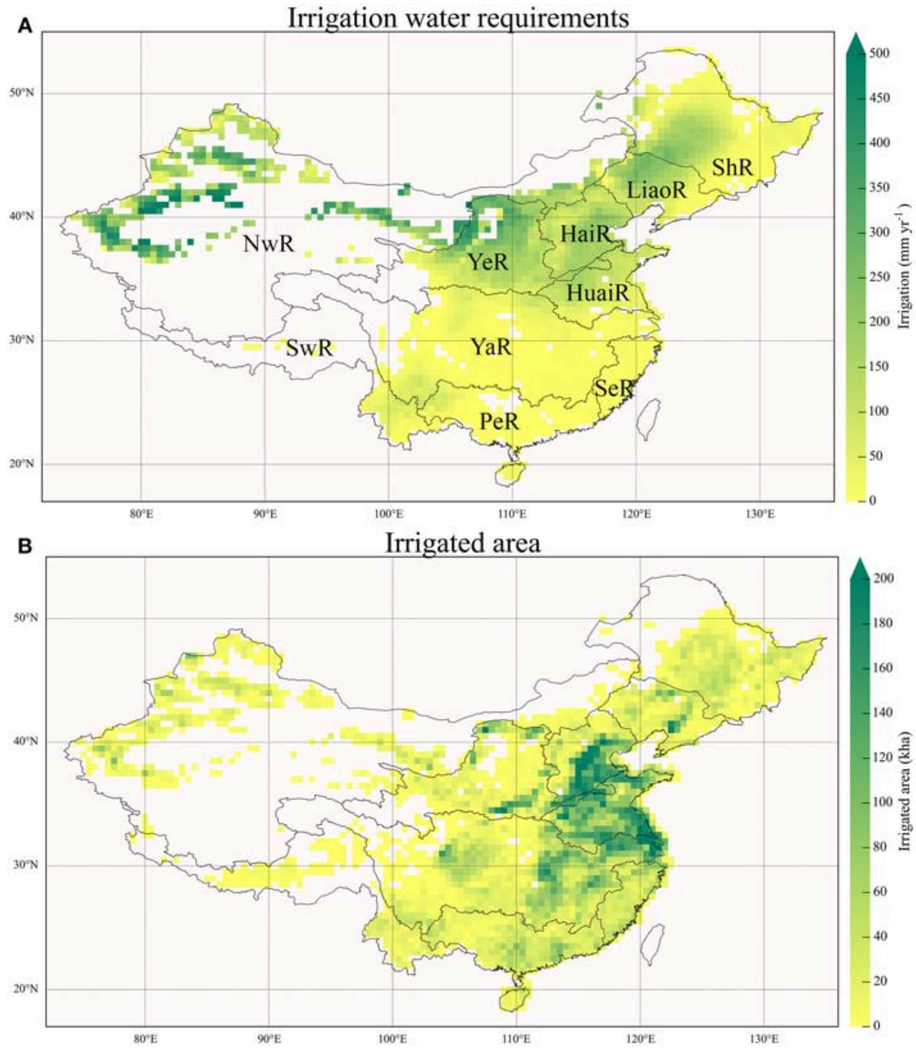

FIGURE 2 | Maps of irrigation water requirements over cropland **(A)** and total irrigation land area in each 0.5 degree grid cell **(B)** of the four crops. Irrigation water requirements were estimated by considering the whole cropland (the MIRCA-2000 dataset) as irrigated land for each crop and then aggregated by using area-weighted average of maize, rice, soybean, and wheat. Ten large river basins (presenting on the top panel) in the mainland of China were used to aggregated regional information, including the Hai River basin (HaiR), the Huai River basin (HuaiR), the Liao River basin (LiaoR), the Northwest River basins (NwR), the Pearl River basin (PeR), the Southeast River basins (SeR), the Songhua River basin (ShR), the Southwest River basins (SwR), the Yangtze River basin (YaR), and the Yellow River basin (YeR).

(10 km^3 yr^{-1}), and the Huai River basin (10 km^3 yr^{-1}) (**Table 1**). The Yangtze River basin has the largest irrigated cropland area in total, while its irrigation water requirements are relatively small due to the relatively high rainfall (3.1 km^3 yr^{-1}).

Effects of Irrigation on Crop Yields

The area-weighted average of rainfed yields (the zero scenario) of the four major crops shows high values in the east parts of China, over 5 ton ha^{-1} yr^{-1} (ton per hectare per year), while the rainfed yields are particularly low (<1 ton ha^{-r} yr^{-1}) in the northwest parts of China (**Figure 3A**). Therefore, irrigation in these low rainfed yield regions can greatly improve crop yields, especially in the Northwest River basins and the middle of the Yellow River basin (**Figure 3B**). It is not surprising that the differences in crop yields (**Figure 3B**) between the full irrigated and full rainfed cultivation show similar spatial patterns to the irrigation water requirements under the 100% scenarios (**Figure 2A**). At the river basin level, irrigation under the baseline scenario can increase crop production by 5.5 times of that under the zero scenario in the Northwest River basins, followed by the Yellow River basin (by 40%), and the Hai River basin (by 38%) (**Table 1**). As for the whole mainland of China, current irrigation (the baseline scenario) increases its crop production by 13%.

Hydropower Potential Under the Zero and Baseline Scenarios

Under the zero irrigation scenario, i.e., without irrigation water withdrawal, the hydropower potential is mainly concentrated in the southwest parts of China (**Figure 4A**), including the Southwest River basins and the head of the Yangtze River basin, with high values >1,000 MW (million watt). This is mainly because there are abundant water resources and large elevation differences in these areas. The hydropower potential is relatively small in the north parts of China, especially in the vast regions of the Northwest River basins, which is lower than 100 MW.

Water used for irrigation under the baseline scenario has largely reduced the hydropower potential in the north parts of China (**Figure 4B**). In some areas of the Northwest River basins and the Yellow River basin, the percentage reduction in hydropower potential is more than 50%. At the river basin level, the baseline irrigation results in the largest reduction of hydropower potential in the Yellow River basin by 10,354 MW (**Table 1**), which accounts for about 17% of its hydropower potential in the condition of zero irrigation. The percentage reductions in hydropower potential in the Hai River basin, the Liao River basin, and the Huai River basin are 11, 10, and 6%, respectively. At the national level, the percentage reduction is only 1.8%, mainly because the reduction in hydropower potential is very small in the four southern river basins of China, i.e., the Southwest River basins, the Yangtze River basin, the Pearl River basin, and the Southeast River basins, where the irrigation water requirements are very small relative to their water resources.

Water-Food-Energy Nexus Under Various Irrigated Cropland Scenarios

Agricultural irrigation has strong effects on the WFE nexus in the north parts of China, especially in the Yellow River basin, the Hai River basin, and Liao River basin, i.e., increases in crop

TABLE 1 | Impacts of irrigation on the Water-Food-Energy nexus under the baseline scenario.

Variables	HaiR	HuaiR	LiaoR	NwR	PeR	SeR	ShR	SwR	YaR	YeR	Nation
Irrigated area (kha)	10556.5	12353.7	3392.2	4131.7	5295.9	2502.4	4389.8	1044.7	20574.2	7733.4	71974.4
Irrigation water requirement (km^3 yr^{-1})	17.9	9.8	4.1	9.8	0.4	0.2	3.4	0.3	3.1	12.8	61.7
Irrigation water supply (km^3 yr^{-1})	47.2	25.8	10.9	26.1	1.0	0.4	9.1	0.8	8.1	33.8	163.1
Total water resources (km^3 yr^{-1})	22.0	88.1	39.3	141.9	499.7	234.0	128.4	517.2	806.0	56.4	2533.0
Percentage of irrigation water supply to total water resources	214.5	29.3	27.7	18.4	0.2	0.2	7.1	0.2	1.0	59.9	6.4
Crop production under zero scenario (kton yr^{-1})	37482.1	75212.5	20454.7	1720.6	32327.0	10341.5	33062.3	7828.2	128337.6	27632.0	374398.6
Increases in production (kton yr^{-1})	14380.4	6215.4	2764.4	9662.7	244.7	49.5	1958.8	361.3	1134.4	11033.0	47804.6
Percentage increases in production (%)	**38.4**	8.3	**13.5**	**561.6**	0.8	0.5	5.9	4.6	0.9	**39.9**	**12.8**
Hydropower potential under zero scenario (MW)	7125.6	3720.7	6607.0	56024.6	61684.4	19267.1	18597.7	275875.5	280801.4	60052.3	789756.3
Reduction in hydropower (MW)	797.3	221.9	624.5	1206.8	225.7	8.7	396.1	89.1	624.7	10354.1	14549.0
Percentage reduction in hydropower (%)	**11.2**	**6.0**	**9.5**	2.2	0.4	0.0	2.1	0.0	0.2	**17.2**	1.8

*Irrigated area is based on MICRA-2000 dataset. Irrigation water requirement was estimated under the baseline scenario. Total water resources were based on MWRC (2007). Increases in production: increases in crop production between baseline and zero scenarios. Reduction in hydropower: reduction of hydropower potential between baseline and zero scenarios. HaiR, the Hai River basin; HuaiR, the Huai River basin; LiaoR, the Liao River basin; NwR, the Northwest River basins; PeR, the Pearl River basin; SeR, the Southeast River basins; ShR, the Songhua River basin; SwR, the Southwest River basins; YaR, the Yangtze River basin; YeR, the Yellow River basin; Nation: the mainland of China. Location of each river basin is described in **Figure 2A**. Bold values highlight regions with strong WFE nexus.*

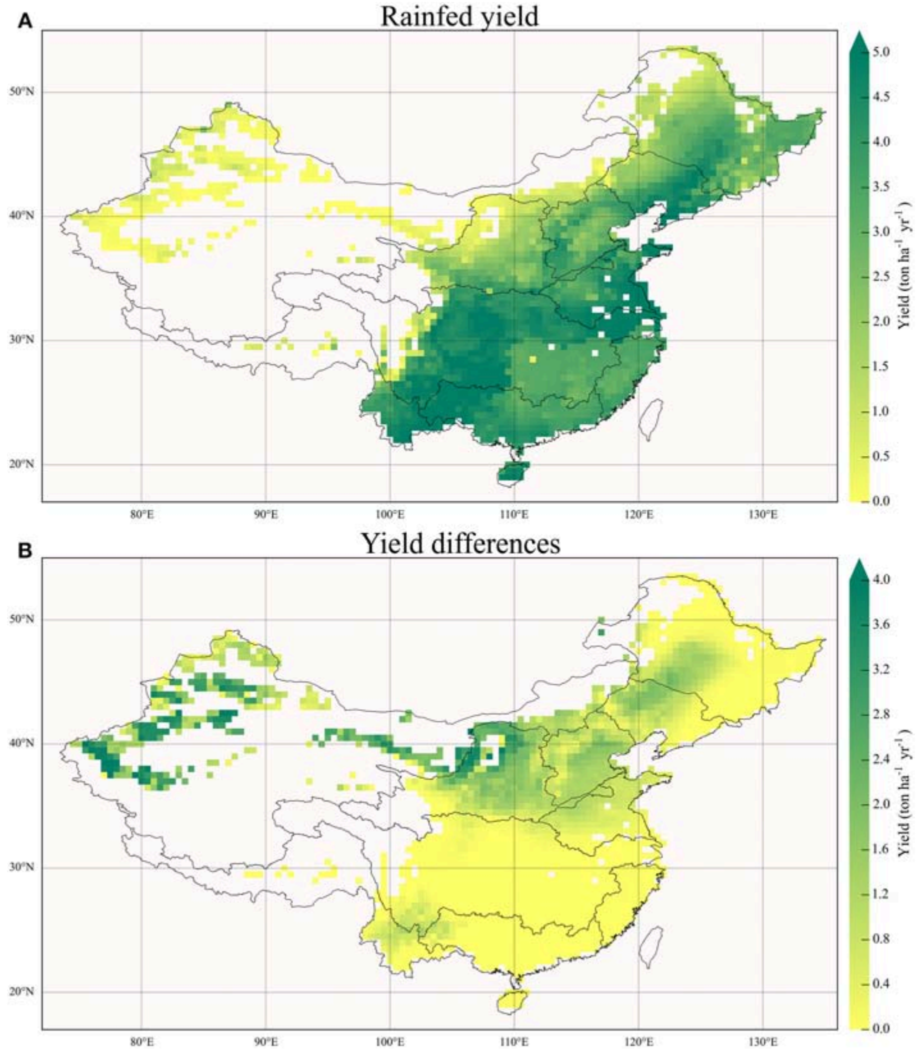

FIGURE 3 | Maps of rainfed crop yields **(A)** and differences between irrigated crop yields and rainfed crop yields **(B)** of maize, rice, soybean, and wheat. Rainfed crop yields were estimated by considering the whole cropland (the MIRCA-2000 dataset) as rainfed land for each crop and then aggregated by using area-weighted average of the four crops. Irrigated crop yields were estimated by using the same way as rainfed crop yields but considering the whole cropland as irrigated land.

production by more than 10% accompanied with reduction in hydropower potential by over 10%. Besides, the Northwest River basins and the Huai River basin have also relative strong WFE nexus. Crop production increases by 560% in the Northwest River basins due to irrigation, although the reduction in hydropower potential is relatively small (2.2%). In the Huai River basin, both the increase in crop production and the reduction in hydropower potential reach 6% (**Table 1**). Therefore, we focus on these five hotspot river basins and the mainland China to further investigate the impacts of irrigation under 10 different scenarios on the WFE nexus (**Figure 5**). Generally, the impacts of irrigation on the WFE nexus get more evident with increasing irrigated areas. The Yellow River basin demonstrates the most significant responses, that is, crop production could increase by 53% under the 100% irrigation scenario compared to crop production under the zero scenario, while hydropower potential would decrease by 25%. At the national level, crop production would have 16% increases and reduction in hydropower potential is about 2.8%.

For the five presented basins and also the mainland China in **Figure 5** except the Liao River basin, points for the baseline scenario locate at the upper and left side of the points for the other different irrigation fraction scenarios. This means that the distribution of current irrigation land (the baseline scenario) has advantages on the WFE nexus over the indiscriminate irrigation fraction scenarios. For example, about 86% of total cropland in the Hai River basin is irrigated land under the baseline scenario. If we consider 86% of total cropland in each grid as irrigated land, irrigation would result in the same increases (about 38%) in crop production compared to the baseline scenario, while it may cause about 2% more reduction in hydropower potential relative to the baseline condition.

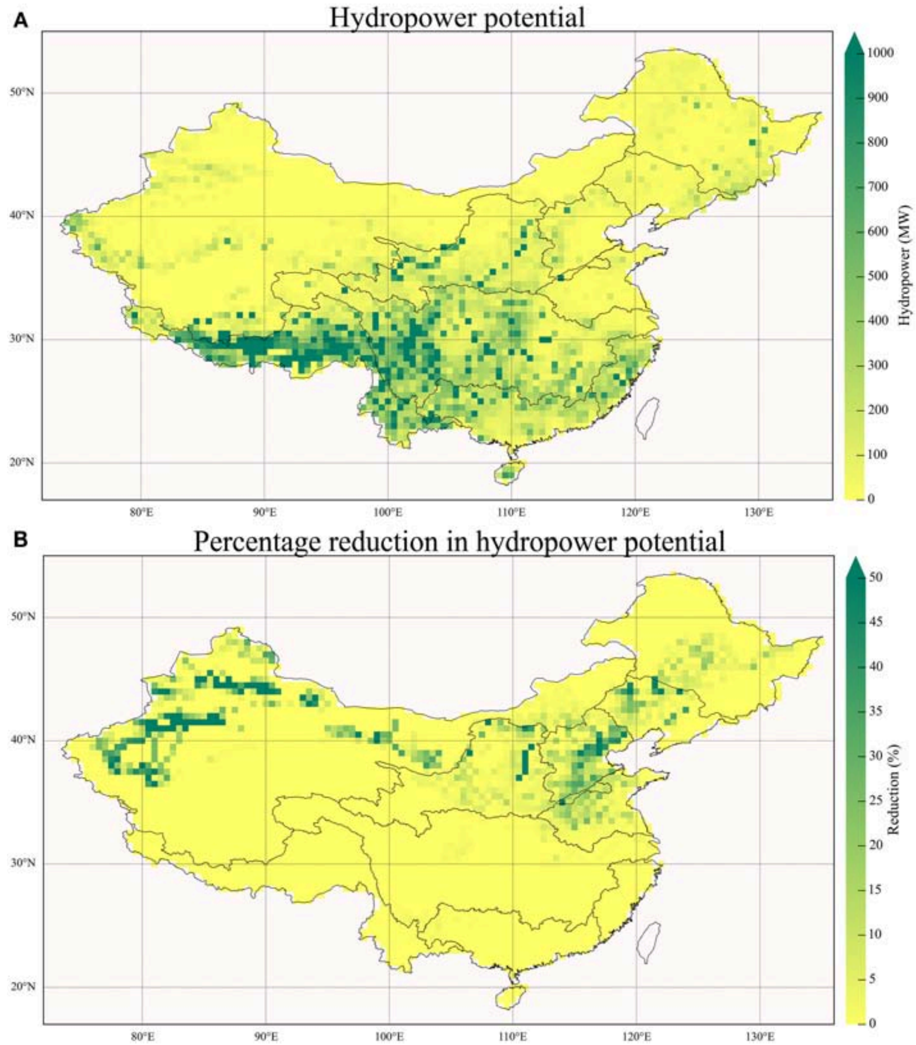

FIGURE 4 | Maps of hydropower potential under the zero irrigation scenario **(A)** and percentage reduction in hydropower potential between the baseline and zero irrigation scenarios **(B)**.

DISCUSSION

The WFE nexus shows various tradeoffs in terms of increasing crop production with irrigation and conserving hydropower potential in China (**Table 1**). Generally, the northern parts of China have stronger WFE interactions than the southern parts of China. This is mainly because growing season precipitation in the south parts of China is much higher than that in the north parts of China (Liu et al., 2018), hence crop production only faces slight water deficiency and less irrigation water is required. Another reason is due to the high amount of hydropower potential in the south parts of China (**Figure 4A**). The reduction in hydropower potential caused by irrigation has therefore little effects on the overall hydropower potential in these regions. In contrast, the north parts of China demonstrate strong WFE tradeoffs. We identified the Yellow River basin, the Hai River basin, and the Liao River basin as the hotspot regions regarding the WFE nexus.

By considering high fractions of total cropland as irrigated land, e.g., the 70, 80, 90, and 100% scenarios, we found that the reductions in hydropower potential are less significant than that under the lower fraction scenarios, e.g., 10, 20, and 30%, in the Huai River basin and the Northwest River basins (**Figure 5**). For instance, the percentage reductions in hydropower potential are 1.2 and 0.3% between 10 and 20% irrigation scenarios for these two basins, respectively. But they decrease to only 0.5 and 0.2% between 90 and 100% irrigation scenarios. It indicates that streamflow is not sufficient to support irrigation water withdrawal under the high irrigation fraction levels in these regions and hence less reduction in hydropower potential is observed. In these cases, reservoir regulation or groundwater withdrawal is necessary to compensate surface water insufficiency for irrigation (Siebert et al., 2010). Reservoir regulation is not considered since we mainly focus on GHP in this study. However, a previous study (Liu et al., 2016c)

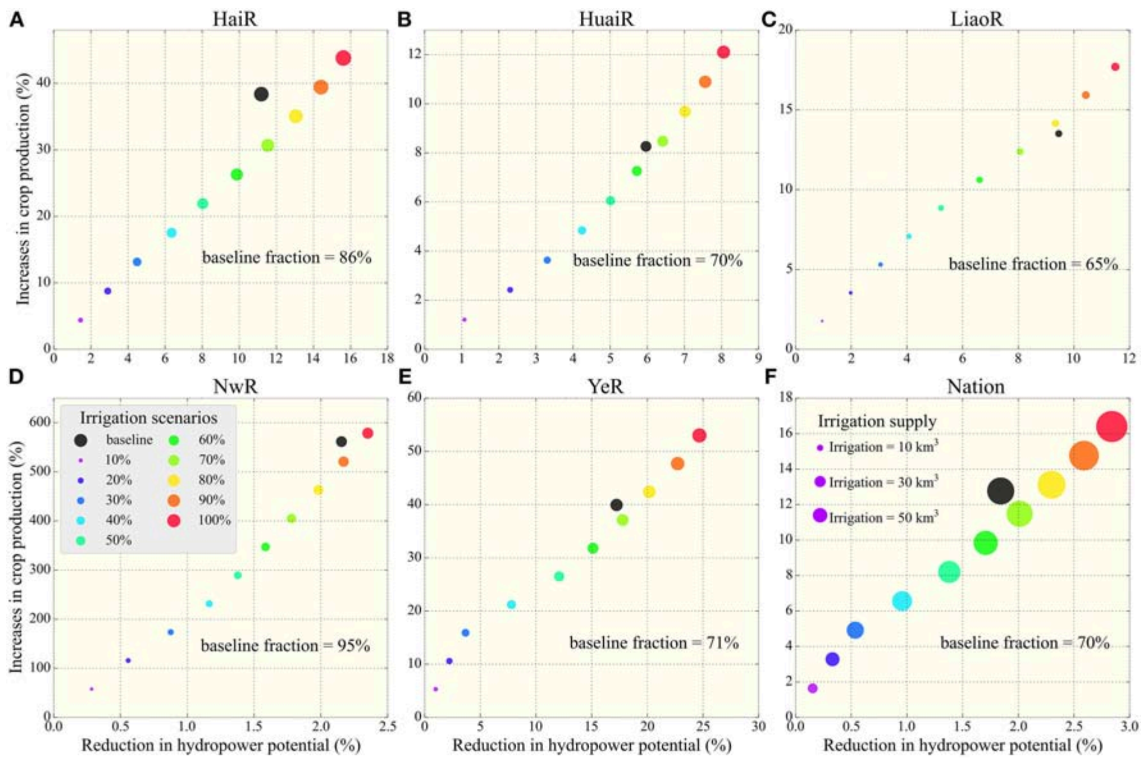

FIGURE 5 | The water-food-energy nexus under different irrigated cropland scenarios for Hai River basin (HaiR, **A**), Huai River basin (HuaiR, **B**), Liao River basin (LiaoR, **C**), Northwest River basins (NwR, **D**), Yellow River basin (YeR, **E**) and the mainland China (Nation, **F**). Increases in crop production: percentage increases in crop production between different irrigation scenarios and the zero scenario. Reduction in hydropower potential: percentage reduction in hydropower potential between different irrigation scenarios and the zero scenario. Color presents different irrigated cropland scenarios. Size presents irrigation water supply. Baseline fraction means the fraction of irrigated cropland area under the baseline scenario to the total cropland area. HaiR, Hai River basin; HuaiR, Huai River basin; LiaoR, Liao River basin; NwR, Northwest River basins; YeR, Yellow River basin; Nation: mainland of China. Location of each river basin is described in **Figure 2A**.

showed that the changes in hydropower based on reservoirs were often consistent with the GHP changes. Therefore, here we can infer similar changes in hydropower potential based on existing reservoirs/hydropower facilities as those in the GHP. Nevertheless, further investigation is needed to address the important role of reservoirs in optimizing the WFE nexus. As a large amount of energy is consumed to pump groundwater for irrigation (Scott, 2013), groundwater consumption for irrigation provides another dimension of the WFE nexus in comparison to surface water consumption. Merging surface water and groundwater into an integrated research system can demonstrate a more comprehensive picture of the WFE nexus and deserves detailed investigation in future studies.

We found that the baseline irrigation pattern performs better in terms of effects on hydropower potential than the indiscriminate irrigation fraction of total cropland in the northern basins. However, in the Liao River basin, it is not the case. The baseline irrigation land accounts for 65% of total cropland. Although the baseline irrigation scenario has higher increases in crop production than that when 65% of cropland as irrigation land in each grid, interpolated from the trend line in **Figure 5**, the percentage reduction in hydropower potential under the baseline scenario is more than the percentage increase in crop production. It implies that there are spaces to optimize the current irrigation patterns for enhancing the WFE nexus there. Transforming more cropland into irrigated land in the regions with higher increase in crop yields and lower reduction in hydropower potential can be a possible pathway toward irrigated land optimization. As climate conditions can have impacts on WFE nexus (Conway et al., 2015; Berardy and Chester, 2017), especially due to the more frequent drought events (Zhang et al., 2017; Cai et al., 2018), such optimization is essential to improve the overall resource use efficiency in the framework of the WFE nexus (Ringler et al., 2013). However, a detailed analysis of optimizing irrigation patterns is beyond the scope of this study.

We acknowledge some limitations in this study. We only considered four major crops in the investigation. Excluding other crops would have some impacts on the analysis the WFE nexus. For example, irrigation water requirements for cotton production are much higher than that for maize and wheat cultivation in the northwest parts of China (Shen et al., 2013). The impact of irrigation on hydropower potential could be largely underestimated without considering cotton. Cotton was excluded from the analysis mainly because it is not a food crop and this study focuses on the tradeoffs between food production and hydropower potential. Besides, the irrigated areas of the four crops in the whole of China account for about 80% of the total irrigated areas of the 26 major crops in the country included in Portmann et al. (2010). Based on our estimation, for all the 26 crops, the total irrigation water requirements will be 25% higher. Consequently, the reduction of hydropower potential will be ∼25% higher. Also, the estimated values by large-scale models are subject to high uncertainties due to model structure and parameters. For example, a previous study shows that the selection of different potential evapotranspiration methods built-in PEPIC can have large effect on the estimation of crop yields and irrigation water requirements (Liu et al., 2016a). Large uncertainty arisen from hydrological models including DBH were reported (Schewe et al., 2014; Liu X. et al., 2017), which indicates that improving model structure and parameters is needed. Although the uncertainty issue is out of scope of this preliminary analysis, it is in our agenda to address this issue in detail. Despite these limitations, this study provides the first attempt to illustrate the WFE nexus with respect to water, food, and hydropower potential relations. The information is of importance for understanding the WFE nexus in China and for formulating appropriate policies to tackle the nexus related challenges.

CONCLUSIONS

In this study, the PEPIC crop model was coupled with the DBH hydrological model to investigate the WFE nexus in mainland China under various irrigated cropland scenarios. The northern parts of China show strong WFE nexus and tradeoffs due to large amount of irrigation water requirements and relatively low water resources there, while irrigation had only little effects on the WFE nexus in the southern basins of China. The Yellow River basin, the Hai River basin, and the Liao River basin were identified as the hotspot regions regarding the tradeoffs in the WFE nexus, where more attention should be paid for detailed investigation. The current irrigated cropland generally presents good performance compared to the indiscriminate irrigation fraction of total cropland. Still, there are spaces for improving the distribution of irrigated cropland to maximize the WFE benefits. Complexity and uncertainties in studying the WFE nexus call for more comprehensive research to promote the usefulness of this concept as a robust tool for managing emerging challenges related to integrated and efficient management of water, food, and energy sectors.

This paper addressed the WFE nexus by specifying quantitatively the tradeoffs between food production increases through irrigation expansion (increased water withdrawal) and the loss of hydropower potential due to the reduction of streamflow. The information is useful for supporting integrated management of water resources for energy and food sustainability in China. However, the study did not go further to address the economic/social significance of the tradeoffs, as such analysis would be location/river basin specific. It is beyond the scope of this study to judge whether a specific river basin/region/country should choose to forego its hydropower potential in order to gain more food production. Such a decision would need much more information on socioeconomic conditions, regional development strategies, environmental status, etc. This would be the topic of our future study. Finally, we should like to mention that although this study focuses on China, the approaches developed can be used in other countries and basins in the world for addressing the WFE nexus quantitatively.

AUTHOR CONTRIBUTIONS

WL, HY, and XL designed the research. WL run the PEPIC model and analyzed the data and wrote the manuscript. XL run the DBH model. All authors participated in the interpretation of results and the writing and editing processes.

ACKNOWLEDGMENTS

This study was supported by the funding from the Swiss Federal Institute of Aquatic Science and Technology (Eawag) and the World Food System Center at ETH Zürich. WL acknowledges the support received from the Early Postdoctoral Mobility Fellowship awarded by the Swiss National Science Foundation (P2EZP2_175096). XL was supported by funding from the National Natural Science Foundation of China (41877164). QT was supported by funding from the National Natural Science Foundation of China (41730645).

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Environmental Science

ORIGINAL RESEARCH
published: 24 April 2019
doi: 10.3389/fenvs.2019.00048

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A Nexus Approach for the MENA Region—From Concept to Knowledge to Action

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Specialty section:
This article was submitted to Freshwater Science, a section of the journal Frontiers in Environmental Science

Received: 07 November 2018
Accepted: 28 March 2019
Published: 24 April 2019

Citation:
Hoff H, Alrahaife SA, El Hajj R, Lohr K, Mengoub FE, Farajalla N, Fritzsche K, Jobbins G, Özerol G, Schultz R and Ulrich A (2019) A Nexus Approach for the MENA Region—From Concept to Knowledge to Action. Front. Environ. Sci. 7:48. doi: 10.3389/fenvs.2019.00048

There is wide agreement that a nexus or integrated approach to managing and governing natural resources such as land, water, and energy can improve environmental, climate, human, and political security. However, few if any countries in the MENA region have made progress in implementing such an approach. There appear to be several constraints inhibiting the development and adoption of nexus approaches. These constraints include strong sectoral silos, insufficient incentives for integrated planning and policy making at all levels, and limited vision, knowledge, and practical experience to guide successful implementation. In turn, the limited implementation and hence lack of empirical evidence of a nexus approach, which could demonstrate its benefits, does little to strengthen political will for the development of adequate incentives, structures, and procedures. Against this backdrop, this paper presents five case studies which take an integrated approach, in three MENA countries, namely Jordan, Lebanon, and Morocco. Based on an analytical framework developed here, the paper analyses and compares the success factors for nexus implementation, and also for transfer and upscaling. The analysis emphasizes the need for appropriate framework conditions, targeted investments and pioneering actors, to make integrated approaches across sectors and levels work. With the evidence presented, the paper aims to set in motion a positive or virtuous cycle of generating more nexus evidence, improved framework conditions, further nexus implementation on the ground, and from that even more nexus evidence. Finally, the paper contributes to overcoming the repeated requests for better definition and conceptualization of the nexus, which often has slowed down adoption of the concept.

Keywords: nexus, tradeoffs, synergies, integrated management, policy coherence, MENA region

INTRODUCTION

The Middle East and North Africa (MENA) region is characterized by extreme water as well as land scarcity, low (cross-) resource use efficiencies despite growing urgency (Sullivan, 2013; Waterbury, 2017) and increasing human insecurities—being the only region in the world with decreasing food security (FAO, 2015). Agricultural production could decrease in future (OECD/FAO, 2018). These trends converge with a rapid transition toward renewable energy as well as toward non-conventional water, with uncertain cross-resource and cross-sector impacts. However, weak governance and large implementation gaps exist in all the sectors, aggravated by a lack of policy coherence, which however is not specific to the MENA region.

This situation begs for the integrated management of natural resources such as water, energy, land and biomass, and integrated governance across sectors. Such integrated approaches will strengthen human, as well as water, energy and food security, environmental and climate security and eventually also political security. This is what the so-called nexus approach[1] promises (Hoff, 2011; Allan et al., 2015; Al-Saidi and Elagib, 2017). However, there is very limited progress so far in the operationalization of the nexus concept in policy making and its implementation on the ground (Leck et al., 2015). This implementation challenge is particularly critical in the MENA region, where several constraints contribute to this dilemma, such as insufficient incentives, limited vision, knowledge, and experience to guide technology development and investment, and in particular the absence of concrete examples and applied practices (Mansour et al., 2017; Weitz et al., 2017a).

The lack of practical nexus implementation implies that there is little empirical evidence of the potential benefits and added value of applying the nexus approach as well as of the challenges associated with it. This lack of evidence in turn limits political will for the development of adequate framework conditions, structures, and funding that would support nexus implementation. In order to break this vicious cycle and turn it into a virtuous cycle, examples of good practice of nexus implementations on the ground and accompanying quantitative analyses are required (Al-Saidi and Elagib, 2017). Such analyses can demonstrate the benefits of integrated approaches and practices. The empirical evidence from such analyses could help to overcome inertia, vested, and short-term interests, path dependencies, and other disincentives to reform and encourage nexus thinking and action. At the same time, such practical evidence can address the cross-sector interdependencies and challenges when implementing the Sustainable Development Goals (SDGs) (Weitz et al., 2014a; Leck et al., 2015; Rasul, 2016), and climate adaptation and mitigation goals of the Nationally Determined Contributions (NDCs) (Rasul and Sharma, 2015; Brandi et al., 2017; Pardoe et al., 2017).

[1]Nexus is the Latin word for interlinkages, a nexus approach assesses interlinkages (synergies and tradeoffs) across sectors and resources, and - based on that evidence – promotes integrated management and governance, see Hoff (2011).

Against this backdrop, our paper presents a set of cases in the MENA region, which were selected for their integrated approaches, involving several sectors and natural resources. These cases provide an initial evidence base for a comparative analysis from a nexus perspective. Our paper aims at identifying success factors for future nexus projects, synthesizing lessons learned, including challenges, and a general way forward in making the nexus work. In order to do so, the paper develops and applies an analytical framework for evaluating and comparing the different cases, drawing on existing literature. The paper is structured as follows:

- The second section provides a review of the current state of the literature in the conceptualization and practical implementation of the nexus, highlighting in particular unresolved issues and criticisms to the nexus approach.
- Taking the findings from the literature review into consideration, section Analytical Framework develops an analytical framework for the analysis and comparison of the different cases, which are involving different sectors and natural resources.
- Subsequently, in section Case studies and selected cross-sectoral approaches the analytical framework is applied to five selected cases in Morocco, Jordan and Lebanon, assessing the associated benefits and added value as well as costs of applying an integrated approach.
- Section Comparative analysis across case studies and lessons learned summarizes key findings from the analysis of the five cases, highlighting in particular good practices, lessons-learned, required framework conditions, opportunities for transfer and upscaling as well as remaining challenges to the operationalization and implementation and of the nexus.
- Drawing on this discussion, the final section Conclusion synthesizes options for overcoming barriers and promoting nexus approaches in management and governance and mainstreaming the nexus across various MENA contexts.

LITERATURE REVIEW

Since its emergence and in particular following the Bonn Nexus Conference in 2011, the concept of the water-energy-food nexus (WEF nexus)[2] has received wide attention in academic literature (e.g., Bazilian et al., 2011; Mohtar and Daher, 2012; Leck et al., 2015; Liu et al., 2017; Albrecht et al., 2018). It essentially underlines the need for integrated approaches to deal with complex issues at the intersection of natural and human systems. Or as Hoff (2011) puts it: "Conventional policy- and decision-making in "silos" (. . .) needs to give way to an approach that reduces trade-offs and builds synergies across sectors—a nexus approach." Already in the 1970s, academic literature on governance of complexity explored how policies could be designed to find integrated solutions to complex problems.

[2]While the water-energy-food nexus is one of the most frequently explored nexus constellations, it should be noted, that a nexus approach can also integrate other sectors (see an overview of different types of nexus in Endo et al., 2017). In the following, the paper will therefore more general refer to the "nexus" without further specification of the topics it relates to.

Scharpf (1972) identified three major pitfalls that hinder policy making for complex issues: (1) segmented problem perception by theme-centered institutions that focus on parts of a problem and therefore tend to overlook interlinkages or problems in the space between different theme-centered institutions; (2) short-sighted solutions that do not enfold the desired impact due to being based on segmented problem perception; (3) neglecting negative implications or tradeoffs in other areas, emphasizing the need for coordination, to limit adverse effects which can reduce the overall efficiency of a system. By embracing complexity rather than trying to over-reduce it, the nexus approach aims to avoid such major pitfalls.

Environmental policy integration (EPI) and integrated water resources management (IWRM) have preceded the nexus approach in addressing cross-sectoral policy challenges (GWP, 2000; özerol et al., 2012; Weitz et al., 2017a). EPI in particular sought the vertical integration (across levels within sectors) and horizontal integration (between sectors) of environmental issues and objectives into governance (Lafferty and Hovden, 2002). EPI differs from the nexus approach by mainstreaming a particular environmental issue into other sectors of policy- and decision-making, however without basically challenging segmented, sector-focused approaches. Similarly, IWRM strives for a more holistic and systemic understanding of a problem, but it still puts water into the center (GWP, 2000; Leck et al., 2015). The nexus approach, by contrast, applies a "multi-centric" (Liu et al., 2017) perspective that not only aims to transcend sectoral boundaries, but also to treat these different perspectives and stakeholders more or less equal in its considerations (White et al., 2017), trying to account for political economies and power differences between sectors when negotiating tradeoffs (Scott, 2017). As Hagemann and Kirschke (2017) point out, there are many similarities between the EPI and the nexus approach, such as the focus on interdependencies and trade-offs between different sectors, the consideration of different scales for problem solving (Hoff, 2018), or the emphasis of participation in management and governance.

Despite distinct features such as the focus on interlinkages, trade-offs and synergies between sectors and the multi-centered perspective, there is no single approach to defining or operationalizing the nexus. Systematically reviewing 245 journal articles and book chapters, Albrecht et al. (2018) found a wide range of approaches, methods and purposes of a nexus approach, ranging from environmental management and economics, to energy and food system modeling and social sciences. The analysis further revealed that nexus studies are still often confined to disciplinary silos and fail to capture the full set of interlinkages between water, energy, and food (ibid.). Endo et al. (2017) also observe that there is no "fixed concept of nexus, and the nexus is internationally interpreted as a process to link ideas and actions of different stakeholders under different sectors and levels for achieving sustainable development." Weitz et al. (2017a) identify three gaps in the nexus literature that are currently only poorly addressed, namely the conditions for cross-sector coordination and collaboration, the dynamics beyond cross-sector interactions and political and cognitive factors as determinants of change. They describe the nexus approach as "conceptually inconclusive" and highlight the need for clarity on overarching objectives and guiding principles. In this vein, Jobbins et al. (2015) come to the conclusion that nexus approaches are not *per se* pro-poor and ask: is "the reduction of trade-offs between water, energy and food security considered an end in itself, or does it support higher-level social goals such as the reduction of poverty?" For this paper we argue that the nexus can help to achieve better social and economic outcomes while reducing pressure on natural resources and the environment—so called "decoupling," e.g., through enhancing resource use efficiencies across resources, through integrated management and governance and policy coherence.

Building on these critical reflections of the nexus concept, we argue that the current nexus literature lacks convincing case studies of cross-sector coordination and concrete implementation of nexus approaches, which would enable an analysis of challenges and opportunities and relevant framework conditions and. This holds particularly true for the MENA region with its urgent need for more integrated management and governance across sectors. This paper therefore aims to address this gap by providing a comparative analysis of five case studies in the MENA region, each of which involves several sectors. By showcasing these concrete examples, we also aim to provide evidence of the value that a nexus approach can add to policy and decision making. The following section describes our framework for the comparative analysis.

ANALYTICAL FRAMEWORK

In line with the mainstream of nexus literature (see chapter Literatur Review), we understand the nexus as a cross-sectoral and multi-level approach to deal with complex sustainability challenges. Rather than providing a set of clear guidelines or measures to apply, the nexus provides an approach that aims at creating a level playing field for all sectors while at the same time having sustainability (as defined in the SDGs) as an overarching aim. How this aim would be operationalized and met, however, is dependent on the specific case and the actors involved. Furthermore, embracing complexity in our view includes revealing and addressing political economies and asymmetries in power relations of involved actors and stakeholders and enabling them to better understand and address complex issues.

Starting from this understanding of the nexus approach, we develop a practice oriented analytical framework which enables a comparative analysis of the five case studies presented in this paper and guidance for future nexus implementation. The framework comprises six categories to be explored in detail for the description and analysis of the case studies:

1) Nexus framing: this category creates a common, context-specific understanding of the key issues from a nexus perspective, explores the interlinkages between the different sectors and resources, and includes synergies and tradeoffs which could be relevant for the case study;
2) Nexus opportunities: this category identifies how a nexus approach could add value in the respective context, e.g., by

improving (cross-)resource productivity, reducing resource and environmental degradation, increasing climate resilience, and reducing human insecurities/poverty/unemployment;

3) Technical and economic nexus solutions: this category assesses and if possible quantifies potential benefits from the implementation of nexus approaches or "nexus savings" in the respective case study, e.g., through multi-functional production systems, municipalities or landscapes, and cross-resources and cross-sector recycling;
4) Stakeholders involved: this category specifies the different types and levels of stakeholders involved in the case study, e.g., from public and private sector and civil society, their respective roles, and what is required to make it successful;
5) Framework conditions: This category addresses relevant conditions and context factors including type (technical solutions, policy solutions, mix of measures) scale and level (e.g., farm-level, community-level, national level etc.) and the actual implementation of a nexus approach. It also aims to answer questions such as: how can the nexus approach be institutionalized, i.e., how can the experience from practical implementation be taken into account in policy and decision making, e.g., by improved cooperation between sectors and institutions? Have any new bridging mechanisms or even new nexus institutions been established yet, including integrated SDG and/or NDC implementation? Does this contribute to improving policy coherence and if so how? Do integrated approaches contribute to innovation (e.g., via entrepreneurs and incubators, also considering relevant framework conditions outside the nexus)?
6) Monitoring, evaluation and next steps: This category defines indicators and required data for monitoring and evaluation (M&E) of the implementation of the nexus approach. It builds on the understanding that nexus implementation is a process with dynamic objectives, composition of stakeholders and processes and therefore requires a self-reflexive mechanism (institutional learning mechanism and multi-loop learning) to further evolve. This section also provides an outlook to the potential of each case study for replication and upscaling.

In the following sections, these six categories will be applied to evaluate and compare five selected case studies in the MENA region.

Note that our analytical framework goes beyond existing frameworks (e.g., Bizikova et al., 2013; Flammini et al., 2014; Mohtar and Daher, 2016) in that it synthesizes experience from existing case studies, each of which involves different sectors.

CASE STUDIES AND SELECTED CROSS-SECTORAL APPROACHES

Given the lack of explicit nexus approaches and implementations, which would have built into their design integrated management and governance across sectors, we analyze opportunistically five cases from Morocco, Jordan and Lebanon, each of which includes interlinkages across the water, energy and food/agriculture sectors. These cases or case studies start from different angles and objectives, cover different scales and contexts, and have different types of actors and stakeholders. Nevertheless, together they provide a rich set of new insights and valuable lessons for the design of future nexus projects and for integrated governance. The five cases included here start from: (i) drip irrigation (Morocco), (ii) solar water pumping for irrigation (Morocco), (iii) solar desalination and use of the desalinated water for biomass production (Jordan), (iv) integrated water, land and energy management at the municipal level (Jordan), and (v) integrated water, land and energy management at the farm level (Lebanon).

The case studies were opportunistically selected from on-going cross-sectoral projects in the MENA region and in-depth knowledge of each case by at least one co-author. The cases thus neither present full nexus implementations, nor are they fully representative for the region, however they give a valuable overview of integrated approaches on the ground. Before presenting the five case studies, we give a short introduction to the contexts of Morocco, Jordan and Lebanon, the countries in which the cases are embedded.

In **Morocco**, the agricultural sector, a major driving force for the national economy, consumes more than 80% of all water resources. The severe water scarcity is further exacerbated by the effects of climate change. Competition between different water uses is growing, besides agriculture also the water demands for industry, tourism, hydro-power (7% of national energy production) and municipal drinking water continue to grow. Energy demand in agriculture (e.g., for water pumping) and in other sector is also rapidly increasing and still primarily met by fossil resources, for which Morocco is a net importer. Rationalization of water and energy use is crucial to develop the agricultural sector, improve farmers' incomes and ensure food security. We show here experience from two different sub-cases where drip irrigation was introduced and one case where solar energy for water pumping was introduced.

Jordan is one of the most water-scarce countries in the world and the situation is increasingly aggravated by population growth, by climate change and by the region's geopolitical situation. The country is heavily relying on (fossil) groundwater which is increasingly depleted. Agricultural production, which is an important source of livelihoods and employment in rural areas, is strongly limited by water scarcity and land and ecosystem degradation is a widespread phenomenon. Urban encroachment further reduces the availability of arable land. Irrigated and rainfed areas are projected to shrink by about 30% by 2050 compared to 2010 (Al-Bakri et al., 2013). Water quality is increasingly threatened by industrial and domestic discharge of untreated wastewater. Furthermore, the demand for energy has been growing rapidly and Jordan's energy sector is strongly import-dependent, resulting in high energy costs. Desalination for meeting drinking and irrigation water demands and for reducing the growing demand-supply gap is very energy intensive, and hence is competing with other energy demands. Moreover, desalination relies on the use of fossil fuels, causing increased greenhouse gas (GHG) emissions. Water transfers are also very energy intensive in Jordan due to large elevation differences over which water needs to be pumped.

In **Lebanon** overexploitation and mismanagement of water resources, water quality degradation as well as energy scarcity (near total dependence on imports of fossil fuels) and deficit government electricity supply, further aggravated by rapid and unorganized development and climate change impacts, present major challenges. Water and electricity infrastructure are poor. The country experiences continued loss of agricultural land to urban expansion or rural-urban migration. Inefficient agricultural practices and increasing cost of agricultural production (also due to higher costs for water and energy) contribute to a shrinking agricultural sector within the overall national economy. Meanwhile agricultural discharges degrade water resources, and water scarcity reduces the hydropower potential.

Case Study 1: Drip Irrigation in Morocco; Sub-cases of Oum Rbiaa River in Tadla-Azilal, Bitit, and Ain Chegag in Sebou, Lamzoudia in Tensift, and Guerdane and Issen in Souss Massa

Nexus Framing

Adopting drip irrigation can increase the efficiency of water and energy use in agriculture (same amount of food production using less water and requiring less energy for pumping). Under certain conditions, this can reduce agriculture's overall consumption of water and energy. However, higher water and energy efficiencies from drip irrigation can incentivise farmers to intensify their production, expand irrigated areas and to adopt more water intensive crops ("rebound effect"). By minimizing excess application of water, drip irrigation also reduces return flows of water to aquifers that are available to other users. These effects mean that despite local savings, pressure on water resources at basin or national level can remain high or even increase. Moreover, it is not clear if all farmers benefit equally from the new technology and if inequities can be reduced.

Nexus Opportunities

Increasing water and energy efficiencies can improve agricultural productivity, gross margins and food security. In principle, additional co-benefits might be realized, but this depends on higher water and energy efficiencies resulting in reduced overall consumption. These co-benefits might include improved environmental flows, enhanced climate resilience, and climate mitigation, mitigation of water- (and energy-) related conflicts and other economy-wide nexus opportunities, e.g., re-allocation of water to other sectors including hydropower and drinking water. While in the Oum Rbiaa River case some of these benefits have been realized, these opportunities strongly depend on appropriate framework conditions in terms of legislation and regulation, otherwise there is a risk of negative outcomes as in the Bitit, Ain Chegag, Lamzoudia, Guerdane, and Issen cases.

Technical and Economic Nexus Solutions

Modernization of irrigation through introduction of pressurized drip irrigation can increase water and energy use efficiency. However, these technical nexus solutions need to be accompanied by effective policy, regulatory, and institutional measures, in order to reduce overall water and energy consumption.

Stakeholders Involved

Civil society—local farmers, private land owners and other stakeholders and NGOs. *Public institutions*—Morocco Agricultural Development Office (Office de Mise en Valeur Agricole), river basin agencies (responsible for water distribution among sectors), sources of public subsidies, policy makers in agriculture, and water. Institutions from different sectors (e.g., water, agriculture and energy) and different levels (e.g., national, regional and local) don't necessarily have consistent policy objectives and coordination between them takes time. Attempts to merge different ministries (e.g., water, energy, and environment) have not been very successful. *Investors*, including World Bank and African Development Bank. *Private businesses,* which pursue goals develop technical innovations.

Framework Conditions

The Government of Morocco, e.g., through the Plan Vert (for a modernized green and pro-poor agriculture) or the *Programme National d'Economie d'Eau d'Irrigation* encourages drip irrigation, with specific investments in irrigation schemes as well as general subsidies. Effective legislation, policies, institutions, and regulations are needed to ensure that increased efficiencies are translated into real water and energy savings rather than leading to overuse and rebound effects. These framework conditions also include the regulation of water abstractions, limiting the number of new wells, and reviewing and revising pricing systems and subsidies. In the absence of such measures, drip irrigation may well make existing problems worse. Knowledge transfer from existing implementations and technical assistance for farmers need to be broadened and intensified, e.g., through the Moroccan Agricultural Development Office and the Ministry of Agriculture, as well as "guichet unique" (one-stop-shops) which treat farmers demands.

Monitoring and Evaluation and Next Steps

The effects of the implementation of new drip irrigation technologies need to be monitored and evaluated systemically (i.e., from a nexus perspective), the potential effects of upscaling e.g., on groundwater levels, need to be modeled and the results and lessons learned need to be communicated to farmers, decision and policy makers for improving implementation and framing it in adequate legislation, regulation, and enforcement (also addressing illegal abstractions). Such a dialogue will have to involve practitioners, policy makers and scientists from universities and think tanks. So far monitoring (by ORMVAs) is limited to local efficiency improvements and fee recovery from users.

Case Study 2: Solar Powered Irrigation at the Farm Level in Marrakesh, Midelt, and TATA Zones in Morocco

Nexus Framing

Irrigation is limited (besides water scarcity) by high energy demand and associated cost. Replacing of fossil fuel with solar energy for pumping irrigation water has the potential to reduce costs and national import dependency for fossil energy. However, as solar energy is abundant in the MENA region, the lack of cost for operating the pumps may cause overexploitation of groundwater, due to the perception that "pumping is for free."

Nexus Opportunities

Solar pumping provides energy- and climate-smart agricultural water supply and supports the shift of the energy system to renewables. With that it contributes to climate change mitigation and it can reduce the cost of irrigation and improve farmers' income.

Technical and Economic Nexus Solutions

Switching from fossil to solar energy driven irrigation systems, e.g., for fruit, olive, and date trees and other crops, increases productivity (because of the improved availability of energy) and reduces fossil energy input into the agricultural sector.

Stakeholders Involved

Solar powered irrigation aims at small, medium-size and large-scale farmers, other stakeholders include cooperatives, economic interest group (*groupement d'intérêt économique*-GIE), Ministries of Agriculture, Energy and Finance, Credit Agricole (for subsidies scheme), and local and national water authorities (in charge of the Programme *National d'Economie d'Eau d'Irrigation*). Vocational training institutions and technology suppliers are also involved.

Framework Conditions

Morocco's "Plan Vert" (for a modernized green and pro-poor agriculture) prescribes a transition to a green economy, phasing out fossil fuel subsidies. A key element of this transition is solar irrigation, which is planned for 100,000 ha through a targeted subsidy scheme. These subsidies are foreseen to directly benefit farmers in plant production and indirectly benefit the whole society through improvement in food security and (ideally) water availability and lower GHG emissions. Solar powered irrigation contributes to a wide range of SDG targets as well as to mitigation and adaptation targets of the NDCs.

Monitoring and Evaluation and Next Steps

Loan schemes and subsidy schemes as well as water governance rules are currently being set up for renewables and solar irrigation, Subsidies and sustainable pumping rates have to be endorsed and enforced by the government e.g., via management contracts. Since there are national solar water pumping programs in other countries as well (e.g., Tunisia and Jordan), this case study not only serves as reference for implementations in other parts of Morocco but also beyond.

Case Study 3: Sahara Forest Project in Aqaba, Jordan

Nexus Framing

Shifting to renewable (in particular solar) energy reduces dependency on fossil fuel imports and greenhouse gas emissions, which is crucial for mitigating climate change. Employing the renewable energy for desalination of seawater and for cooling of greenhouses in integrated production systems can enhance water availability, increase crop productivity and generate co-products and co-benefits (e.g., algae, fish, dryland restoration, greening of the desert).

Nexus Opportunities

The Sahara Forest project integrated production system uses amply available natural resources, namely solar energy and seawater for improving water availability and agricultural/biomass production, that way providing new employment opportunities. Using hydroponic system and the humidity in the air, water needs for food production are 50% lower compared to other greenhouses.

Technical and Economic Nexus Solutions

Several major technologies are combined in the Sahara Forest Project[3], namely electricity production through the use of solar power (PV or CSP), freshwater production through seawater desalination using renewable energy, seawater-cooled greenhouses for food production, and outdoor revegetation using run-off from the greenhouses.

Stakeholders Involved

The key stakeholders which benefit from such an integrated production system are from the water sector which urgently requires an augmentation of irrigation (and other) water, as well as from the agricultural sector, which relies on the additional desalinated water to maintain and increase agricultural production. The project also involves public and private sector partners from Jordan and abroad, with little engagement of the civil society so far.

Framework Conditions

The Sahara Forest Project has been implemented at pilot scale so far, including the first pilot with one hectare and one greenhouse pilot in Qatar and a larger "launch station" with three hectares and two greenhouses in Jordan). These pilots have been funded by international organizations such as the Norwegian Ministry of Climate and Environment, Norwegian Ministry of Foreign Affairs and the European Union. Alignment with national policies, institutions and funding as well as upscaling of the project is underway or planned.

Monitoring and Evaluation and Next Steps

The multi-sectoral planning and investments that are needed to up-scale the project require cooperation among the water, agriculture, and energy sectors and an active involvement of local actors, private companies, and investors. These cooperation and involvement mechanisms are currently being established in Jordan. Given the emphasis on the economic value of the project, public-private partnerships are considered as the appropriate business and governance model, when the project is up-scaled. Scenarios for upscaling (seawater use primarily in low lying areas close to the sea, to avoid energy-intensive pumping) include 50 MW of CSP, 50 hectares of greenhouses, which would produce 34,000 tons of vegetables annually, employ over 800 people, and sequester more than 8,000 tons of CO_2 annually.

[3]https://www.saharaforestproject.com

Case Study 4: Lajoun Integrated Ecology Centered Development Area, at Municipal Level, Karak Governerate, Jordan (MINARET Project)

Nexus Framing

Increasing water scarcity and water quality degradation and high energy costs (imports of fossil energy) constrain agriculture, contributing to high food import dependence. Non-conventional water solutions (desalination, wastewater reuse, water transfers) make the sector more energy and greenhouse gas intensive.

Nexus Opportunities

Renewables provide cheaper and climate-smart energy. Recycling across sectors can reduce pressure on natural resources and mitigate water scarcity, recycling of nutrients also saves energy (less energy-intensive industrial fertilizer required). Integrated land use systems and greening of municipal areas can make land more productive, reverse land degradation, restore ecosystems, and improve live quality. Water-, energy-, and climate-smart municipalities can increase their overall resource productivity, generate additional employment, promote economic development, and enhance human well-being.

Technical and Economic Nexus Solutions

Wastewater is treated and recycled for irrigating crops, for nursery plants and for trees (including constructed wetlands and reed vegetation in wadi); crops are also used as livestock fodder, recycling of agricultural/plant residues/nutrients e.g., through a composting facility improves biomass production; a 3 MW solar power plant provides local energy (e.g., for nurseries) and feeds excess energy into the public grid (legislation has been adjusted e.g., in terms of feed in tariffs—currently 0.25$/kWh); land rehabilitation through ecosystem-based solutions, e.g., greening along roads, in parks and in the wadi (also for recreation) with plants from the local nursery, improves overall land productivity; native plants are recultivated for fodder, aromatic, medicinal and ornamental purposes (including seedbanks), reed grown in the wadi is used as construction material in the village.

Stakeholders Involved

Karak municipality is an independent institution which cooperates with many partners in this project, e.g., local families and communities for which the project provides additional jobs. Farmers bring their residues and receive compost and use the treated wastewater. Public institutions include the local, governorate level, and national administration, which coordinate and collaborate across sectors and scales, e.g., for all needed approvals from authorities and ministries, e.g., Ministries of Planning, Municipal Affairs, Water, Energy, and Agriculture (approved composting facility) and Energy. Other partners include Royal Scientific Society (performs studies to determine most suitable native plant species), universities (e.g., Mutah University which also performs studies in the project) and funders. The integrated approaches and experience gained support sustainability transitions beyond the municipality, e.g., strategic planning of national ministries. The private sector is involved e.g., through contracts for wastewater reuse which the project signed with the neighboring industrial complex, as well as a joint solar project with the electricity company. Products from Lajoun are economically competitive in the local context and for local partners.

Framework Conditions

Policies and legislation in Jordan, e.g., the sustainable energy and climate action plan (SECAP), encourage private sector involvements and investments in technologies such as photovoltaics at all levels. Private investment has been attracted e.g., through DBOT (design, build, operate, transfer) schemes. Local communities, NGOs or CPOs assist the municipality to develop and fund additional activities and promote recycling and the use of local products. The Karak municipality is also member of the Covenant of Mayors for energy and climate which promotes energy efficiency measures and indirectly also integrated/nexus solutions. Stakeholders are engaged from planning through implementation all the way to monitoring and evaluation.

Monitoring and Evaluation and Next Steps

Cooperation has been established with local societies/communities and universities (Mutah University) and other institutions. Learning, transfer and upscaling are promoted through workshops, meetings, agreements etc., raising awareness about environmental protection and sustainable use of natural resources. The project also improves technical capacities within the municipality's own administration for the management of natural resources.

Case Study 5: Arc en Ciel, Taanayel Farm in the Bekaa Valley, Lebanon

Nexus Framing

Water and energy scarcity/costs constrain agricultural production; poor water, and energy infrastructure and low use efficiencies mutually affect all three sectors (water, energy, agriculture); urban sprawl competes with agriculture for water and land (and energy); the driving forces are bottom up related to the needs and challenges that operating and managing a farm in the Bekaa Valley entails with regards to all the elements of water, energy, land and food and their interlinkages.

Nexus Opportunities

Water storage and treatment using renewable energy, recycling of wastewater (treatment and reuse) and agricultural residues in multi-functional systems can increase resource use efficiencies and reduce pressure on water, land and energy, reducing pollution of surface, and ground water bodies while increasing agricultural production efficiency. Diversification of products and services (different crops, viniculture, and ecotourism) can increase resilience to climate and other shocks. Opportunities arise from integrating climate change adaptation (e.g., increasing water availability through wastewater recycling) and mitigation (employing water-smart renewable energy).

Technical and Economic Nexus Solutions

Solutions include irrigation with reclaimed wastewater, sludge reuse as soil amendment, use of agricultural byproducts for energy (heating and cooking), economic savings from renewables (solar and wind) which are now becoming cheaper than electricity from fossil energy, use of photovoltaics for electricity for water pumping in irrigation and for cooling of agricultural products, enhanced water storage to buffer climate extremes and avoid agricultural losses, and implementation of smart irrigation systems to improve efficiency.

Stakeholders Involved

Civil society is represented most directly by the NGO managing the farm. The Catholic Church is renting out the farm to the NGO. The local community and some local farmers are employed. More broadly neighboring farmers, municipalities, and unions of municipalities, cooperatives or other user groups could become stakeholders when adopting some of the interventions and the new farm model. Public institutions that could eventually benefit include e.g., local authorities, regional authorities such as the Litani River Authority or the Bekaa Water Establishment (who are the main public institutions concerned with water service provision and management) and national authorities or ministries, e.g., Ministries of Energy and Water, Agriculture, and Environment. Also public and private research institutes (e.g., Lebanese Agricultural Research Institute) could learn from this project. Key private actors are winemaking companies which purchase their grapes from the farm. Other winemakers in the region can benefit from the model practices of this project.

Framework Conditions

The farm model described in this case study can be managed by NGOs, unions, cooperatives, or other user groups who jointly invest in various activities, e.g., in wastewater treatment, water storage, renewable energy, or composting. This approach could be replicated rather than upscaled, requiring knowledge transfer for deployment of new and adapted technologies. Arc en Ciel could serve as a demonstration farm to gain acceptance of farmers as they can see the concrete benefits themselves and moreover this project could also inform nexus policy making, in particular highlighting the obstacles presented by existing policies, e.g., the current law organizing the electricity sector in Lebanon including metering and the absence of feed-in tariff which does not allow the sale of electricity into the grid; also national standards for re-use of treated wastewater are still missing. Institutional and financial support can potentially come from loan schemes for implementing photovoltaics or more efficient irrigation systems, these investments may come from multiple (international) sources over time. The Arc en Ciel farm puts together piecemeal the various nexus components through donor funding; however, farms in Lebanon are typically small holdings and would have difficulty in securing funding for similar projects. The case opens the door for the small farms to pursue such an integrated and "nexused" development in a collective manner by collaborating through existing cooperatives to secure the funds needed for such a development. An added benefit to this approach is that it would revitalize the cooperatives and better engage local communities.

Monitoring and Evaluation and Next Steps

The development of a new national agricultural strategy and the current on-going review of the water strategy present opportunities to mainstream elements of a WEF nexus approach in consultation and coordination with other concerned stakeholders from different sectors such as the Ministry of Agriculture, the Ministry of Energy and Water and the Ministry of Economy and Trade. Another opportunity for more integrated management and governance is in the development of national standards for the re-use of treated wastewater in agriculture as an alternative source of water. The government targets for renewable energy and the drive to consistently improve the existing laws due to the renewed interest by the current government could be another entry point. Intended revisions of Law 221 (by which the water sector is governed) as required by the newly passed Water Code present an opening for local water users associations to be set up and for farmers to coordinate activities and even embark on nexus activities on their properties. Furthermore, the intended revisions to Law 221 would enable municipalities to resume their role in water management, a role which the original version of the law had taken away. Such a resumption would enable local authorities, long shunned from action, to be involved in the fields of energy, water and agriculture—three fields in which they have always assumed an indirect role.

COMPARATIVE ANALYSIS ACROSS CASE STUDIES AND LESSONS LEARNED

All cross-sectoral case studies presented above address the growing problems of resource scarcity and competing resource use both at local and national level. In the context of the extreme water scarcity in the MENA region (Hoff et al., 2017; Waha et al., 2017; FAO, 2019), it is not surprising that water features centrally across all case studies, in terms of the need for increasing water availability, reducing demand, or increasing water use efficiency, e.g., by desalinating water (case study 3), recycling of wastewater (case studies 4 and 5) or introducing drip irrigation (case study 1) and reducing costs for pumping (case study 2), with knock-on effects on energy use, agricultural production and farm income. Incidentally this water-centricity mirrors the bias toward the water sector which the water-energy-food nexus has had from the beginning (Hoff, 2011).

The cases in Jordan and Lebanon (case studies 3, 4, and 5) are further tackling scarcity of arable land, by reducing land degradation, increasing land productivity and rehabilitating ecosystems. Their ecosystem-based solutions are in fact closely aligned with the nexus approach. All case studies strongly invest in renewable (in particular solar) energy, reflecting the key trend of energy transitions toward renewables in the MENA region (Hoff et al., 2017), thus reducing fossil fuel dependency and cutting GHG emissions. The case studies thus highlight solutions at the interface of water, land and agriculture, mostly also closely linked to the energy sector.

Link to SDGs and NDCs

None of the case studies presented here explicitly aims at SDGs or NDC implementation. However, all of them provide nexus solutions, which—if upscaled—can facilitate integrated SDG and/or NDC implementation. We demonstrate potential outcomes of these interventions in terms of relevant SDGs and other sustainability targets (**Figures 1**, **2**). This information derived from the case studies can support national integration activities such as the planned SDG dashboard by the Jordanian Ministry of Planning (Nassar, 2017).

Building on Weitz et al. (2017b) and their cross-impact matrix for analyzing the interactions between SDG targets, we use a seven-point scale, ranging from high (+3), moderate (+2), and low synergies (+1) to low (−1), moderate (−2) and high tradeoffs (−3) between interventions and SDG targets (see **Figure 1**), and between case studies and SDG targets (see **Figure 2**), respectively.

The scores of the interlinkages were based on expert judgement by those co-authors who are most familiar with the respective case study and literature review. The initial scores were reviewed by all other co-authors. Those scores which are not straightforward are referenced with an explanatory note. We acknowledge that the scoring process remains qualitative and judgement-based but argue that it gives a good impression on synergies and tradeoffs that need to be explored further. In sub-sequent research the scoring can be made more robust and inclusive of a differentiation of magnitude vs. likelihood, so it can be used directly by policy makers.

Figure 1 shows the effects of different interventions on selected SDGs and other sustainability targets—from drip irrigation, renewable energy for water pumping and desalination, to reuse of wastewater and agricultural waste products and ecosystem rehabilitation. Several of these interventions are applied in more than one case study.

Figure 2 summarizes synergies and tradeoffs for all case studies in terms of relevant SDG targets. The more positive (further away from the center), the stronger the synergies with the respective SDG targets (negative values indicate tradeoffs or negative impacts). The larger the total area encompassed by the respective colored line, the more positive outcomes the case study enables. The graph thus shows the different foci of each case study. For instance, all five cases are considered to have a positive impact on food security. Case studies 4 and 5 additionally improve water quality and resource use efficiency. The graph further shows where negative impacts may occur (where the colored lines of the case studies enter the inner red area of the graph), calling for measures and institutions to turn tradeoffs into synergies. For example, drip irrigation (case study 1) can improve water use efficiency, but in the absence of effective policies and regulations may not improve water availability, instead leading to increased overall water stress. Similarly this also applies to solar powered irrigation (case study 2) which may lead to over-extraction and depletion of ground water, unless preventive measures are taken. These cases thus support the analysis of tradeoffs between SDGs and the need for incorporating sustainable livelihood perspectives into nexus approaches.

By plotting the potential synergies and tradeoffs of individual interventions and case studies against the different SDG targets (and other sustainability targets), we demonstrate the need for context-specific integrated planning across sectors. While comprehensive quantifications of nexus synergies are still missing (Liu et al., 2018), such qualitative scoring substantiates the role of nexus approaches in the integrated implementation of the 2030 Agenda (Bird et al., 2014; Weitz et al., 2014b; Yumkellaa and Yilliaab, 2015; Rasul, 2016; FAO, 2018; Hoff, 2018). Similarly could the nexus analysis presented in the five case studies facilitate the integrated implementation of the NDCs.

Mitigation targets may for example be addressed through solar powered irrigation systems (case study 2) and through the enhancement of rangelands (case studies 3, 4, and 5), while at the same time these interventions can also contribute to national adaptation goals. Another example for a nexus approach to NDC implementation through integrated adaptation and mitigation is the use of solar power for cooling greenhouses and desalinating seawater (case study 3), which reduces the reliance on fossil-fuels and at the same time increases water availability.

Horizontally and Vertically Coordinated Stakeholder Involvement

In all presented case studies, we find a broad range of stakeholders from different sectors involved—from civil society, to public institutions and private companies. However, institutions from the energy sector seem to be under-represented in most cases. We argue that they should be strongly engaged, given the sector's large investments and ambitious renewables targets in all Arab countries (Hoff et al., 2017), and the close interlinkages with other sectors.

The case studies and their sometimes limited level of integration to date, provide valuable lessons learned for stakeholders across different sectors and levels, for planning, policy making, and implementation.

For example, drip irrigation and solar pumping (case studies 1 and 2) with their unintended rebound effects in terms of overall water use (see **Figure 2** and also IRENA, 2016; Font Vivanco et al., 2018; Wong, 2019) emphasize the urgent need to involve stakeholders across different sectors and scales, addressing the "horizontal and vertical nexus" (Hoff, 2018). However, there is only limited evidence of this happening.

The need for cross-sectoral and cross-scale coordination applies similarly to the threat of land degradation in response to practices narrowly defined by e.g., the water sector alone, such as irrigation of marginal land, which in combination with other inputs such as fertilizer can cause salinization and other non-sustainable side effects (**Figure 2**, case studies 1 and 2, see also Rasul, 2016).

The fact that the Sahara Forest Project (case study 3), which is featured by many publications, depends on international donor funding, is an indication for the difficulty of anchoring (and funding) cross-sectoral projects in a strongly sectoral institutional landscape. The way forward consists of (i) bridging institutions and (ii) better interlinkages between existing institutions (Mansour et al., 2017). Examples of such bridging

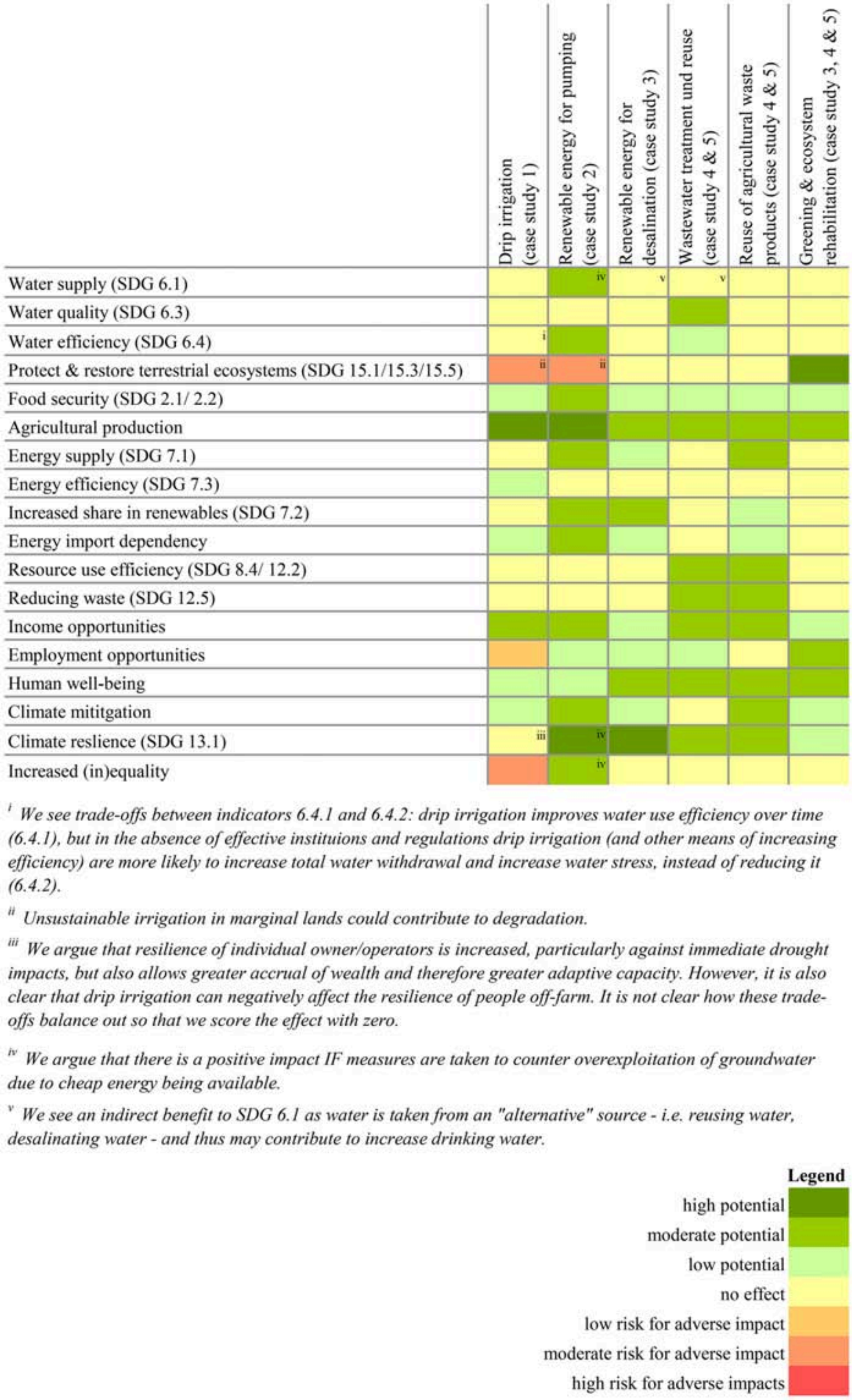

FIGURE 1 | Positive and negative effects of different interventions on selected SDGs and other sustainability targets.

institutions are the Karak municipality (case study 4) which coordinates across sectors and scales and the Litani River Authority, with case study 5 being located in their area of responsibility.

Eventually the engagement of stakeholders engaged at different levels, in different sectors and with different sustainability goals (see Link to SDGs and NDCs) holds chances in two directions: on the one hand it may enhance horizontal

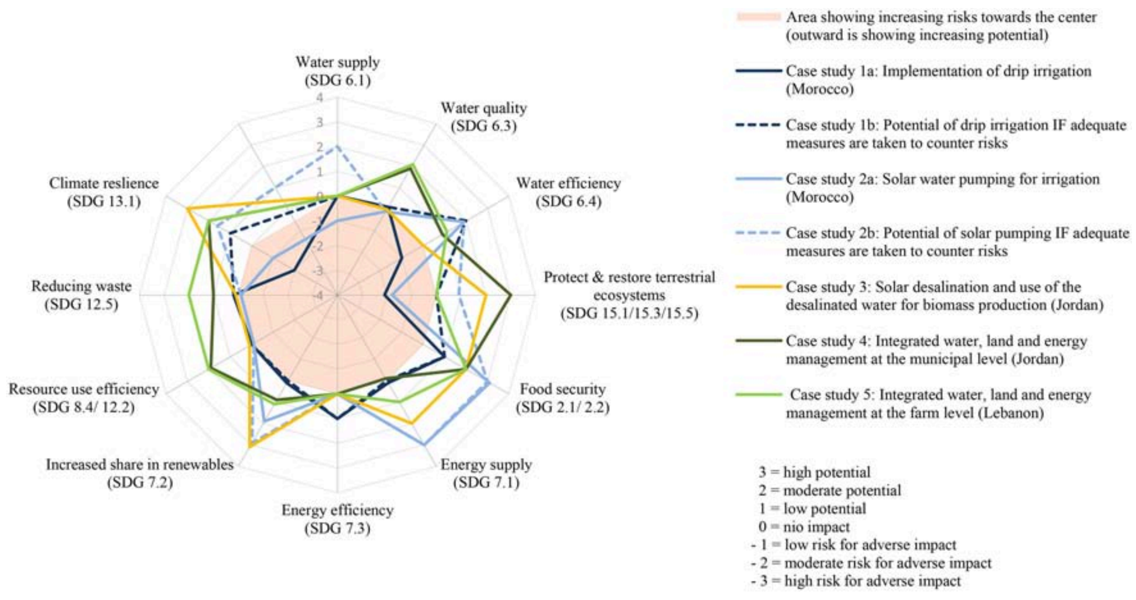

FIGURE 2 | Synergies and tradeoffs for the case studies in terms of relevant SDG targets.

and vertical feedback loops for better informed policy making, and on the other hand it may unleash unconventional funding mechanisms for nexus solutions.

Good Governance and Law Enforcement

The case studies presented above highlight the need to go beyond a technological focus of nexus implementations and provide complementary policies and regulations. These also need to factor in institutional and socio-economic, in particular poverty reduction objectives and aspects of accessibility of technologies for small-scale farmers (integrated SDG implementation which simultaneously addresses environment and development targets). Biggs et al. (2015) argue in this line, that livelihood perspectives should be an integral part of any planning and implementation of nexus approaches. For example introducing drip irrigation schemes (case study 1) was shown to potentially result in increased social inequity in rural areas (Jobbins et al., 2015). Aligning strategies and action plans across sectors—as promoted by the nexus approach—can also support rural development objectives, by pro-actively addressing potential adverse effects on poverty or inequity. The Karak municipality (case study 4) demonstrates the socio-economic benefits for the local population and businesses of an integrated approach. In Morocco the government plans subsidy schemes for solar powered irrigation systems, which take into account farm size, beneficiaries and other socio-economic criteria for eligibility of these subsidies. The development of this targeted subsidy scheme is informed by the results of case study 2.

Case study 1 also shows that new technologies can only be successfully introduced and their potential side-effects (here: rebound effects) can only be controlled in an effective policy and regulatory environment. Water security and poverty alleviation depend on enforcement and compliance of cross-sectoral and multi-level governance measures which may be difficult to implement in the rural context of case study 1 in which currently hundreds of legal and illegal wells are active and where sometimes water use is regulated by customary laws. If basic elements of a sustainability transition are lacking, such as feed-in tariffs for decentrally produced electricity, as in Lebanon (case study 4), nexus approaches are bound to fail.

Case study 2 (solar pumping for irrigation) also shows the need for aligning technological, regulative and governmental considerations, emphasizing the need for integrated adaptive planning, policy making and implementation. Stakeholders engaged in case study 2 identified the following requirements: firstly the proper dimensions of the technology (systems design) must be determined in line with the safe yield of the aquifer, this needs to be verified by independent governmental bodies, and these technologies need to be implemented by authorized suppliers providing good quality equipment with traceability and maintenance service. Secondly, the conditionalities of subsidies must be carefully designed (and if needed adapted over time) and recipients have to be trained for the new technology. Governance should—by way of management contracts between farmers and government—specify e.g., the volume of water per farmer and the area of irrigated land, prohibit intercropping, and prescribe remote monitoring of pumps or water flow meters.

The Need for and Challenges of Monitoring Systems

Good governance and law enforcement require monitoring (including the metering of water use). However, in most of the presented case studies there is little evidence of a monitoring and learning system in place. This means important experience and knowledge on nexus opportunities, but also on potential negative impacts and risks may get lost. We further did not find evidence of feedback loops between local on-the-ground-experience and the respective policies and funding schemes. In case study 1 (drip irrigation), monitoring of success is limited to the local level but does not address the overall outcomes at national level. One positive exception in terms of monitoring and evaluation is the case of solar pumping for irrigation in Morocco (case study 2), where multi-loop social learning is practiced, and local experience is used to inform decision makers when tailoring the planned solar irrigation subsidy.

In general, monitoring may be challenged by specific local contexts, e.g., in terms of hydrology, water resources, agriculture, and value chains, which need to be fully understood before the impacts of new technologies, interventions, and projects can be evaluated ex ante. Particularly important in the MENA context is a monitoring of water-related impacts and outcomes at the basin level and the use of that knowledge for adaptive management and policy making. While monitoring of the impacts of wastewater reuse (as in case studies 4 and 5) generally provides a clear picture of positive impacts across sectors and scales, specific challenges exist with regards to effective monitoring and regulation of abstractions related to solar pumping (case study 2). Smart meters might be one option, but many of the wells are illegal and fitting such smart meters would be politically and practically difficult.

However, the initial monitoring and evaluation in some of the case studies, already indicates the potential for synergies across sectors and resources, and the potential contribution of integrated approaches to local, national and regional sustainability goals (see **Figures 1**, **2**). This initial evidence from the case studies underlines the importance of systems for monitoring and evaluation (see also Bhaduri et al., 2015) and institutionalized feedback loops. Nair and Howlett (2014) further highlight monitoring and evaluation as key factors for enabling transfer and up-scaling. As the local effects, e.g., benefits for farmers, may differ from societal, or environmental effects at large (e.g., reduction of GHG emission or of import dependence for fossil fuels), monitoring systems need to address all levels and scales (from local to national and regional) into account to inform coherent policy making across levels and scales.

Bottom Up vs. Top Down Approaches, and the Potential for Transfer and Upscaling

Most of the presented case studies take a bottom-up approach, which starts from small-scale solutions (e.g., solar irrigation and drip irrigation in case studies 1 and 2). These solutions operate at the scale of individual farms or communities (e.g., wastewater recycling and biomass production in case studies 3, 4, and 5) and through private public partnerships (e.g., desalination and land rehabilitation in case studies 3, 4, and 5). However, while in principle these bottom up cases have high potential for transfer and up-scaling, only one—case study 2: solar powered irrigation—has already gone to larger scale.

Besides strong political support and synergies with ongoing policies/programmes and adequate monitoring (Nair and Howlett, 2014), transfer and upscaling depends on the capability of farmers or communities to invest. Moreover, farmers—in particular small farmers—experience administrative barriers (e.g., farmers don't have permits to dig wells), institutional barriers (e.g., farmers don't have private land tenure, etc.), or technical barriers (e.g., farms are too small to make investment profitable). Westermann et al. (2018) further point out in their review of eleven case studies, that addressing equity issues and integrating knowledge across multiple levels are additional challenges in scaling up.

A combination of public money (subsidies, interest-free credit) and/or private investment can promote new technologies and integrated approaches, as can small farmers cooperating to adopt shared integrated systems. Up-scaling depends further on knowledge transfer and skills development (FAO, 2018). Stakeholders involved in case study 2 noted that economic viability can have a remarkable impact on knowledge transfer and uptake: pioneer farmers financed and successfully operated solar irrigation systems on their own. Their experiences and demonstrations created a demand by other farmers. This cumulated demand called for action by the government to support the investment into solar powered irrigation, including targeted subsidies. Seeing a system working on neighboring farms thus remains very convincing, highlighting the need for demo projects, study tours and other forms of knowledge transfer for farmers, extension officers and policy makers. The international network of solar powered irrigation projects also promotes knowledge transfer across countries and regions. The Karak municipality (case study 4) is a good example where these forms of knowledge transfer are facilitated at the local level. Integrated solutions and lessons learned are showcased to farmers, entrepreneurs and policy makers by actively facilitating visits and study tours.

We can also draw important lessons from case study 1 (drip irrigation in Morocco). The Government of Morocco has been encouraging drip irrigation for several decades, with focused investments in specific irrigation schemes as well as general policies subsidizing and incentivizing the adoption of drip irrigation. This has helped to improve the resilience of Morocco's agricultural sector against drought (Sadiki, 2017). However, the top-down approach by the government (to save water and energy) and the bottom up approach by farmers (searching for profit) are not well aligned, and hence farmers don't always use the technology efficiently or in the way anticipated by the policymakers. As a consequence aquifer levels continue to fall in some areas and energy subsidy bills increase.

CONCLUSION

The nexus approach has the potential to enhance human well-being, while reducing pressures on the environment and natural resources ("decoupling"), through integrated management and governance and consequently improved resource use efficiency. Such an approach is urgently needed, given the enormous pressures the MENA region is faced with. However, as we show in this paper, technological improvements need to be embedded in appropriate framework conditions, including appropriate policies, regulation, and monitoring mechanisms. Only then can the benefits of the nexus approach materialize, without causing negative environmental or socio-economic side effects in other sectors or at other scales. Also there is a need for capacity building and sharing of experience from initial implementations with a wide range of actors from different sectors and scales. The case studies presented and synthesized here provide for the first time consolidated evidence for the MENA region from a set of integrated projects and implementations on the ground. While there is no quantification of the benefits and added value of a nexus approach yet, the evidence from the case studies can already be used by policy makers for better coordination across sectors and improvements in terms of horizontal and vertical policy coherence. Such changes toward more integrated governance can incentivize further nexus implementations and investments and upscaling of solutions beyond pilot scale, which in turn would further strengthen the nexus evidence and knowledge base. Continued dialogue and feedback loops between implementers of the nexus approach on the ground, policy makers, and the general public are the way forward to make the nexus a key approach for contributing to the integrated implementation of the SDGs and other sustainability goals. We recommend to further populate the basic framework developed here with additional evidence from more case studies within and beyond the MENA region, in order to develop a solid and generalizable evidence base for successful nexus implementation.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Environmental Science

POLICY AND PRACTICE REVIEWS
published: 25 April 2019
doi: 10.3389/fenvs.2019.00038

The Development of the INFEWS-ER: A Virtual Resource Center for Transdisciplinary Graduate Student Training at the Nexus of Food, Energy, and Water

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Edited by:
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Reviewed by:
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University of Arkansas, United States
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Specialty section:
This article was submitted to Interdisciplinary Climate Studies, a section of the journal Frontiers in Environmental Science

Received: 03 October 2018
Accepted: 07 March 2019
Published: 25 April 2019

Citation:
Rodríguez LF, Marshall A-M, Cotton D, Koelsch R, Koziel J, Meyer D, Steward D, Heemstra J, Padmanabahn A, Classen J, Meyer NJ, Ruddell BL, Ryan SM, Cai X, Habib E and Saundry PD (2019) The Development of the INFEWS-ER: A Virtual Resource Center for Transdisciplinary Graduate Student Training at the Nexus of Food, Energy, and Water. Front. Environ. Sci. 7:38. doi: 10.3389/fenvs.2019.00038

Problems at the nexus of Food, Energy and Water Systems (FEWS) are among the most complex challenges we face. Spanning simple to complex temporal, geographic, social, and political framings, the questions raised at this nexus require multidisciplinary if not transdisciplinary approaches. Answers to these questions must draw from engineering, the physical and biological sciences, and the social sciences. Practical solutions depend upon a wide community of stakeholders, including industry, policymakers, and the general public. Yet there are many obstacles to working in a transdisciplinary environment: unfamiliar concepts, specialized terminology, and countless "blind" spots. Graduate education occurs in disciplinary 'silos', often with little regard for the unintended consequences of our research. Existing pedagogical models do not usually train students to understand neighboring disciplines, thus limiting student learning to narrow areas of expertise, and obstructing their potential for transdisciplinary discourse over their careers. Our goal is a virtual resource center—the INFEWS-ER—that provides educational opportunities to supplement graduate students, especially in their development of transdisciplinary competences. Addressing the grand challenges at the heart of the FEWS nexus will depend upon such competence. Students and scholars from diverse disciplines are working together to develop the INFEWS-ER. To date, we have sponsored both a workshop and a symposium to identify priorities to design the initial curriculum.

We have also conducted surveys of the larger community of FEWS researchers. Our work confirms a widespread interest in transdisciplinary training and helps to identify core themes and promising pedagogical approaches. Our curriculum now centers upon several "Cohort Challenges," supported by various "Toolbox Modules" organized around key themes (e.g., communicating science). We plan to initiate the first cohort of students in October of 2018. Students who successfully complete their Cohort Challenges will be certified as the FEW Graduate Scholars. In this paper, we describe the development of this curriculum. We begin with the need for training in transdisciplinary research. We then describe the workshop and symposium, as well as our survey results. We conclude with an outline of the curriculum, including the current Cohort Challenges and Toolbox Modules.

Keywords: collaborative learning, pedagogy, convergence research, divergent thinking, team-based learning, online education, active learning, wicked problems

INTRODUCTION

Food, energy, and water systems provide fundamental resources so central to human existence that, if we are FEW-secure, we may not even spare a fleeting moment pondering their availability. Nations that succeed in maintaining low-cost food, energy, and water release their social, human, and financial capital for investment in areas far beyond the provision of life's basic resources (Brown, 1981; Hodell et al., 1995; Kick et al., 2011; van der Ploeg, 2011). FEW secure nations have made these investments, developing abundant solutions to these problems and significant social capital, both of which offer many potential benefits (Visser, 2000; Phelan, 2009). Such investments have even given rise to an economic engine of international aid organizations, intergovernmental agencies, and non-governmental organizations dedicated to the implementation of solutions alleviating pressures.

FEW solutions are desperately needed where security is not assured, especially considering shifts in population and demographics, which places increasing stress on the subsystems that deliver these vital resources. We know that if a population is insecure in its access to any one of these resources, the likelihood that it is insecure in all three is overwhelming.[1] Responding to the increasing global needs for food, energy, and water demands dramatic improvements in both sustainability and resiliency.[2] Whether we are applying lessons learned from FEW secure regions to insecure regions or developing innovations, there is no doubt increasing overall security will be increasingly challenging. This is well understood from the perspective of the FEW Nexus: influences in any one of the three subsystems will precipitate responses in at least one of the other two, but very likely both. Our FEW systems are tightly intertwined and interconnected, resulting in a "wicked problem" (Levin et al., 2012). The potential risks of unintended consequences, with impacts—technical, economic, or social—is significant. In fact, it may be inherent in our standard "silo-ed" approaches to solving problems that we need to be especially cautious as we seek to innovate in this environment. Individuals are now challenged at all levels to quantify the qualitative, to make decisions with incomplete or fuzzy information, to accept the liability associated with the intangible, to minimize the virtual impacts on bordering systems, and to collect and analyze the data describing all of these features and make it actionable. Individuals are now challenged to increase their depth of knowledge in multiple disciplines to solve these complex problems (NSF, 2014; Ruddell, 2017). Or they are challenged to develop transdisciplinary teamwork skills and transdisciplinary fluency in concepts, data, terminology, theories, and methodology.

Fundamentally neither food, energy, nor water is a discipline; indeed, they all encompass a spectrum of disciplines. As we continue to innovate, the results of our efforts are not just represented by the ideas we create, but also by the approaches we take when innovating. Individuals working in teams have a new opportunity to prepare themselves to have new access to both the depth and breadth necessary for the grand challenges of the future (**Figure 1**). The necessity for the meeting of multiple disciplines is not unique to complex problems in FEW. The convergence of engineering, computational, and the life sciences presents us today with revolutions in various aspects of healthcare, the Department of Defense ARPA-E program, industrial biotechnology, and the bio-based economy (NRC, 2014).

The success of these fields attracts a variety of groups, in addition to the US National Science Foundation (NSF, 2016; Saundry and Ruddell in review), to propose future grand challenges for our societies. Numerous other nations have proposed similarly named food, energy, and water-focused grand challenges (EC, 2013; Belmont Forum Urban Europe, 2016; Tilbury and Easterling, 2018). The National Academy of Engineering lists 14 grand challenges in engineering, half of which touch upon either energy, water, or the environment, or several simultaneously (NAE, 2008). The USDA-NIFA strategic

[1] More than 800 million are food insecure (Gustavsson et al., 2011), more than 1 billion of us are either energy (IEA, 2014) or water insecure (FAO, 2007). It is unclear what the intersection of these three sets are, but the authors assert that it is significant in number.

[2] Estimates suggest that food demand will increase by 70% (FAO, 2009), energy demand by 48% (EIA, 2017), and water demand by 55% (OECD, 2012).

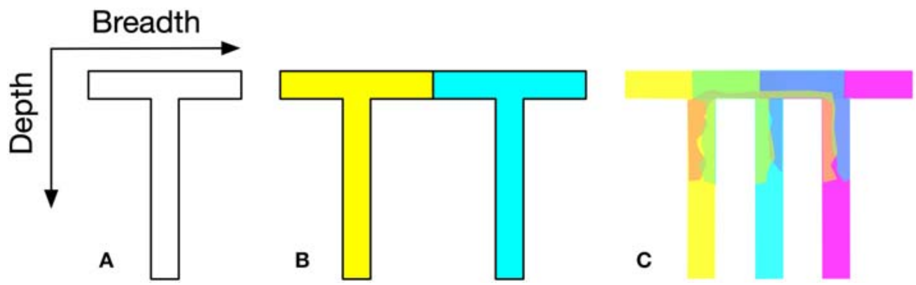

FIGURE 1 | Subject-matter depth and breadth in transdisciplinary education. In typical disciplinary education models of most universities **(A)**, individuals are encouraged to seek depth in their field, with some breadth in related areas, as represented by the T-bar shape (Enders and de Weert, 2009; Karjalainen et al., 2009; Oskam, 2009; Barile et al., 2012; Barile and Saviano, 2013; Harris et al., 2013; Sanchez et al., 2016). Multidisciplinary research **(B)** lines up multiple students, from multiple disciplines (represented by color) on common projects, but limits them to showing depth and breadth within their respective fields. Transdisciplinary research, as advocated here **(C)**, seeks to ensure that students have the tools to appreciate and build upon their peers in other disciplines. Their T-bars are closer, their disciplinary boundaries are removed, and knowledge permeates, revealing new shades of disciplinary integration, and thus new potential achievements by the participants.

goals for 2014–2018 similarly target issues of food security, climate change, and energy independence (USDA-NIFA, 2014). Seventeen sustainable development goals are advocated for by the United Nations[3], nearly all addressing the concerns of growing populations and changing demographics, more than half of which refer to core fundamental resources like food, energy, or water (UN, 2018). Explicated grand challenges are certainly useful for increasing the public awareness of ongoing efforts which support our future societies; they are also compelling motivating forces driving the research and technology development efforts associated with their resolution (NRC, 2014; Wolfe et al., 2016).

Thus, while the FEWS community has largely recognized that the grand challenges associated with this research agenda demand a transdisciplinary skill sets (Esler et al., 2016), we have relatively few resources for training students and researchers in the necessary research skills. There are some exceptions—for example, the US National Science Foundation has funded programs like the National Research Traineeship (NSF, 2018), formerly known as the IGERT, and the USDA-NIFA National Needs Fellowships (USDA-NIFA, 2017). Both seek to formulate a solid foundation in interdisciplinary and transdisciplinary training (Morse et al., 2007; Schmidt et al., 2012). As a result of these programs, several investigators have summarized the hallmarks of transdisciplinary achievement in student training (Manathunga et al., 2006; Borrego and Newswander, 2010; Graybill and Shandas, 2010; Kemp and Nurius, 2015). Still, we have a long way to go. We are building a virtual resource center (VRC)—the INFEWS-ER—to address this need, and below, we describe the work we have done thus far. We describe our efforts to define the curricular needs of the VRC, using two scholarly meetings and a survey. We also outline elements of the curriculum, including "Cohort Challenges" which will be offered beginning October 2018.

[3]Not unrelated are the Millennium Development Goals, declared by the United Nations in 2000, with a target date of 2015 (UN, 2015). We would interpret that the Sustainable Development Goals would follow the Millennium and build upon those successes.

MATERIALS AND METHODS

Kick-Off Meeting

In April 2017, we invited a group of scholars working in FEW fields to an initial kick-off meeting. The 29 participants were drawn mostly from the USDA Multistate Research Committee S-1032 on Sustainable Livestock and Poultry Production (S1032, 2013), a group of researchers who focus on the environmental impacts of food production. The goal of the meeting was to have this community identify learning outcomes and educational experiences for graduate students who engage with the INFEWS-ER. To this end, the agenda of the meeting offered presentations about online education and existing online resources for FEWS projects, as well as focus groups to help set priorities for INFEWS-ER content.

In the first set of focus groups, participants developed learning outcomes by first identifying a cognitive action verb associated with learning; that verb specified what students must be able to accomplish when engaging with transdisciplinary challenges, including, for example, "understanding," "writing," and "analyzing." These learning outcomes also included a learning statement—the specific content of the material students will be expected to master. These two elements define the conditions of acceptable performance, focusing on the desired end-product of the learning experience rather than the means or process of delivering instruction. After brainstorming, the participants placed the learning outcomes into different groups, creating general categories of inquiry, and then elevated learning outcomes that participants agreed were most important.

In the second set of focus groups, participants identified learning experiences that would generate the learning outcomes for students. Participants again brainstormed ideas for projects and curriculum, which were discussed and evaluated by other meeting participants. These groups then linked learning outcomes to learning experiences and identified the most promising options.

After the meeting, we synthesized the ideas and content discussed and developed a conceptual framework for the INFEWS-ER. In that process, we identified five thematic areas for transdisciplinary research skills needed to work on wicked problems in FEW fields:

- Asking Transdisciplinary Questions,
- Creating High Performance Learning Communities,
- Communicating Science,
- Understanding Stakeholders, and
- Understanding Data, Modeling, and Analytics.

Based on the feedback obtained at the kick-off meeting, we determined that the INFEWS-ER should offer training in each of these areas through Toolbox Modules (described in more detail below). We also determined that the INFEWS-ER should offer students more extensive training by having them work through more complicated wicked problems, called "Cohort Challenges," in the FEWS fields. We identified three separate topics for these challenges (again, described in more detail below):

- Nutrient Loss Reduction, Recovery, and Reuse;
- Dairy Carbon; and
- Community Odor.

In these Cohort Challenges, students will work with a transdisciplinary team to formulate research questions, find the right kind of data to answer those questions, conduct relevant analyses, and produce final projects with tangible "products."

Inaugural Symposium and Survey of Symposium Participants

The goal of the Inaugural Symposium was to elicit more feedback from our collaborators in FEWS related fields to offer additional perspectives on the curriculum and to refine the learning outcomes. The participants in the Symposium were drawn from the kick-off meeting, as well as other researchers who were active in conducting FEWS-related research. We also invited graduate students, nominated by the participants working in the field, who might be interested in contributing to the INFEWS-ER or participating in its projects. Thus, they were a group of researchers and agent scientists whose work might be featured in the INFEWS-ER, who might contribute to the INFEWS-ER curriculum, and whose students might benefit from the additional training it may offer.

In the course of planning the symposium, we had questions about what the FEW research communities might want from the INFEWS-ER and what kinds of skills and expertise prospective contributors might bring to the project. To that end, we piloted two surveys for the participants in the Symposium that we hope to deploy to the wider FEWS field. The pre-symposium survey was designed to assess the participants' experience with delivering online education, as well as their priorities—for both their students and themselves—for the skills necessary for working in transdisciplinary teams on FEW problems. We received 24 responses, which amounted to a response rate of 85%. Fifty-two percent of the responses came from faculty members; 40% were graduate students; and the remaining 8% were other educational professionals.

The participants in the Symposium had extensive experience with some aspects of online pedagogy—for example, 82% had made notes or presentations available to students online; 68% had offered tests or quizzes in some learning management system; and 46% had collected students' written work online. In addition, many participants reporting having experience with asynchronous online interactions with students (50%) and blended learning using both online and classroom techniques (41%). Less common but still present were participants who had experience with synchronous online interactions with students (32%) and flipping the classroom (32%).

The survey also showed that there was widespread interest in the topics identified for the INFEWS-ER curriculum. The modules that generated the most interest, with 80% or more respondents reporting that they thought additional training was important, were those regarding building high performing interdisciplinary teams, understanding stakeholders, and communicating science to both lay audiences and scholarly communities.

Based on these materials, we formulated an agenda for the Symposium that introduced participants to existing online resources for researchers working in the FEWS field and that solicited participant input on effective online curriculum on the six topics for Toolbox Modules: High Performance Teams, Modeling Systems and Managing Data, Asking Transdisciplinary Questions, Communicating Science, and Understanding Stakeholders. In focus groups, we generated more specific ideas for curriculum tied to these topics. In addition, the Symposium offered focus groups for designing Cohort Challenges, exploring in more details the "wicked problems" that would constitute the basis for these exercises. Finally, the Symposium offered opportunities to hear from graduate students about how to fit the demands of engagement with the INFEWS-ER into their existing graduate programs, focusing on the logistics of delivering the curriculum.

THE DESIGN OF THE INFEWS-ER

The curricula of the INFEWS-ER are centered upon the matriculation of students into Cohort Challenges (**Figure 2**). All cohorts will be composed of students from numerous disciplines interested in grand challenges defined by FEW-related research endeavors. The student groups will maneuver through a Cohort Challenge under the guidance of one or more mentors, who help define the scope of the challenge and provide basic resources for initiating the work. As students become engaged with these challenges, mentors encourage them to sharpen their skills within the context of the thematic Toolbox Modules or by leveraging extant education resources already available to them. Conceptually, depending on the composition and past experiences of a given cohort, we would anticipate that the cohort would seek to enhance their abilities in the key skills their cohort is collectively lacking until their team has a complete set of basic competencies. They should know where they are strong, where they are weak, and where they need to seek assistance outside of their immediate cohort.

Cohort challenges culminate in the formation of one or more products suited to the specific team and challenge. The

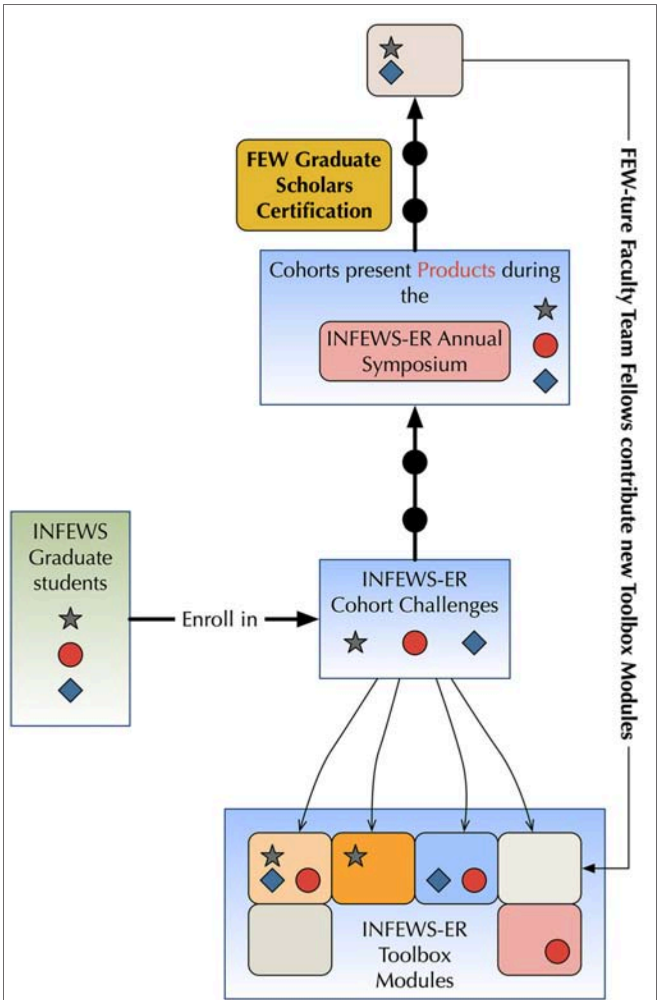

FIGURE 2 | Student participation in the INFEWS-ER. The curricula of the INFEWS-ER revolve around the Cohort Challenges. Students from multiple disciplines (represented by the symbols ★●◆) will enroll directly into open Challenges. Depending on the specifics of the cohort challenge, and their own mixture of disciplines, students will engage in a selection of Toolbox Modules. Working with a mentor, as indicated by the black dots (●) they will work toward a product responding to their challenge, to be presented during the INFEWS-ER Annual Symposium. Students completing the challenge will be certified by the FEW Graduate Scholars Program. Students interested in continuing and documenting the response to their Cohort Challenge as a case study are invited to prepare a Toolbox Module and add it to the Virtual Resource Center. These students will be invited to join the FEW-ture Faculty Team Program.

specific product for their challenge is similarly selected by the cohort, in consultation with their mentor(s); example products are described below with the current Cohort Challenges. The products will be presented publicly during the Annual INFEWS-ER Symposium. Many different products for their efforts may be possible. Some include: an extension product, a web learning module, or a science summary for a lay audience. The attendees during the symposium will include not only members of the INFEWS-ER development team, but also stakeholders with interests in the resolution of cohort challenges. This creates an environment where participants are tested to communicate their ideas effectively, while actively soliciting real feedback for their contributions to the grand challenges they are targeting.

The Cohort Challenges

The Cohort Challenges are the primary vehicle for transdisciplinary training for graduate students in the INFEWS-ER. They will be offered to cohorts of 5–10 graduate students recruited from different disciplines and are expected to require about a semester's worth of effort to complete. The students will be expected to work collaboratively in these multidisciplinary teams on a variety of different tasks that will introduce them to the complexity of working on "wicked problems." Through each Cohort Challenge, the participating student groups will be coached in critical collaborative processes of developing ground rules for decision-making and shared responsibilities, criteria to measure performance, to formulate relevant questions, to collect relevant data, to conduct necessary analyses, and to prepare the necessary reports and other final products for stakeholders and other audiences.

With its inaugural cohorts, the INFEWS-ER will offer three different Cohort Challenges. The first is the Dairy Carbon challenge, where students will be asked to model the carbon cycle on a simulation of a dairy farm, communicate those models to lay audiences, and explore the possibilities for reducing carbon losses. Students participating in this cohort challenge will track carbon entering a farm in animal feed, fuel, or animals and exiting a farm in animal products (milk, meat, or animals), as carbon emissions (volatile organic compounds, methane, carbon dioxide), or manure. Dairy farms are a complex connection of carbon cycles producing both human edible proteins and nutrients from non-edible sources and harmful greenhouse gases and odors. Students will generate final products that improve the sustainability of dairy systems by influencing the decisions of dairy farmers, policy makers, and food supply chain companies, potentially packaging these products as a web learning module augmenting an existing "Virtual Farm" developed by a team of investigators (PSU, 2017).

The second Cohort Challenge is about modeling and managing odor associated with animal production systems and the myriad impacts this has on neighboring communities. These systems emit odor, gases, and particulate matter that present challenges to neighboring communities, workers, and the wider environment. Many argue that the sustainability of the concentrated animal production industry in the United States and around the world depends on proactively addressing odor. The project asks students to investigate technologies for minimizing air emissions, while also accounting for the regulatory and economic environment governing animal production. Students participating in this project will contribute to existing assessment and planning tools for producers and their advisors.

The third Cohort Challenge addresses problems associated with nutrient loss reduction, recovery, and reuse. The chronic nutrient loss in food production, through both point and nonpoint sources, has a number of deleterious effects on a variety of environmental sinks, often large bodies of water.

Moreover, the nutrients themselves are limited in availability at the production phase and costly to transport, thus raising the energy costs associated with food production. While nutrient recovery and reuse would lower these energy costs, as well as create sources of renewable energy, these practices have not been widely adopted. Students working on this challenge will develop recommendations for water quality standards in one of several different locations where nutrient loss has presented a special problem. Students will be asked to collect data and perform relevant analyses to support those recommendations.

The Toolbox Modules

Via our interactions and surveys with FEWS scholars, we have identified thematic areas that provide a strong foundation for transdisciplinary collaborations, but these skills are sometimes taken for granted. Graduate programs rooted in traditional disciplines may not offer the training necessary to develop these skills. Thus, the INFEWS-ER will offer "Toolbox Modules" targeting each of these thematic areas and designed to enhance the performance of transdisciplinary teams and the quality of the resulting research products. These modules are being designed to be delivered in different ways—some emphasize group meetings; others will draw on asynchronous forms of instruction.

In the thematic area entitled "Asking Transdisciplinary Questions," students will be introduced to the challenges of developing research questions from a number of perspectives. Students will learn methods to identify gaps in scientific knowledge, to evaluate the scholarship of different fields that provide insights on relevant solutions, and to identify appropriate metrics for assessing answers to the questions. Throughout this module, students will see that defining compelling transdisciplinary research questions is an iterative process that will require ongoing input and refinement from a broad base of team members, including scientists, engineers, and stakeholders.

The INFEWS-ER will also offer a thematic area to train "High Performing Learning Communities" to enhance the productivity of transdisciplinary teams that address questions about FEW systems. Too often, teamwork is attributed to personal chemistry, when in fact, successful teams depend on mutual trust, accountability, and shared leadership. Through webinars and group meetings, students will learn how to expand their access to expertise by building "Personal Knowledge Networks;" how to set goals and assign responsibilities to ensure progress toward mutually identified goals; and how to work with assessment tools for measuring team performance. Students will be able to use these team-building skills not just in their Cohort Challenges but throughout the rest of their careers when working on collaborative projects.

The Toolbox Modules also seek to strengthen students' proficiency in engaging with the many audiences for FEWS research and scholarship. One such thematic area, "Communicating Science," focuses on communicating across disciplinary boundaries to build on existing sources of knowledge and to understand and design innovative solutions to FEWS problems. This Module seeks to formalize the communication processes within a team to identify best practices, avoid cross-disciplinary misunderstandings, and produce effective written and visual communications products. In a separate Toolbox Module, skills will be developed in transdisciplinary FEWS teams to engage with stakeholders who may vary in their familiarity and comfort with scientific knowledge. These stakeholders may be in a related scientific community, associated with different allied industries, or interested neighbors or consumers. In all cases, transdisciplinary research teams will need to convey their findings to publication outlets that serve both professional and public audiences that may be constrained by disciplinary boundaries or guided by unconscious bias. Through written and oral exercises, students will get valuable experience targeting their scientific communications for a number of different audiences.

Another thematic area will focus on "Understanding Stakeholders." Most FEWS problems have an impact on communities across many different scales—local, regional, national, and even global. Stakeholders from these many scales of communities have interests in the definition of these problems as well as the impact that the solutions might have on the social and economic life of neighbors. Moreover, the adoption of these solutions might require the cooperation of governmental authorities, where, again, jurisdiction may spread across many geographical boundaries. These modules will introduce students to different definitions and categories of stakeholders, guiding students through the process of identifying relevant organizations and assessing what level of interest the stakeholder has in the underlying problems and projects.

The final thematic area focuses on the integration of both quantitative and qualitative perspectives on FEW systems by "Understanding Data, Modeling, and Analytics." The complexity of FEW grand challenges inherently suggests that the development and testing of theory will rely on computational tools for analysis, expanding the potential reach of cohorts beyond the capabilities of most experimental methods of synthesis. Cohorts will need to conceptually visualize and articulate across disciplines the current state of "wicked problems" and opportunities for future enhancements. They will marshal existing and new forms of data indicative of the current and proposed system state. They will select from a growing variety of analytical tools, understanding and interpreting the validity and applicability of the output. Finally, by engaging with data, modeling, and analytics, cohorts will begin to substantiate their conclusions with data and analytical support, which will subsequently need to be communicated to and verified by their stakeholders.

THE POTENTIAL OF THE VIRTUAL RESOURCE CENTER

As we build the online content for the INFEWS-ER, we are emphasizing and enhancing graduate training. The Cohort Challenges and the Toolbox Modules are being designed to offer the initial cohorts of graduate students opportunities to work through FEWS problems, as well as some introduction to supporting skills. In the longer term, however, the INFEWS-ER will become a virtual resource center, providing FEWS scholars with ongoing access to a wide range of materials to support teaching and research in the field. Indeed, we are maintaining active efforts to seek FEWS researchers from across the US and the world interested in developing content. For example, several Toolbox Modules that fit within the various thematic areas previously described are currently in the early stages of development: Effective Communications within Transdisciplinary Teams, Engaging Citizen Scientists as Stakeholder, Mesoscale FEW Datasets and Data Science, Basic Network Analytics, Geospatial Analytics using Python, and Systems Thinking. This is similarly true for Cohort Challenges where we are in the early stages of recruiting collaborators or developing cohort challenging for Disaster Relief Projects, Emergency Management, FEW Issues for Indigenous Communities, and Food and Energy Factors Affecting Water Quality in the Yangtze River.

We anticipate that over time, contributors will design modules for the INFEWS-ER content that can be offered as self-guided tutorials for individuals or small groups. Where synchronous interaction or mentor-guidance is essential, the resource center will provide future cohorts of faculty and students with learning resources including syllabi, exercises, and rubrics. We hope to encourage the use of best practices in educational design that allow single users to navigate the learning modules and even assess their mastery of the material. By using discussion forums, self-directed quizzes, and templates for finished projects, we hope that the INFEWS-ER can become a valuable resource for students and researchers in the field who need to engage with new topics to further their transdisciplinary goals. In addition, we expect that members of the FEWS community might draw on the Cohort Challenges and Toolbox Modules as sources of assignments and group projects for their own course offerings, departments, or labs.

Finally, we anticipate that the INFEWS-ER can become a repository for the web-based resources generated by others in the FEWS community. To date, in addition to the six universities represented by our primary team, we are now working with representatives from six new institutions to develop current and forthcoming Cohort Challenges and Toolbox Modules. With continued growth we hope to have an INFEWS-ER including representation from a wide variety of FEW challenges with entry points from every perspective in food, energy, and water. Given this basis of collaborators, we are also developing a FEWS-related bibliography, as we work on Cohort Challenges and Toolbox Modules. The bibliography is being collected in Zotero, an open-source citation management system (Zotero, 2018). The bibliography is organized thematically, offering newcomers to the field an entry into FEWS topics. As students and faculty engage through the INFEWS-ER, we expect the bibliographies to grow. The National Science Foundation's program on Innovations at the Nexus of Food, Energy, and Water Systems is designed to drive collaborative, transdisciplinary research that will lead to high-impact solutions. One key to collaboration is being able to find others working on similar problems and learn about their research. We expect that the INFEWS-ER can become a resource hub that empowers such collaborations by offering a central location for learning about the latest developments in research, teaching, and extension activities.

Despite all the promise, even an effective INFEWS-ER will not resolve all pedagogical challenges facing future graduates from programs targeting FEWS problems. Students will still transition to professional life, either in industry, the public sector, or academia, and they will still be tied to their selected discipline. The INFEWS-ER will offer certification for students who successfully complete Cohort Challenges, but until these certifications are tested in the field, we will not know their perceived value. To combat this concern, we maintain relationships allowing us to seek feedback on the quality of our programs via a steering committee and via related stakeholder groups including professionals in industry and academia. To provide this steering committee with the resources necessary for evaluation of the INFEWS-ER, the VRC shall develop a system providing templates for formative and summative assessment of student works generated via both toolbox modules and cohort challenges.

We also plan to cultivate stakeholder relationships with the academic institutions and graduate programs where our students are currently enrolled. The academic requirements associated with standard graduate training requirements are significant, and currently student engagement in the INFEWS-ER is extracurricular. Thus, far, we have been successful in recruiting students, including some students who have participated in multiple ways. Their engagement with the INFEWS-ER should not, however, come at a detriment to their programs; rather, it should augment the overall quality of their training. As a matter of fact, we recognize that there will be instances where students may need additional incentive, beyond the FEW Graduate Scholar Certification, to justify participation. To ensure that the opportunities within the INFEWS-ER are indeed valued and recognized by the students, their advisors, and their graduate programs we are working with interested graduate advisors to provide "independent study" credit via their home institutions. To facilitate this, we will share all documented products produced from both Cohort Challenges and Toolbox Modules to advisors who would later award the independent study credit to students. We would consider this a strong representation of the potential value of the learning opportunities offered here. We anticipate in the future that this will support the overall sustainability of the INFEWS-ER.

In building the INFEWS-ER, we have engaged widely with research groups around the world who are working on projects to advance FEWS sustainability. In these engagements, our colleagues have noted the need for resources to support transdisciplinary training and collaboration. They have also been enthusiastic enough about the promise of the INFEWS-ER to collaborate with our team and work to provide those resources themselves. If we are successful, we hope to see students developing systematic processes to transition from multidisciplinary behaviors to transdisciplinary. It would thus be this generation of student cohorts who would be in the best position to target large societal problems, at the nexus of food, energy, and water, and indeed beyond.

AUTHOR CONTRIBUTIONS

LR conceived of the idea, furthered the development of the idea through the kick-off meeting and inaugural symposium, outlined and drafted the manuscript, solicited suggestions from the co-authors, managed the revision process, submitted the manuscript, and stewarded the submission through the review process. A-MM conceived of the idea, furthered the development of the idea through the kick-off meeting and inaugural symposium, outlined and drafted the manuscript, and participated in the revision process. RK, JK, DM, AP, and JC conceived of the idea, furthered the development of the idea through the kick-off meeting and inaugural symposium, and participated in the revision process. DC, DS, BR, and EH furthered the development of the idea through the kick-off meeting and inaugural symposium and participated in the revision process. JH, SR, NM, XC, and PS furthered the development of the idea through the inaugural symposium and participated in the revision process.

FUNDING

This work has been generously funded by the National Science Foundation via grant number: 1639340. This work was further supported by the National Institute for Food and Agriculture via the S-1032 Multistate Research Group Project entitled Sustainable Livestock and Poultry Production. In addition, contributors to this article have funding for INFEWS-related projects, including BR, NSF/USDA ACI-1639529, and LR and DS, NSF 1833225.

ACKNOWLEDGMENTS

The authors are especially grateful to the many other participants who attended the Kick Off Meeting and the Inaugural Symposium of the INFEWS-ER. Their inputs have been captured here to the best of our abilities.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Environmental Science

HYPOTHESIS AND THEORY
published: 07 May 2019
doi: 10.3389/fenvs.2019.00056

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A Design for a Data and Information Service to Address the Knowledge Needs of the Water-Energy-Food (W-E-F) Nexus and Strategies to Facilitate Its Implementation

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Food security is essential to sustain human societies. Food production flourishes when water, energy, and land are abundant, but more often it is limited by scarcities in one or more of these resources. In particular, food production is limited by the relatively fixed amount of water that circulates in the hydrosphere, the lack of new land for crops in many countries, and the depletion of critical minerals and fossil fuels in many source regions. An integrated Water-Energy-Food (W-E-F) Nexus planning and management approach promises improved resource efficiencies, new business opportunities, more coherent resource and environmental policies, and economies of scale for the data and information services underpinning better decision-making. This paper distills discussions on data and information from four regional workshops held as part of a Future Earth W-E-F Nexus Cluster project. The workshops reviewed ways to enhance the sustainability of the W-E-F Nexus through better governance; collecting, analyzing, and communicating data and information; and integrating both with management for better planning and decision-making. The focus of this paper is to explore the potential application of an integrated data and information system to enhance water, energy, and food sustainability. In particular, this paper's objective is to explore how a multisector W-E-F Nexus data and information system could be developed and operated to meet the planning and decision-making information needs of practitioners and to facilitate the implementation of the W-E-F Nexus concept. This "Hypothesis and Theory" paper provides a hypothesis and system design and proposes steps that could be taken to implement and test the system in a W-E-F Nexus environment. Data and information, along with modern technologies, can play a central role in facilitating paradigm shifts that reinforce the W-E-F Nexus by explicitly assessing environmental services, meeting the growing urban food demand, valuing water and other resources used to produce food and energy for export, promoting resource use efficiency through integrated planning and management, and strengthening links between the W-E-F Nexus and appropriate Sustainable Development Goals.

Keywords: W-E-F Nexus, data and information system, satellite observations, decision-making, *in situ* observations

OPEN ACCESS

Edited by:
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Specialty section:
This article was submitted to Freshwater Science, a section of the journal Frontiers in Environmental Science

Received: *01 October 2018*
Accepted: *10 April 2019*
Published: *07 May 2019*

Citation:
Lawford RG (2019) A Design for a Data and Information Service to Address the Knowledge Needs of the Water-Energy-Food (W-E-F) Nexus and Strategies to Facilitate Its Implementation.
Front. Environ. Sci. 7:56.
doi: 10.3389/fenvs.2019.00056

BACKGROUND

Providing adequate food for the world's growing population is a major challenge. Developing the necessary food production capabilities will require more effective and sustainable use of key input resources, most notably water and energy. Securing sustainability in the water, energy, and food sectors is critical for safeguarding terrestrial, freshwater, and marine natural assets; sustaining critical ecosystem services; building healthy, resilient, and productive cities and more prosperous rural futures; and reducing human health risks. As computer power, satellites, and communications technologies improve, they expand the potential to effectively inform decision-makers with requisite resource management information and outlooks.

The W-E-F Nexus refers to the interactions among the water, energy, and food sectors (**Figure 1**). According to the Food and Agriculture Organization (FAO) of the United Nations (UN), the agri-food sector is responsible for 70% of global water withdrawals and uses about 30% of the world's total energy production (Food and Agriculture Organization, 2017). Land is also an important resource: globally, 4.9 billion hectares of land are used for agriculture, of which 33% are moderately to highly degraded (Food and Agriculture Organization, 2017). Food production capabilities and water and energy availability vary across the globe, which has led to food becoming an extensively traded commodity. The global water cycle, which distributes precipitation and runoff in highly variable regional patterns, cycles a relatively fixed amount of water through the hydrosphere. Both energy and water availability vary from country to country but water is generally treated as a public good, while oil and gas reserves are treated as valuable commodities. Renewable energy, which meets a growing proportion of the world's energy needs, has decentralized supply patterns and its emergence is affecting the energy industry in terms of the demand for oil and, consequently, its price.

The water, energy, and food sectors tend to be managed as three independent ministries in most national governments, which Tett (2015) describes as siloes. It is reasonable to expect that their joint management would provide new efficiencies and lead to synergistic policy developments in areas of ecosystem services and sustainable development. Joint governance could be supported by an information service that provided data products for all aspects of the W-E-F Nexus. Integrated governance and management frameworks, such as the W-E-F Nexus, that rely on open access to data and information in support of advisory services and joint planning would be advanced by the development of joint information services.

A growing number of articles have discussed various aspects of the W-E-F Nexus framework over the last 5 years (Liu et al., 2017). Along with the World Economic Forum's *Global Risks 2014* report (World Economic Forum, 2014), these articles introduce the benefits of managing interactions in a more coordinated way. The W-E-F Nexus introduces an integrated approach for systematically analyzing and planning synergies by giving more attention to these interdependencies.

This paper, which fits the Frontiers "Hypothesis and Theory" category best, explores the hypothesis that a suitably defined data and information system that integrates and consolidates W-E-F Nexus data could support the implementation of a Nexus approach. In particular, its objective is to explore how existing selected sector-specific data and tools can be incorporated into a multi-sectoral information system that would meet W-E-F Nexus needs and support its broader implementation. This paper includes: a description of the data and information needed to support planning, management, and trade-offs in the W-E-F Nexus (The W-E-F Nexus Approach, its Benefits, and Its Information Needs); a brief review of W-E-F Nexus data sources and collection systems such as satellite and *in situ* observational networks (Data Inputs); the supplementary role of models and data assimilation systems (Models and Data Assimilation); an overview of the design and development of an information system that would build on existing systems (Implementing the W-E-F Nexus Data and Information System [WEFDIS]); and conclusions based on the main points addressed in the paper (Developing and Implementing a WEFDIS Network).

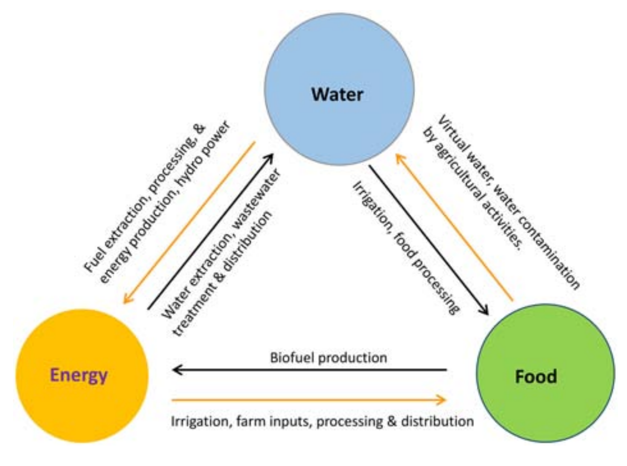

FIGURE 1 | Interactions among the sectors that make up the W-E-F Nexus.

THE W-E-F NEXUS APPROACH, ITS BENEFITS, AND ITS INFORMATION NEEDS

The W-E-F Nexus is a multidisciplinary framework designed to ensure that interactions, synergies, and trade-offs are properly understood and decision-makers have access to the information and tools they need to take full advantage of these potential co-benefits. Globalization, urbanization, industrialization, and climate and environmental change continue to put pressure on water, food, and energy security. The W-E-F Nexus community needs to understand the influences of many factors: trade policies that either promote free trade or protectionism and tariffs, changing prices for oil and gas depending on the politically determined rate of supply, changing affluence and dietary requirements, increasing climate variability and extreme climate events, and the trade-offs needed to balance long- and short-term needs.

This paper derives many of its insights from four regional Future Earth W-E-F Nexus Cluster project workshops held between June 2016 and November 2017. Each of the workshops included sessions on *in situ* and satellite data sources and applications for decision-making and planning. Their findings have been documented and are available at http://water-future.org/past-events-2/ or from the author. The workshops were held in: North America (Washington, D.C.), Europe (Karlsruhe, Germany), Eastern Asia (Kyoto, Japan), and Southern Africa (Hilton, South Africa) and each drew on the expertise available in these regions.

Based on the four workshops, the data and information needs for W-E-F Nexus decision-makers were clarified. Planners need credible predictions and scenarios for developing W-E-F Nexus plans and identifying hotspots where W-E-F Nexus problems are emerging. Operational decision-makers need information to provide guidance on maximizing the benefits of resource use and minimizing the impacts of Nexus operations on environmental quality and biodiversity. Evaluators require information for assessing the viability of biofuels and other renewables to meet energy demands within the W-E-F Nexus and for conducting management reviews. Economic advisors need data for providing recommendations on beneficial trade-offs and for confirming plans to advance W-E-F Nexus productivity.

Critical interactions within the W-E-F Nexus and the availability of observations for monitoring critical processes need to be identified. Consistent observations need to be based on a common understanding of how variables are defined in each sector. A precise and widely accepted lexicon and associated ontologies would facilitate the quantification of interactions among the sectors. Engineered systems can be accurately defined but social, economic, and ecosystem interactions will include uncertainties, so identifying and defining the most critical terms becomes very important. In addition, the W-E-F Nexus itself will need to be defined so that it can encompass environmental effects and anthropogenic change. In addition to trends in land use (Ringler et al., 2013), the Nexus is influenced by growing populations, increasing wealth, changing food preferences, the effects of climate change on water and temperatures, unplanned urbanization, and technological change.

Test beds and use cases could be undertaken to help clarify definitions for terms in a W-E-F Nexus lexicon. A pilot project that explores stresses on the W-E-F Nexus using preliminary integrated definitions and appropriate geospatial data would be useful. It could include an analytical framework that would serve as a test bed for identifying and addressing data gaps more generally (Vörösmarty, 2017).

Information Gaps

A comprehensive analysis of current data gaps should be undertaken. In some cases, data are missing entirely; in others, only short-duration research data sets exist (see **Table 1** for a partial listing). Some data gaps exist because science has not yet fully addressed certain W-E-F Nexus issues or governments have not found the issues important enough to introduce observational networks.

TABLE 1 | Examples of missing observations needed for analysis of the W-E-F Nexus.

Missing observations for W-E-F Nexus Analysis
Water use in thermoelectric power generating stations and mines
Actual irrigation water use
Runoff and infiltration from land with tile drainage
Soil carbon data
Volume of recycled water
Volume of water used in hydraulic fracking
Volume of food waste
Near real-time water use

Innovative approaches to monitoring are needed to provide information on the sources and volumes of water used for all W-E-F Nexus activities and possible impacts of these activities on the environment. Global water use estimates in agriculture and forestry are needed for improved management and to assess the feasibility of W-E-F Nexus trade-offs. A systematic data and information service based on available techniques needs to be developed.

Links between the W-E-F Nexus and the environment must be better understood and monitored. Water quality data are important for monitoring the relevance of and pathways for food and energy by-products. Nitrogen and phosphorus from crop fertilizers that find their way into waterways and lakes cause eutrophication. The safety and other possible effects of recycled wastewater on crops irrigated with reclaimed water need to be assessed.

Food waste is an emerging W-E-F Nexus issue that also needs to be monitored. SDG Target 12.3 calls for nations to, "By 2030, halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses" (United Nations Development Program, 2019). Food waste and its implications for water and energy resources need to be assessed. Data on food waste for both crops and livestock are needed at every point along the value chain, from the farm gate to the processing plant and to the consumer. These data are also needed to assess the potential for converting food waste into energy.

Future growth in supply and demand must be anticipated. Projections of future water availability are subject to uncertainties in climate model projections of precipitation amounts. Observations, tools, and models are needed to assess the uncertainties associated with water availability estimates. Uncertainties regarding the adoption rate of renewable energy technologies and electric cars complicate energy projections. Variable weather and fluctuating global food prices introduce year-to-year uncertainties into food scenarios. Near real-time data and information are needed to support rapid, localized responses on critical W-E-F Nexus issues. Artificial intelligence and neural network analysis tools hold the promise of optimizing resource availability and consumption and providing important guidance for decision-making.

Using indices to summarize the effects of multiple complex processes on a resource or human condition can be very useful

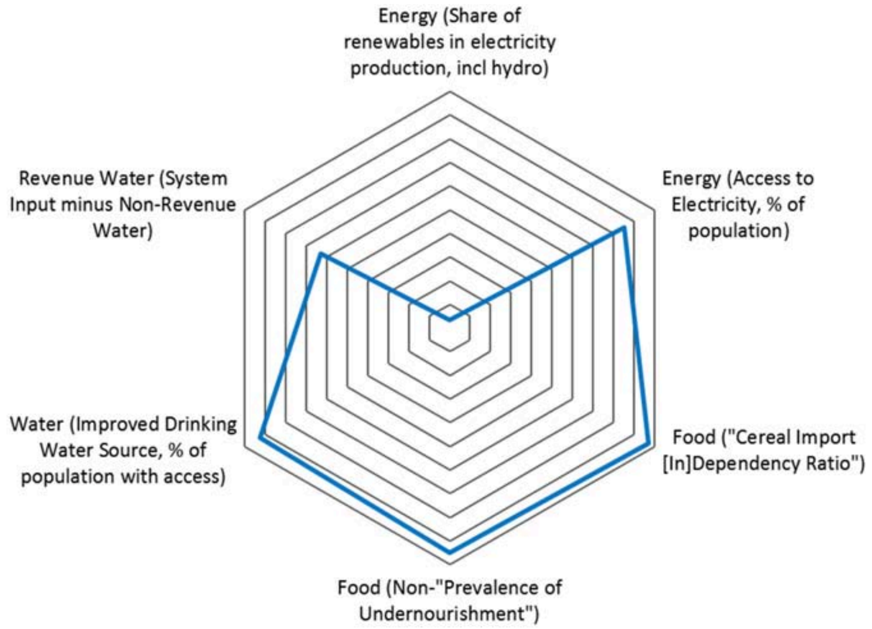

FIGURE 2 | Potential W-E-F Nexus indicator for application in South Africa (Simpson and Berchner, 2017).

for communicating with the public and policymakers (Smeets and Weterings, 1999). Indices could be designed for the W-E-F Nexus and used to measure progress toward its policy objectives. **Figure 2** gives an example of a prototype W-E-F Nexus indicator from South Africa that monitors resource availability for water, energy, and food (Simpson and Berchner, 2017) that could be extended to other countries.

The risk concept can be used to rank sources of uncertainty and can help interpret longer-term scenarios and the likelihood and consequences of their realization. To address risk in a systematic way, all contributing factors (climate, consumer demand, and economics) and the interactions among them must be assessed. Risk frameworks can identify risk hotspots, requirements for trade-offs, and options for distributing risk. Evidence-based decision-making depends on reliable observation systems that provide data for a risk assessment framework. To make this approach feasible, however, W-E-F Nexus management must have access to all reliable data and information services whenever needed.

DATA INPUTS

The W-E-F Nexus data and information system (WEFDIS) proposed in this paper will make data and information products available to users. Data generally come from satellites and *in situ* data networks, but increasingly data from non-traditional data sources are also available. Communicating and consolidating data from different sources will rely on full access to data sources, standardized data formatting, and new data products that facilitate the design of solutions.

TABLE 2 | Preliminary assessment of variables essential to the W-E-F Nexus (***: very critical; **: critical, *: helpful).

Variable\sector	Water	Energy	Food
Precipitation	***	**	***
Air temperature	**	***	***
Evapotranspiration/evaporation	***	**	***
Water quality	***	**	**
Water storage (reservoirs, lakes)	***	***	*
Soil moisture	***	*	***
Streamflow/runoff	***	**	*
Groundwater	***	*	**
Shortwave solar energy	*	***	**
Land use/land cover	**	**	**
Primary productivity	*	**	***
Boundary layer winds	*	***	*

Systems approaches should form the basis of new data collection and information systems. Arguably the development of and reliance on an information system is a core element of a W-E-F Nexus implementation and management strategy. Knowledge management and dissemination of best practices are critical for promoting the W-E-F Nexus and engaging stakeholders. Well-structured dialogue facilitated by a reliable data and information service and discussions stimulated by these services could contribute to policy development and action plans at national and international levels.

Synergies in planning a WEFDIS can be identified by assessing which sectors have similar data needs. **Table 2** shows the results of a preliminary analysis of critical or essential variables and the

TABLE 3 | Organizations and groups developing essential variables.

Organization/group	Data
Global Observing System for Climate (GCOS)	Essential climate variables
Group on Earth Observations (GEO)	Essential variables for biodiversity and water
Global Earth Observations System of Systems	*The GEOSS water strategy: from observations to decisions* (Group on Earth Observations, 2014)
GEO user needs studies	Water (Friedl and Unninayar, 2010), energy, and food

TABLE 4 | Current NASA and ESA data sources for the W-E-F Nexus variables.

Agency	Mission	Observation
NASA	Global Precipitation Measurement (GPM) mission	Precipitation
	Moderate Resolution Imaging Spectroradiometer (MODIS) mission	Vegetation cover and irrigation
	Soil Moisture Active Passive (SMAP) mission	Soil moisture
	Landsat 8	Land use and cover
	Gravity Recovery and Climate Experiment (GRACE) Follow-On Mission	Groundwater and soil moisture
ESA	Sentinel-1	Floods, water bodies, and wetlands
	Sentinel-2	Urban, forest, and agricultural environments
	Sentinel-3	land monitoring, vegetation, land surface temperatures, altimetry, and lake water quality
	Soil Moisture and Ocean Salinity (SMOS) mission	Soil moisture, freeze/thaw

sectors that use them. It can be used as a tool for planning the WEFDIS data holdings and as a focus for discussions with users and stakeholders that will facilitate the articulation of priorities for the WEFDIS.

The approach to determining essential variables will be based on the efforts of a number of global organizations and groups (listed in **Table 3**). It also draws on the discussions held during the regional workshops in which participants gave their views on data needs. Unfortunately, not all sectors were equally represented at each workshop and the questions that elicited their responses were more directly addressed in some workshops than in others. Participants agreed on the importance of acquiring data and delivering data products at scales that capture the spatial variability and support informed decision-making.

Satellite Data

Workshop participants argued that any W-E-F Nexus information platform needs relatively complete data sets for the whole W-E-F Nexus system and offer the possibility to "drill down" to higher resolutions. Many key water and land cover variables can be measured or at least reliably estimated from space and standard products are routinely produced (precipitation, vegetation, shortwave radiation, evapotranspiration, soil moisture). Agriculture and energy are also supported in this way, although more data validation may be needed for some variables, such as crop type.

Satellites provide globally consistent data at regular intervals. Algorithms relate the radiances measured by satellites to physical atmospheric and surface variables such as precipitation and soil moisture. **Table 4** lists current satellites from the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) that provide global data sets for many of the essential W-E-F variables listed in **Table 2**. Satellite data can be used to supplement current *in situ* monitoring networks that may have inadequate data densities, continuity and consistency problems, diverse data formats, delayed reports, sensor failure, and political restrictions on free and open data exchange.

According to a recent survey of satellite needs and plans (National Academies of Sciences, Engineering, and Medicine, 2018), the W-E-F Nexus will soon benefit from the Surface Water Ocean Topography (surface water and river stage) mission and Landsat 9 (land use and cover) mission. Other new remote sensing platforms include drones and cube satellites, which promise to increase the frequency of satellite maps of land surface conditions (National Academies of Sciences, Engineering, and Medicine, 2018). Space agencies in Japan, China, India, France, Germany, and Brazil also make satellite data available for W-E-F Nexus monitoring. NASA and ESA have specific niches for the W-E-F Nexus issues embedded in research activities such as ESA's joint program with Future Earth and NASA's Food Security program.

The National Oceanic and Atmospheric Administration and the European Organization for the Exploitation of Meteorological Satellites collect regional data from geostationary satellites. Their satellites provide data from the same domain every 30 min or less over their field of coverage overcoming the low repeat times associated with observations from polar-orbiting satellites.

Limitations

In some cases, imperfect algorithms are used to convert measured signals into values for a particular variable (e.g., root zone soil moisture), resulting in increased uncertainty for these measurements. Depending on resolution and sensor technology, polar-orbiting satellites may have repeat times of 24 h to 15 days, limiting their usefulness for monitoring rapidly developing phenomena. Maintaining continuity in Earth observation data used for analysis and assessment purposes is also critical for monitoring the W-E-F Nexus. Some nations find it difficult to use satellite data because they cannot handle high data volumes, nor can they acquire specialized analysis and mapping software and associated expertise due to resource limitations.

In situ Data

Capabilities

Precise local, high-frequency observations provide more accurate data for many variables at the point of application. For example, measurements of streamflow, soil moisture, and groundwater at a specific location are best determined by *in situ* measurements at that location. In many cases, *in situ* data can provide historical context because data sets are often multi-decadal. They are also important for satellite data calibration.

Citizen science data could become a new source of *in situ* W-E-F Nexus data. It encompasses mobile phone photos, narrative information, and tweets that can be submitted by students and laypersons. In some cases, citizen science data archiving has taken the form of mobile apps that collect water quality data from multiple devices and assemble it into a single database. The data producers, scholars, and citizens who provide data are currently responsible for their quality control.

Limitations

Operational networks that provide W-E-F Nexus observations need attention. Governments support these networks for public health and safety and economic reasons, while the private sector often supports local observations for operational efficiency and added value. However, coverage by hydrometric stations for the W-E-F Nexus and, by association, the SDGs is affected by the decline in streamflow gauges that has taken place in many countries (Fekete et al., 2015). Nations frequently maintain multipurpose networks, which may have complications for addressing specific W-E-F Nexus issues. For example, if precipitation data are collected only at airports, they may not provide the best inputs for streamflow prediction in nearby basins during the convective rain season.

In situ measurements of water quality need to be enhanced to strengthen environmental monitoring. Governments need to ensure industries provide accurate information on their emissions to the environment and account for missing information. Furthermore, more effort is needed to harmonize global and local data sets for water quality. Integrating observations for the W-E-F Nexus provides an opportunity to integrate emerging Nexus capabilities and concepts with traditional data programs. However, the range of possible data and analysis capabilities is so diverse that it must be prioritized through consultation with stakeholders and users using the list in **Table 2** as a starting point.

Socio-Economic Data

Capabilities

Social, economic, and biophysical data are needed to support W-E-F Nexus decisions. Information systems need to support the development and implementation of effective, integrated policies for the W-E-F Nexus and account for their impact on future outcomes. Information systems need to inform decision-makers of development opportunities (e.g., agricultural incentives for economic and environmental sustainability) and regulatory requirements. Socio-economic data include economic data, census data, trade statistics, employment profiles for each sector, studies of demographics and social behavior, and general and targeted surveys. Food and energy data are collected by many governments for trade strategies and reporting purposes. Given the space and time scales involved and the diversity of socio-economic information, it is challenging to incorporate them into a data and information platform focused on high-resolution physical data. New tools are required to make full use of narrative-oriented and qualitative citizen data and to develop procedures and standards for quality controlling these data. New directions for the acquisition of data are emerging through "big data" projects such as the UN's Planet Pulse project.

Limitations

Existing economic databases generally provide high-level, low-resolution data, allowing only macro-level explanations of the W-E-F Nexus. National economic data need to be downscaled to state and county levels for further analysis. Data on property ownership and use and associated legal rights are needed by nations to support W-E-F Nexus governance research, but they are not collected systematically across all nations. For some countries and some issues, census statistics and citizen science may prove to be the best tools for tracking policy implementation, particularly where regular and systematic data collection programs exist. Site-specific data are needed to validate census and national reporting data.

The development and application of new analysis techniques that produce reformatted and gridded socio-economic data that can be better integrated with physical data. For example, mapped data on regulations and ordinances have been used to successfully coordinate policy implementation in areas with multiple agencies and overlapping responsibilities. A geographical approach also enables the integration of biophysical and socio-economic data in addressing these governance problems (see Taniguchi et al., 2017 for an example). A similar W-E-F Nexus service could identify hotspots and provide updates on the impacts of storms, floods, and droughts as well as longer-term W-E-F Nexus information that only needs annual updates. Targeted monitoring is also important to assess the impacts and benefits of W-E-F Nexus management and interventions.

Data Provenance and Coordination

As a principle, data systems should be designed to maximize the value of information for the users. Reduced data latency is needed because the value of data for W-E-F Nexus decisions tends to decrease with time. Given the many scales of W-E-F Nexus decisions, it would be helpful to have regional data frameworks to facilitate the transfer of data and improve its utility for national, regional, and local scales. An international framework (with reporting requirements) for the W-E-F Nexus and strengthened links with the SDG framework could advance this aspect of W-E-F Nexus implementation.

It is important to have realistic data expectations. Without data, planners will not be aware of changes in resources and the environment. Without links to policy, benefits to the Nexus could become somewhat transient and overridden by legislation and directives from other government levels at other times. Arguably, the most efficient way to support users is to develop a platform through which data, information, tools, models, and policy updates are made fully interactive, accessible, and useable.

MODELS AND DATA ASSIMILATION

Models integrating different data sets are needed to support decision-making. Models can also be useful to W-E-F Nexus implementation: they consolidate available knowledge and assess interactions among processes and sectors. Integrated data products resulting from model and data assimilation system outputs can be combined to fill data gaps, reduce uncertainty, and improve spatial scale. Models can also be used to upscale and downscale data and results to provide outputs that meet the needs of decision-makers for information at different scales.

Some data needs are known but the desired spatial resolution and temporal frequency can only be achieved with assimilation systems or models. Many data types are difficult to downscale to counties and towns; however, Earth observations and data assimilation models can help provide local estimates and disaggregate to local scales using algorithms. Trade-offs may be needed between spatial and temporal scales. Well-focused, mission-oriented questions and assessments can be used to help define scale, accuracy, and data latency requirements, along with other W-E-F Nexus data needs.

Models used in W-E-F Nexus information systems should include biophysical, socio-economic, agent, policy, ecological, and landscape models. Optimally, they will function in the same environment, draw data from the same databases, and use common definitions and units. Predictive models also play a key role in making projections that can underpin planning decisions. Predictive and scenario models should assess and project the consequences of long-term changes such as climate change and consequences of different development trajectories. A suite of models could be combined in different ways to assess future opportunities. For example, to examine food security, researchers should combine climate or weather, crop, and food demand models. The development of this model suite should engage experts from each sector and focus on an architecture that can provide an interactive hierarchy of interlinked models. Improving the accuracy of extended-range weather and climate forecasts for essential W-E-F variables (at 30–90 days) should also be a priority research issue to support shorter-term projections of W-E-F Nexus conditions.

Data assimilation models are needed to fill data gaps and generate the best data products possible for the scales at which decisions are being made. Integrated data analysis systems should also combine different data types, upscale data for comparison purposes, and downscale system outputs to support decisions and problem identification at local scales. Solutions include merging data sets or using a model to unite different data types and to estimate missing data. It is important to develop assimilation capabilities that can combine *in situ* and satellite data to produce integrated products. NASA's Land Data Assimilation System and Land Information System are examples of systems that meet these requirements.

IMPLEMENTING THE W-E-F NEXUS DATA AND INFORMATION SYSTEM (WEFDIS)

Scope of the WEFDIS

A "one-stop" system designed to meet the data and information needs of W-E-F Nexus managers and document the interactions of the constituent sectors could strengthen the W-E-F Nexus approach. As managers from each sector gain confidence in the system and in each other, they could be encouraged to identify and discuss policy inconsistencies and issues, thus building a foundation for more in-depth W-E-F Nexus planning and decision-making. Integrated information systems should provide planners and decision-makers with Nexus data as well as access to all the data from each sector. In particular, a WEFDIS would ingest *in situ* data and space-based information and produce integrated products related to essential W-E-F Nexus variables and critical processes.

Addressing specific data requests through an integrated data and information system can pose some structural challenges. Open, standardized metadata catalogs could help in cross-referencing data sets from different sectors. Metadata should be complete, including information on data latency, scales, and measurement methodologies. Water, energy, and food metadata should be collected in a systematic fashion, using a series of templates (questions, data, models, and scenario options). However, since not all the data that are incorporated into the information system will have been originally collected with the purpose of addressing W-E-F Nexus issues, the original purpose of the data collection effort should be included in the metadata. Synergies should be used when collecting and curating data at one center. Data stored in existing portals also need to be evaluated and incorporated or linked wherever feasible. Blockchain technologies offer ways of ensuring the reliability of data and metadata even though they come from many different sources and are accessed for many purposes.

Cloud computing services are increasingly being used in support of data services to provide rapid access to large quantities of data. This approach removes the need for downloading individual data files because the analysis can be undertaken directly at the source. Data dissemination and use is facilitated by format protocols used in the cloud, which in turn encourages data merging and comparison. Cloud computing should be implemented where it is practical and affordable to do so. The computer systems supporting cloud storage also provide powerful capabilities for running W-E-F Nexus models and data assimilation systems.

In order to communicate with most policymakers at the national level, a W-E-F Nexus indicator test bed needs to be developed and applied within the WEFDIS. For developing countries, where national data sets are often far less uniform, the WEFDIS should build on other networks and systems in their region. For example, NASA and the U.S. Agency for International Development have developed a network of regional information systems known as SERVIR to support data availability in developing countries. The SERVIR network currently consists of five regional hubs providing large satellite data sets and products. Other transmission systems such as GEONETCast have become popular for transmitting data between agencies without the Internet. These systems could be used to transmit products from the WEFDIS.

Developing and Implementing a WEFDIS Network

Critical steps in developing a W-E-F Nexus data and information system are described below. Some actions will be sequential, while many can be carried out in parallel.

1. Undertake user surveys and conduct consultative workshops to identify or confirm W-E-F Nexus data needs and strategies to support decision-making at regional and local scales. This consultative process should clarify data needs for multi-scale, transdisciplinary research as well as the basic data and services. Users would be given opportunities to specify their priorities among the available variables, including those listed in **Table 2**, for a given country or region and to clarify their needs for data resolution, frequency, and latency.
2. Provide scientific support for an integrated WEFDIS. The data, information, and tools needed for decision support at multiple scales should be assessed. Consultations would be held with groups experienced in managing large data portals, such as GEO, the World Climate Research Programme, the World Data Centers, and institutions that manage large data systems in the private sector, before finalizing the design for WEFDIS.
3. Assess existing information platforms to determine which features could contribute to a WEFDIS. In addition to evaluating the most desirable system features, mutually beneficial links should be developed to support the W-E-F Nexus community. A number of relevant information portals, such as the Climate and Environmental Data Retrieval system, which makes its data and comprehensive information available to users (Toussaint et al., 2007), can be used as examples of best practices in creating a WEFDIS. **Appendix 1** provides a preliminary listing of other information platforms that should be considered in this assessment. Services requiring consolidation across the water, energy, and food sectors should be identified so that shared platforms with national and international data components can be developed.
4. Develop an inventory of the existing tools, models, and databases that should be included in the WEFDIS and the desirable links with other data portals. This would include assembling the appropriate data sets from each sector that meet data standards and are needed for W-E-F Nexus decision-making.
5. Co-design information system outputs that meet the needs of decision-makers and can help build trust between data providers and users. In an ideal participatory process, scientists, experts, and stakeholders identify critical W-E-F Nexus issues and action plans are collaboratively developed. This participatory model, which has been used successfully in W-E-F Nexus studies in Japan (Endo, 2015), could be implemented more broadly by incorporating a WEFDIS into W-E-F Nexus planning.
6. Conduct pilot projects that test a basic data and information system and its interactions with users. To ensure systems are user-friendly for these pilot studies, global data sets would be subdivided into smaller data sets covering geographical areas of interest for the pilot project and stored as an additional set of products within the system. Information could be displayed through Web-based applications, information dashboards, and time series viewers (Few, 2013). The output formats would be adjusted to cover the range of user preferences and required services.
7. Develop a governance structure to support effective implementation and promote system sustainability and to provide a set of operating principles for the system management group to follow. The WEFDIS will be highly dependent on the availability of regular data inputs routinely harvested from open databases. In many countries (but not all), publicly funded research and data collections are freely and openly accessed. One essential principle that should not be compromised is a commitment to free and open data access at all steps in the process. Participation in a regional WEFDIS by a nation should mean its agencies are fully committed to providing data to the system under an open data policy. Data collection costs are high and it is often not economically efficient to acquire them for just one application. In countries where data are not freely available, governments should be encouraged to support the provision of data to the WEFDIS at no cost.
8. Where appropriate, institutional models should be considered to see how best to combine the efforts of a few national and regional centers into a global network. GCOS, which successfully advanced climate data by developing clear statements about the role of data and data services within the UN Framework Convention on Climate Change, would be a good model for the W-E-F Nexus especially if similar levels of policy support could be developed.

A number of data-related considerations and data flows for the WEFDIS are shown in **Figure 3**. The system would ingest numerical and textual data in a number of formats and languages. Automated data transfer will be used wherever possible to retrieve data, although specialized data may only be available by exploring the Web. The system design elements will be developed through consultations with representatives of each sector. The internal language used for communicating data (NetCDF, HDF, or another language) and the expected products and services will be part of the design. A metadata library would be maintained to allow users to determine which data are available. Information about data quality and completeness would be supplied by data providers and provided through a metadata library. Integrated modeling systems would be used to assess the internal consistency of these data for W-E-F Nexus decision-making and to facilitate projections of future conditions.

Developing User Capacity

As with other data systems, the benefits of WEFDIS will go to those who have the capacity to use it. The user criteria of near real-time information, free access to data, knowledge of

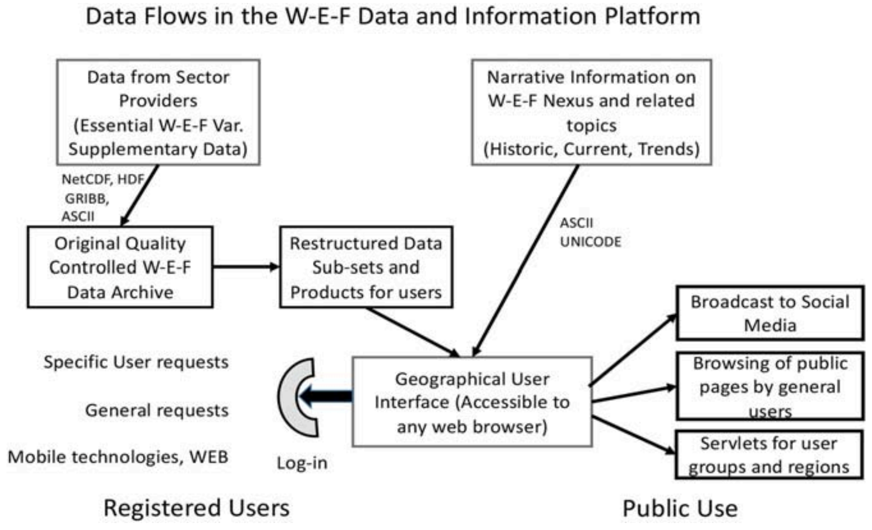

FIGURE 3 | A proposed structure for the W-E-F Nexus data and information system.

how to use the data, and translating the information effectively into every nation's official languages may not always be fully possible. Countries and organizations worldwide should be given an opportunity to gain these capabilities. To this end, a cadre of experts who can use these data and train others to do likewise should be developed. Providing all nations with equal access to the system in their own official languages will be a challenge but the system should be capable of serving major language groups.

Evolving user capability needs to be considered. Given that farmers and other data users are making extensive use of mobile phones, it will be important for the WEFDIS to effectively interface with mobile networks and technologies. The potential to uptake information and data from these distributed sources should be developed and local data sets should be integrated into larger domain products. This engagement of the local public could contribute to better and more widely accepted W-E-F Nexus products.

Regional W-E-F Nexus discussions and coordination should be promoted for joint ownership of information resources and assets. Data collection activities and system maintenance and experts that curate the service should all be continuously funded.

Capacity development must occur at both the infrastructure and the individual levels. To develop parity among users, the discrepancy in Internet accessibility and speed among developing and developed countries should be addressed. This "digital divide" prevents users in the developing world from accessing and using many data products that could contribute to managing the W-E-F Nexus. Training experts to interpret data for decision-makers is a central capacity development need, especially in developing countries.

CONCLUSIONS

This paper described the opportunities for bringing data from the latest observational systems together within a new multidisciplinary data and information platform design to support the implementation of an integrated W-E-F Nexus planning and decision-making management approach. The paper reviewed the information that is required by Nexus decision-makers, described the available satellite, *in situ*, and socio-economic data, and introduced the role of models and assimilation systems to fill the data gaps. The paper focused on the design of a data and information system and outlined eight steps needed to develop and implement such a system. While the plan is ambitious, it is more focused than most of the other W-E-F Nexus implementation approaches that were discussed during the W-E-F Nexus regional workshops. Furthermore, this system is not only a stand-alone system, it can also be used in conjunction with other more policy-oriented implementation approaches if the appropriate data and model needs are satisfied.

The paper identified a number of key W-E-F Nexus issues that have not received adequate attention, including food waste and its implications for resource use efficiency; the source, use, and fate of water used for fracking; and the estimation of water use and water quality at local, national, and global scales. The paper also explored the implications of these issues for the W-E-F Nexus, and for monitoring W-E-F Nexus variables. These gaps would be most comprehensively addressed within a W-E-F Nexus framework.

The paper concluded by outlining elements that should be integrated in a W-E-F Nexus data and information platform. Although most of the technologies mentioned are not new, their integration into a multi-sectoral application that supports resource management and stewardship of related environmental sectors is novel. The paper mapped out a pathway for bringing information from different sectors into a single system to meet the needs of an emerging W-E-F Nexus management perspective. It outlined a way to engage users in the system's design and, through pilot projects, to ensure they will have the training and experience necessary to exploit the system. System development would go hand in hand with W-E-F Nexus implementation. The hypothesis that access to data and information would promote acceptance of the changes and adjustments that would come with the adoption of the W-E-F Nexus approach seems sound based on the rationale presented but remains to be proven by a successful pilot project. Next steps in the implementation process should involve the development of implementation teams for pilot projects at different scales with support from national governments and international agencies. In addition, engagement by the UN and other international agencies would be needed to ensure that the international dimensions of the W-E-F Nexus are effectively addressed and that policies essential to maintaining the free exchange of W-E-F Nexus data among and within countries are followed.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

ACKNOWLEDGMENTS

The author gratefully acknowledges the Belmont Forum, Future Earth, and the Sustainable Water Future Programme for supporting the four regional W-E-F Nexus workshop through a Belmont Forum (National Science Foundation) grant that led to many of the insights presented in this paper. The contributions of approximately 200 workshop participants from five continents are also acknowledged. In addition, the author thanks Dr. Claudia Pahl-Wostl, the project's co-Principal Investigator, who organized the governance discussions for each workshop, and Dr. Anik Bhaduri, Executive Director of the Water-Futures Progamme, who administered the Belmont Forum funding. The contributions of the four workshop's local organizers are grateful acknowledged: Dr. Rabi Mohtar (Texas A&M, USA), Dr. Kim Watson (Karlsruhe, Germany), Dr. Aiko Endo (Research Institute for Humanity and Nature, Japan) and Dr. Sylvester Mpandeli, (Water Research Commission, South Africa), and Drs. Sabine Stuart-Hill and Graham Jewitt (University of KwaZulu-Natal, South Africa). The author also thanks the NASA Water Applications Program, and its director, Dr. Bradley Doorn, for support through the GESTAR program at Morgan State University, and Andrée-Anne Boisvert, Peter Lawford, and Dr. Sushel Unninayar for their editorial comments.

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Conflict of Interest Statement: The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

APPENDIX 1

Brief description of some information platforms and portals that address the needs of one or more of the W-E-F Nexus sectors

Various information systems that support some aspect of the W-E-F Nexus should be examined to assess their needs for data handling, modeling, and information dissemination capabilities. Systems to be assessed include GEO's Global Agricultural Monitoring Initiative (www.geoglam.org) for monitoring crop conditions, the Global Drought Information System (www.drought.gov/gdm/current-conditions) for monitoring drought, the GEO Global Water Sustainability Initiative website (under construction), and the World Data Centre for Climate. Other platforms that support water management include ESA's Thematic Exploitation Platforms (https://tep.eo.esa.int) and the Copernicus projects (www.copernicus.eu/projects/connectingeo).

W-E-F Nexus-related information projects include the Vision on Technology for a Better World, a system that facilitates data processing and distribution and analyzes global trends affecting the W-E-F Nexus (https://vito.be/en), and the GIZ Water, Energy & Food Security Resource Platform (http://www.water-energy-food.org/). An example for the energy sector is a system being developed by Haupt et al. (2018) to forecast solar energy outputs. The water sector is covered by the Aqueduct system, developed by the Water Resources Institute, which has more than a decade of experience in shaping outputs for those needing water risk assessment tools (http://aqueduct.wri.org).

Each of these platforms could be assessed separately so that their most useful elements can be incorporated into the WEFDIS.

frontiers in Environmental Science

REVIEW
published: 18 June 2019
doi: 10.3389/fenvs.2019.00086

Competition for Land: The Water-Energy-Food Nexus and Coal Mining in Mpumalanga Province, South Africa

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OPEN ACCESS

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Ben Stewart-Koster,
Griffith University, Australia
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Specialty section:
This article was submitted to Freshwater Science, a section of the journal Frontiers in Environmental Science

Received: 07 September 2018
Accepted: 27 May 2019
Published: 18 June 2019

Citation:
Simpson GB, Badenhorst J, Jewitt GPW, Berchner M and Davies E (2019) Competition for Land: The Water-Energy-Food Nexus and Coal Mining in Mpumalanga Province, South Africa. Front. Environ. Sci. 7:86. doi: 10.3389/fenvs.2019.00086

The Mpumalanga Province is a key source of South Africa's coal supply with over 60% of the province's surface area either being subject to mining rights or prospecting applications. Mpumalanga also possesses almost half of the country's high potential arable land. While South Africa is currently largely self-sufficient in terms of cereal grains, what this assessment of Mpumalanga highlights is that food security is increasingly being threatened by coal mining interests that serve the nation's energy needs. Water availability and quality for mining, agriculture and energy production in this province are also becoming increasingly strained. The water quality deterioration generally results from either acid mine drainage (AMD) or contaminated runoff from mines and agricultural lands. This assessment of Mpumalanga highlights the interconnectedness of energy, food, and water security, with their resultant trade-offs. The water-energy-food (WEF) nexus provides a focussed lens through which to evaluate resource security in a holistic manner. Only once regulators, NGOs, industry, and the public view the resource security challenges in Mpumalanga in an integrated manner can planning and policies that lead to sustainable development be advanced, and objectives such as the Sustainable Development Goals (SDGs) be achieved. There is, therefore, a need for WEF nexus science and data to influence integrated public policy within this province.

Keywords: water-energy-food nexus, Mpumalanga, coal, South Africa, land

INTRODUCTION

The Mpumalanga Province, which is the second smallest of the nine provinces in South Africa, contains almost half of the country's high potential arable land. Beneath its grasslands and cultivated farms are vast coalfields, which not only play a major role in the generation of this nation's electricity but also garner significant revenue from the export market. Approximately 25% of South Africa's coal is exported (Webb, 2015). Most of the nation's coal-fired power stations are in Mpumalanga, strategically situated near the mines that supply them. Another large consumer of coal in this province is Sasol's coal-to-liquid fuel plant.

Water that flows through this relatively high rainfall region is predominantly utilized for agriculture. Before the major rivers in this province flow across the international border with

Mozambique, they pass through the Kruger National Park. Other rivers in the province result in transboundary flow to and from Swaziland. Mpumalanga is also considered to be important in terms of biodiversity, possessing ∼5,000 pan wetland systems (Ferreira, 2009) and numerous other important habitats of interest, including a large portion of the Kruger National Park. Irrigation, energy, and food security are closely related in Mpumalanga with 25% of the staple food in South Africa being grown on irrigated land, requiring high energy inputs (Bazilian et al., 2011).

THE WATER-ENERGY-FOOD NEXUS

The global status quo is that resource and spatial planning and policy development often occur independently in "silos" with conflicting policies being developed (Bazilian et al., 2011; Leck et al., 2015). The nexus approach, which has gained prominence in the twenty-first century (Pandey and Shrestha, 2017), requires that resource and spatial planning occur in an integrated manner that seeks to consider linkages, dependencies and trade-offs (Hoff, 2011). The word nexus means to "connect" and therefore points to the interdependencies within a particular nexus configuration (De Laurentiis et al., 2016). A key consideration in a nexus assessment is that the attainment of the security of one resource sector should not compromise an adjacent resource sector (Simpson and Berchner, 2017).

Amongst the various nexus configurations, the water-energy-food (WEF) nexus has garnered particular interest (World Economic Forum, 2011). This is due to the finite nature of each of these resources coupled with the ever-increasing demand (and competition) for them due to population growth and changes in consumption patterns (Beddington, 2009).

The primary motivation for evaluating the WEF nexus in Mpumalanga is the ongoing tension between agriculture (i.e., food security) and coal mining (i.e., fossil-fuel based energy security) in terms of the competition for land. Related to this, and equally important is the deterioration of the quantity and quality of water in the region due largely to agricultural and mining activities (Ololade et al., 2017). The deteriorating water quality together with the diminishing quantity thereof already has and will continue to have, a negative impact on water security in this province. This, in turn, impacts not only agriculture, mining, and electricity production in terms of their input water requirements, but also poses a risk to human health and the environment and places pressure on other competing water users (including transboundary water users).

A further motivation for addressing the WEF nexus, or resource trilemma (Wong, 2010; Perrone and Hornberger, 2016), within Mpumalanga is the impact that climate change is predicted to have, particularly on water resources. The majority of climate models project a decrease in mean annual precipitation for southern Africa by ∼20% by the 2080s (Conway et al., 2015). Reductions in annual precipitation will threaten, amongst others, the availability of water for irrigation and hydropower. Some farmers have adopted more energy-intensive irrigated agriculture due to the reduction in available rainfed water for crop and livestock production (Grafton et al., 2016). An expected rise in temperature will increase evaporation volumes and decrease soil moisture and runoff. Lower food production, coupled with the reduced availability of water, will threaten sustainable economic development. This reduction in rainfall will also affect the achievement of several Sustainable Development Goals (SDGs), principally SDG 2 "Zero Hunger," SDG 6 "Clean Water and Sanitation," and SDG 7 "Affordable and clean energy." Other SDGs that are dependent upon freshwater resources will also be impacted (Rockström and Sukhdev, 2016).

The goal of this paper is to critically review the Mpumalanga Province through the lens of the WEF nexus. This will be performed by assessing each of the three resource sectors in turn. Where interactions and tradeoffs exist, they will be identified and investigated. Following the sectoral reviews, an analysis of the nexus interactions will be undertaken. Conclusions will subsequently be drawn regarding the existing or potential threats to water, energy, and food security in the province. Trade-offs between resources, i.e., where ensuring the security of one sector will impact the security of another, will be highlighted and assessed. Finally, recommendations of potential corrective actions needed to remedy possible threats to the security associated with the three sectors in Mpumalanga will be presented. The first resource sector to be reviewed is fresh water.

WATER SECURITY

Since the 1990s, Integrated Water Resource Management (IWRM) has been the dominant water management paradigm (Movik et al., 2016). According to the Global Water Partnership, IWRM aims to "promote the coordinated development and management of water, land and related resources in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" (GWP, 2000). IWRM approaches resource management by focussing on water as the central resource, whereas the WEF nexus proposes resource management in a multi-centric matter, providing equal weight to each resource (Ololade et al., 2017). The implementation of IWRM has been troublesome in some parts of South Africa, mostly due to a lack of capacity, innovation and experience (Claassen, 2013).

South Africa is the 30th driest country in the world (DWA, 2016). Ensuring adequate water supply to meet the country's social and economic needs is an ever-increasing challenge. Climate change will exacerbate this situation. Low rainfall and the consequent droughts in 2015 resulted in the Limpopo, KwaZulu-Natal, North-West, and Mpumalanga provinces being declared disaster areas. The drought in the first half of 2018 in Cape Town drove water reserves to the lowest levels that had been experienced in many years, with dam's levels being critically low. The principles of International Water Law (cooperation, equitable and reasonable utilization, no-harm) become relevant when considering different water uses in international basins, as is the case with South Africa sharing four major river systems with six neighboring countries (Belinskij, 2015).

Figure 1 presents the Water Management Areas in Mpumalanga. In the south-west, water drains inland toward the Vaal River system. The south-eastern portion of the province flows across the national border with Swaziland. Runoff that is generated in the northern portion of the province drains

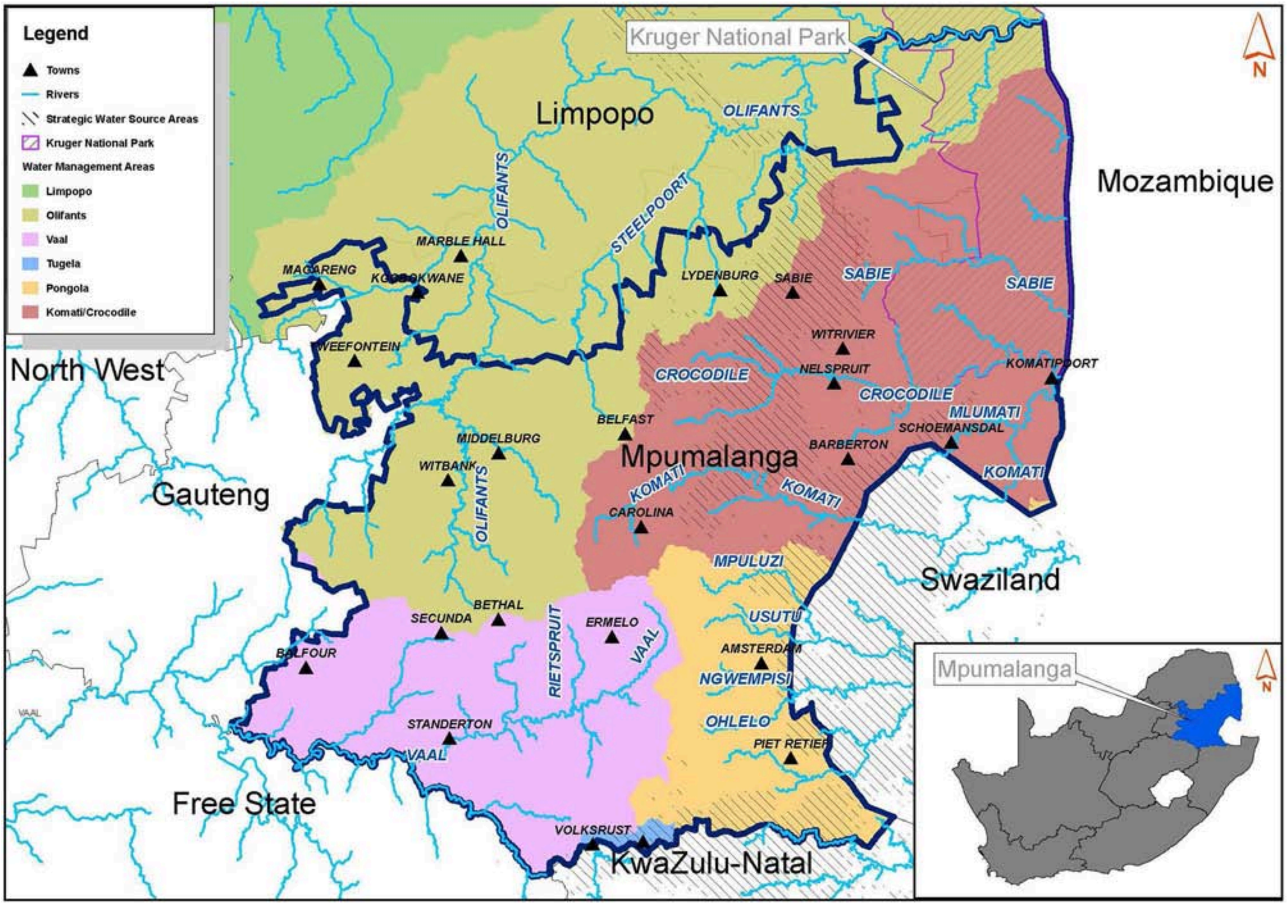

FIGURE 1 | Map of the Mpumalanga Province indicating Water Management Areas, main rivers, and major towns (Lotter, 2010).

predominantly in a north-easterly direction toward the Limpopo and Incomati Rivers, which pass through the Kruger National Park and subsequently into Mozambique.

Mpumalanga is characterised by annual rainfall that ranges from 400 to 600 mm per annum in the north-east, and 600–800 mm per annum in the west, while portions of the central zone receive annual rainfall exceeding 1,000 mm per annum. This high rainfall region in the center of the province is indicated by the hatching entitled "Strategic Water Source Areas" in **Figure 1**. Yearly evaporation generally increases from east to west across the province, from ∼1,800 to 2,200 mm per annum.

Approximately 46% of the surface water in the province is utilized for irrigation, 9% is utilized for electricity generation, 9% for mining and bulk industrial users, 9% for afforestation, 8% for urban water usage (3% for rural), while ∼16% of the surface water within this province is transferred to Gauteng (MDACE, 2003). The proportion of water utilized for irrigation in Mpumalanga is less than the average global agricultural water usage, which constitutes ∼70% of freshwater supplies (NIC, 2012).

Significant water loss in South Africa is attributed to the encroachment of invasive alien plants (IAPs). It is estimated that ∼10 million hectares of South African land are covered with IAPs, with the Western Cape and Mpumalanga provinces being the most affected (Le Maitre et al., 2000). The extent of IAPs in the Olifants River catchment in Mpumalanga was calculated by Kotzé et al. (2010)—it was determined that *Acacia* species and *Arundo donax* are the most prevalent, covering condensed areas of 6,700 ha and 5,406 ha, respectively. These IAPs impact river flows and groundwater availability, thriving in warm regions with high rainfall (Le Maitre et al., 2016). IAPs reduce riparian water yields in the Olifants River catchment by an estimated 50 million cubic meters per annum (Cullis et al., 2007).

Both agricultural and mining activities have significant impacts on the local water quality and quantity in Mpumalanga, while competing for land (Ololade et al., 2017). Ferreira (2009) explains that due to increased pressure from coal mining and agricultural activities, it is essential that perennial pan systems in Mpumalanga are protected and conserved to avoid a loss in aquatic invertebrate biodiversity. After opencast coal mines are rehabilitated "land is returned to low levels of biodiversity as rehabilitation programmes preferentially use commercially available seed, with high nutrient and water requirements" (Aken et al., 2012). The CER (2016) argue that the Department of Mineral Resources (DMR) grants mining rights "without having regard to cumulative impacts on water resources, biodiversity, air quality, and food security, nor to the health or well-being of affected communities, despite the consideration of these factors being required by law." The WWF supports this view, explaining that the "DMR does not take account of important natural assets such as biodiversity and the water provided by headwater catchments to agriculture and urban areas when issuing licenses" (Colvin et al., 2011).

Mpumalanga, like much of South Africa, is characterised by a significant disparity in the income and living standards of its citizens. This is reflected in people's access to water resources and sanitation services. While 91.4% of households in Mpumalanga had access to improved drinking water sources in 2015, less than two-thirds (65.8%) of households had access to improved sanitation facilities (Stats SA, 2016a). It is concerning that the percentage of people with access to improved drinking water in Mpumalanga decreased during the thirteen years leading up to 2015 from 92.9% in 2002, to 91.4% in 2015 (although this decline is small and could be within the margin of error for the census it should not be ignored since the change is negative). Equally concerning is that 16.5% of households in Mpumalanga experience water pollution (Stats SA, 2016a). This pollution is related to agricultural and mining activities, as well as frequently poor levels of municipal management in terms of sewerage treatment (Lodewijks et al., 2013).

These statistics indicate that access to improved drinking water and improved sanitation facilities in Mpumalanga are not universal, and that about one in six households is directly impacted by polluted water. Based on SDG 6, which amongst other goals seeks to achieve universal and equitable access to safe and affordable drinking water and access to adequate and equitable sanitation and hygiene for all, Mpumalanga has much room for development.

The water security challenge in Mpumalanga is being further compounded by the fact that the proportion of non-revenue water, which is the sum of unbilled authorised water and system losses, between 2005 and 2010 ranged between 33.6 and 51.3% for various municipalities (Mckenzie et al., 2012). The national average is 36.8%, and although this value is close to the world average of 36.6%, this loss represents a significant volume of water. The goal of reducing the proportion of non-revenue water in municipalities within Mpumalanga through reducing water losses must become a key intervention. International best practice in real losses is generally agreed to be 15% (Bruinette and Claasens, 2016). This means that municipalities in Mpumalanga have a long way to go in this regard. Water Service Providers such as Rand Water (2016) in Gauteng are seeking to train 15,000 plumbers and artisans as part of their "War on Leaks" programme, and Mpumalanga would do well to implement a similar programme. By reducing the proportion of non-revenue water losses, combined with water demand management, not only can water be saved, but significant energy savings can be realized, particularly in systems where water must be pumped at some point in the supply cycle. Water loss savings will also often result in energy savings due to a reduction in the water treatment costs, which is an energy intensive process.

While the irrigation of crops is beneficial to society in that it contributes to food security, agricultural practices also negatively impact on water quality through nitrogen and phosphorous pollution resulting from chemical fertilizers, as well as erosion from agricultural lands. Eutrophication is pervasive throughout the Upper Olifants River catchment and urgent interventions are required to reduce these nutrient inputs (Lodewijks et al., 2013).

In 2015 there were 239 operating mines and 788 derelict and ownerless mines in Mpumalanga (Solomons, 2016). **Figure 2** presents the farm portions[1] where mining rights have been granted and prospecting applications have been submitted. These mines are often the source of water pollution in the form of contaminated runoff and/or acid mine drainage (AMD). Coal mining is known to seriously degrade water by consuming, diverting and polluting the resource (Olsson, 2013). River systems, such as the Olifants River, have been significantly impacted upon in terms of quality (and quantity) by extensive coal mining within its catchment area (McCarthy, 2011). The Olifants River catchment has experienced over 100 years of coal mining and now has some of the poorest water quality in the country (Colvin et al., 2011). The water quality of the Olifants River is such that it cannot be used by Eskom's (the national utility) new coal-fired power station Kusile because the water is too polluted (Olsson, 2013). Irresponsible mining and regulatory failure are key aspects leading to the decline in water quality and quantity in Mpumalanga (Forrest and Loate, 2018).

An analysis of long-term monitoring data indicates that total dissolved salt concentrations (of which sulphate is the major constituent) frequently exceed resource water quality objectives at sites upstream of the Witbank and Middelburg dams (Lodewijks et al., 2013). Surface and groundwater sources are negatively affected by AMD in Mpumalanga due to the abundance of coal mining activities (Mabhaudhi et al., 2016). The 2010 Expert Team of the Inter-Ministerial Committee, which was established to assess the threat posed by AMD, identified the Mpumalanga coalfields as one of six vulnerable areas that require monitoring (DWA., 2010). Dealing with AMD in the three priority areas identified by the Expert Committee, namely the Western, Eastern and Central Basins, has been estimated to cost ∼US$770 million. In the absence of intervention in these six vulnerable areas, the financial costs required for dealing with AMD will be immense. This water quality impact, combined with a high proportion of non-revenue water, and the fact that South Africa is a water scarce country, yield a potential crisis in terms of water security, and pose a challenge to the achievement of SDG 6 in this province. These statistics need to guide the development of policies to rectify the inequalities that exist, as well as trends that point to the situation deteriorating even further.

Water security in Mpumalanga provides a useful lens through which to understand the extent of the interdependencies between the sectors included in the WEF nexus. Agriculture relies on water (both rainfall and irrigation) for food production but also contributes to the pollution of the very resource upon which it depends (Dabrowski et al., 2009). Similarly, water is a critical

[1] Mpumalanga comprises 4,341 parent farms, each with a unique name and region number e.g. Kromfontein 234 IR. Over time these parent farms have been subdivided into farm portions, which keep the parent farm name and number, with the addition of a portion number e.g. Kromfontein 234 IR Portion 1. There are 76,543 farm portions in Mpumalanga (Lotter, 2010).

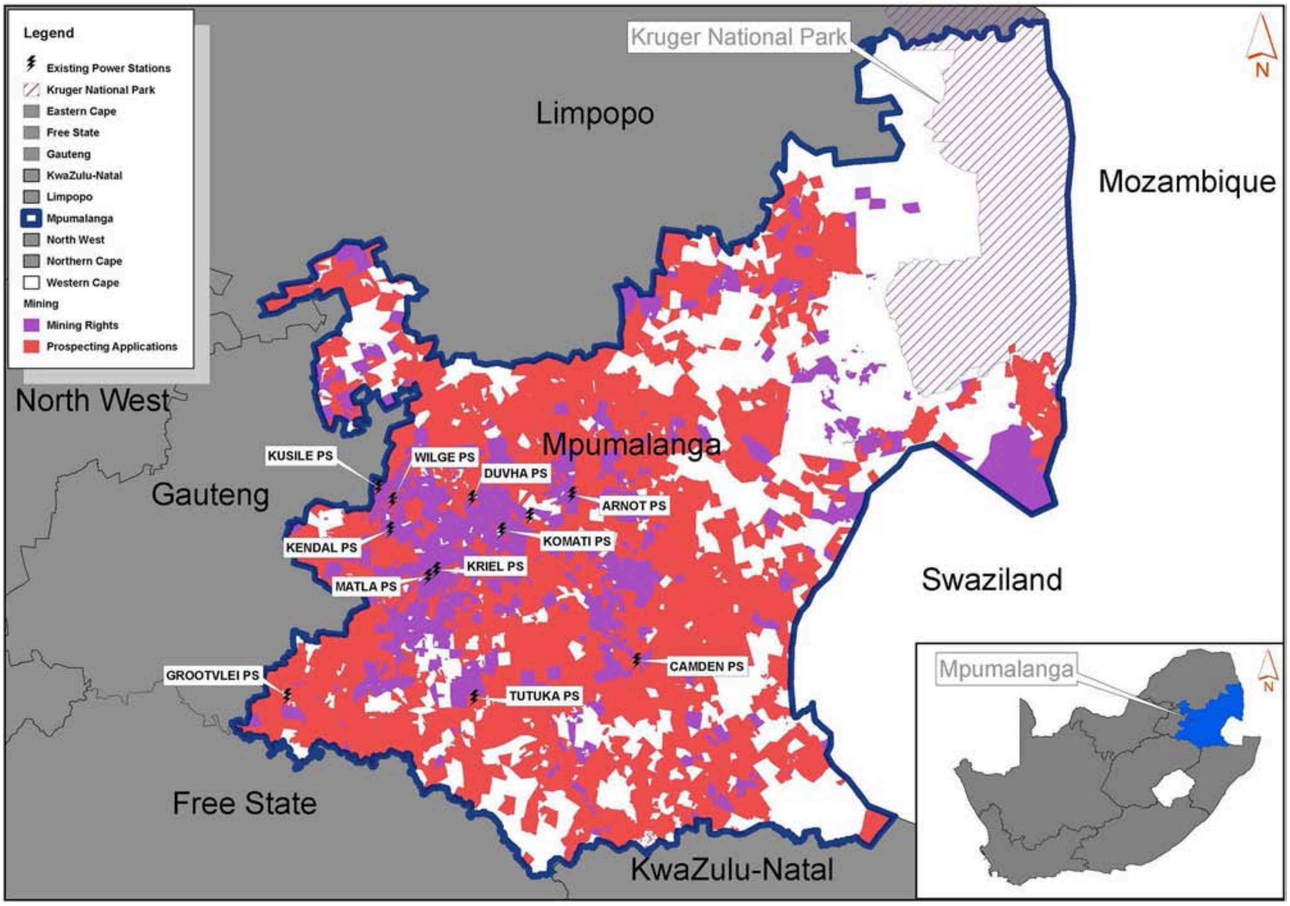

FIGURE 2 | Map of the Mpumalanga Province indicating the location of power stations, mining rights areas, and farm portions where prospecting applications have been submitted (Lotter, 2010).

input in energy generation (and coal mining as part of the value chain), but these activities are exerting pressure on the water resources upon which they too rely, particularly in terms of quality (Spang et al., 2014). This in turn directly impacts at least one in six households within this province in terms of exposure to contaminated water. Dealing with water pollution and ensuring an adequate supply of good quality water, in turn, requires energy (e.g., to pump and/or treat the water), which is the next resource sector considered.

ENERGY SECURITY

Jeffrey Sachs writes that "Of all the problems of reconciling growth with planetary boundaries, probably none is more urgent and yet more complicated than the challenge of the world's energy system" (Sachs, 2015). This statement is largely motivated by the world's dependence on fossil fuels since the industrial revolution, and the resultant emission of greenhouse gases, principally CO_2. In South Africa, energy security is inextricably linked to coal mining, since Eskom purchases approximately half of the locally produced coal (Chamber of Mines of South Africa, 2018). Eskom is guaranteed a supply of water since it is listed as the only "strategic water user" in the National Water Act 36 of 1998 (Olsson, 2013).

In 2014, South Africa generated ∼253 TWh of power, almost 92% of which was generated by means of coal (Agora Energiewende, 2017). Based on long-term contracts which commit several coal mines to supply coal to Eskom, South Africa will probably continue to rely on coal-fired power stations for the next 30–50 years (Delport et al., 2015). Due to the relatively slow transition to a low-carbon economy, it would be prudent to implement retrofitting measures to increase the efficiency and flexibility of the existing relatively old coal-fired power station fleet to facilitate the addition of electricity generated from fluctuating renewable energy sources (Agora Energiewende, 2017). These measures could also reduce coal consumption and CO_2 emissions.

A large proportion of the coal mined, and most of the coal-fired power stations, are situated in Mpumalanga, as shown in **Figure 2**. Although South Africa has in recent years been developing numerous renewable energy systems, their capacity is dwarfed by the capacity of coal-fired power stations such as Kusile (located in Mpumalanga Province) and Medupi (located in Limpopo Province), that are currently being constructed. Each of these power stations has a gross generating capacity of nearly 4,800 MW (DOE, 2016). Together with these state-owned coal-fired power stations, several coal-based Independent Power Producers are at varying stages of planning or constructing new facilities (Mathu, 2017). Of the total volume of electricity distributed in South Africa in September 2016, 2,713 GWh (or 14.6%) was delivered to Mpumalanga (Stats SA, 2016b). The percentage of households in the Mpumalanga Province that are connected to the national electricity grid increased from 75.9% in 2002 to 89.8% in 2014 (Stats SA, 2015).

In contrast to the dearth of coal reserves in other African nations, South Africa has 95% of the continent's proven coal reserves (Agora Energiewende, 2017) and is the seventh largest producer of coal in the world (IEA, 2017). Coal has played and continues to play, a very important role in South Africa's economy. Fine and Rustomjee (1996) argued in the late 1990s that the South African economy was characterised by a dependence on what they termed the Mineral-Energy-Complex. Many agree that this remains true today (Mohamed, 2009; Power et al., 2016). It is estimated that between 1987 and 2011, 7.5 billion tons of coal were extracted from the Mpumalanga coalfields, yet it is estimated that South Africa still has a run-of-coal reserve of about 66.7 billion tons (Webb, 2015).

While coal mining continues in the Mpumalanga Province, much of South Africa's remaining coal reserves are in the Waterberg and Soutpansberg areas, in the north-western portion of the country. It is estimated that ~72% of the remaining coal reserves in South Africa are located within these two areas (Webb, 2015). Although coal is plentiful in these regions, there are various obstacles to unlocking these vast resources. Challenges include the general lack of water, the sensitive biodiversity, the vast distance to most of the power stations and the Richards Bay Coal Terminal, and the coal in the Waterberg area generally being of a poorer quality than the coal mined in the Mpumalanga Province (Jeffrey et al., 2014; Cullis et al., 2018).

Only a little more than 3% of South Africa's electricity is generated by means of renewable sources (FAO, 2016), yet the cost of these technologies is falling rapidly (Walwyn and Brent, 2015). South Africa is endowed with significant potential in terms of solar and wind power generation (Gies, 2016). This could lead to the development of a southern African "Desertec" within the Northern Cape Province and in neighboring Namibia. Such a system could potentially generate power for the Southern African Development Community (SADC) states situated on the mainland. Examples of systems already installed in the Northern Cape include the Khi One steam-driven solar thermal plant near Upington, the De Aar Solar PV project and the Kathu photovoltaic project, near Deben (Craig et al., 2017).

The South African Department of Energy's *Integrated Resource Plan Update* recognizes the vast renewable energy potential that the nation possesses, with the base case planning 55,000 MW of new renewable energy to be delivered between 2,020 and 2,050 (DOE, 2016). This comprises of 37,400 MW of wind power and 17,600 MW of solar photovoltaic power generation. There are however some concerns regarding the constraints that are specified in this plan, particularly regarding the annual allowable capacity of renewable energy systems that may be installed. Another proposal that could result in a decreased dependency on coal recommends that South Africa lift their existing restriction on hydropower imports (Conway et al., 2015). This importation of energy could reduce the required investment in renewables. In addition, it could offset one of the main challenges associated with a high share of electricity from solar and wind power plants, namely that these are fluctuating energy sources. Hydropower can, however, result in negative impacts on aquatic ecosystems through changes to the natural flow regime and migratory routes. Couto and Olden (2018) state that 82,891 small hydropower plants (SHPs) are operating or are under construction worldwide, and "provide evidence for not only the lack of scientifically informed oversight of SHP development but also the limitations of the capacity-based regulations currently in use."

The energy and food security components of the WEF nexus are brought into sharp focus when it is realized that almost all opencast mining activities in Mpumalanga occur on high potential arable land (Collett, 2013). In 2014, 61.3% of the surface area of Mpumalanga fell under prospecting and mining right applications (Solomons, 2016), as presented in **Figure 2**. Large tracts of formerly high production agricultural land within this province (overlapping with areas containing high concentrations of coal reserves) have been mined to power the economic development that has taken place in South Africa (Ololade et al., 2017). Mpumalanga's coal mines and coal-fired power stations are the power-house of the nation (Winkler and Marquand, 2009). Yet the insatiable hunger of these power stations is not only consuming the carbon-based fuel but is also severely impacting upon the agricultural potential of the province, as well as the water quality within its rivers.

In a country such as South Africa, where there is such a large dependence on coal, to stop the development of new coal mines in the short to medium term would be tantamount to switching the lights off on a national level. Further, the coal industry in South Africa employs ~90,000 people (Webb, 2015) and generates valuable export income. In 2015, mining was South Africa's largest foreign exchange earner (Delport et al., 2015). The value of coal to the country means that to significantly reduce coal production would result in a negative impact on the economy in terms of jobs, energy security and export revenues. However, the environmental and human health impacts associated with the coal value chain need to be more thoroughly mitigated, especially when it is understood that "specific CO_2 emissions from power generation in South Africa are as high as 900 gCO_2/kWh. By contrast, specific CO_2 emissions in Germany amount to 500 g CO_2/kWh" (Agora Energiewende, 2017). Further, the trade-offs between the sectors making up the WEF nexus need to be better understood. When the province of Mpumalanga is considered, the trade-off between energy supply and food security is of supreme concern.

FOOD SECURITY

Efficient agricultural production in South Africa is hampered by limited arable areas; about 30% of the land surface is classified as rangeland, used mainly for game ranching where rainfall is low (Milton and Dean, 2011). Areas with high potential arable land, such as Mpumalanga, compete with coal mining for land and water use. Modern agriculture is heavily dependent on fossil fuels, which is reflected in the correlation between food and energy prices (De Laurentiis et al., 2016). Both mining and agriculture contribute to environmental damage, particularly relating to water quality, soil structure, and the loss of native habitats for ecosystem services (Foley, 2005).

Less than 14% of South Africa's land is suitable for dry land cropping with only about 3% regarded as high potential arable land (Collett, 2013). It has been calculated that 46.4% of the nation's high potential arable land is situated within the Mpumalanga Province (BFAP, 2012), and much of this is utilized for the production of commercial timber. Jeffrey D. Sachs notes that "there is actually an economic sector with comparable or even greater environmental impact than the energy sector: agriculture" (Sachs, 2015). Since the 1970s, South Africa has considered the water needs for agriculture subordinate to those of the energy sector, urbanization, and industrial development (Ololade et al., 2017). The area of land under various forms of cultivation in the Mpumalanga Province is summarized in **Table 1**.

There is a need for improved technology and techniques to maximize water efficiency and minimize the loss of crop production in South Africa. In the Mpumalanga Province, sugarcane is generally produced under irrigation (Jarmain et al., 2014). The areas listed as being cultivated by means of horticulture and under shade-net are assumed to be irrigated areas. Sugarcane production is a strategic crop in Mpumalanga. Based on climate change projections of a 2°C increase in temperature worldwide (from pre-industrial era levels), farmers in Mpumalanga may have to change from sugarcane (heavily dependent on irrigation) to a crop that is more heat tolerant, like sorghum (Gbetibouo and Hassan, 2005).

The Department of Agriculture, Forestry and Fisheries (DAFF) developed eight land capability classes, which are presented in **Figure 3**. This map indicates that large portions of the province of Mpumalanga have a high potential for cultivation. In 2012, as part of the development of a new policy on the *Preservation and Development of Agricultural Land* DAFF conducted a spatial analysis of available agricultural land in accordance with the national land capability classification classes. This was undertaken to determine the status of agricultural land per province, and the availability thereof through the exclusion of permanently transformed areas, i.e., agricultural land that has been lost due to, for example, urban development or opencast mining. The analysis concluded that the surface area of arable agricultural land in South Africa that had been converted to non-agricultural uses through urban and mining developments "equals the size of the Kruger National Park" (Collett, 2013). The area of this world-famous game reserve is almost two million hectares.

TABLE 1 | Areas of various types of cultivated lands in the Mpumalanga Province (DAFF, 2017).

Cultivation details	Area (hectares)
Sugarcane	61663.43
Rainfed annual crop grain cultivation or planted pastures	1118654.64
Non-pivot irrigated annual grain crop cultivation or planted pastures	2417.12
Horticulture—vineyards, flowers, trees or shrubs (orchards)	43421.16
Pivot irrigation—irrigation by means of center-pivots	50461.94
Old fields—old field boundary that is not currently planted	59804.91
Subsistence 1—usually close to small villages, fields are 5–10 ha	94593.67
Subsistence 2—usually close to commercial farms, larger hectarages	1559.00
Shade-net—crops are grown under shade protection	377.78
Smallholdings—small portions of land in peri-urban settings	5812.53
Total cultivation for Mpumalanga Province	**1438766.18**

As described in the foregoing section appertaining to energy security, the available area of high potential arable land in Mpumalanga is under threat from coal mining. At the current rate of coal mining in this province, it has been calculated that ~12% of South Africa's high potential arable land will be transformed, while a further 13.6% is subject to prospecting (BFAP, 2012).

The loss of arable land in Mpumalanga due to mining activities, for the highest two arable land capability classes, is presented in **Table 2**. These values indicate that current and future mining activities will have a significant negative impact on agricultural production, as well as long-term implications for food prices and food security. Even after rehabilitating an opencast mine in accordance with best practice standards, the land capability will be significantly decreased as some effects, such as soil loss, may be latent for several years following rehabilitation (Limpitlaw et al., 2005). Inadequately rehabilitated lands are also susceptible to settlement, erosion and the establishment of invasive plant species.

The significant backlog in the rehabilitation of mined land, combined with the failure of many rehabilitation efforts, is a cause of great concern. The negative impact of mining upon agricultural lands is not limited to opencast mining operations. Underground coal mining's impact on agriculture and water is not negligible, with the potential for subsidence, cracks, or sinkholes forming above areas where underground mining has taken place. The risk is significantly heightened if high extraction methods of mining are employed, e.g., high extraction or longwall mining. The impacts resulting from these forms of mining can threaten catchment runoff, wetlands, groundwater, infrastructure, and animal and human safety.

The food produced in Mpumalanga is for both local and national supply, as well as for export. In terms of food security, rising food costs are a global trend. In South Africa, food prices are increasing due to input costs such as energy, e.g., pumping costs, thus emphasizing the importance of the nexus approach. Inadequate (8.4%) or severely inadequate (19%) access to food is experienced in Mpumalanga in 27.4% of households (Stats SA, 2015). These statistics indicate that this province requires significant progress in order to achieve SDG 2, "Zero hunger." This challenge in term of adequate access

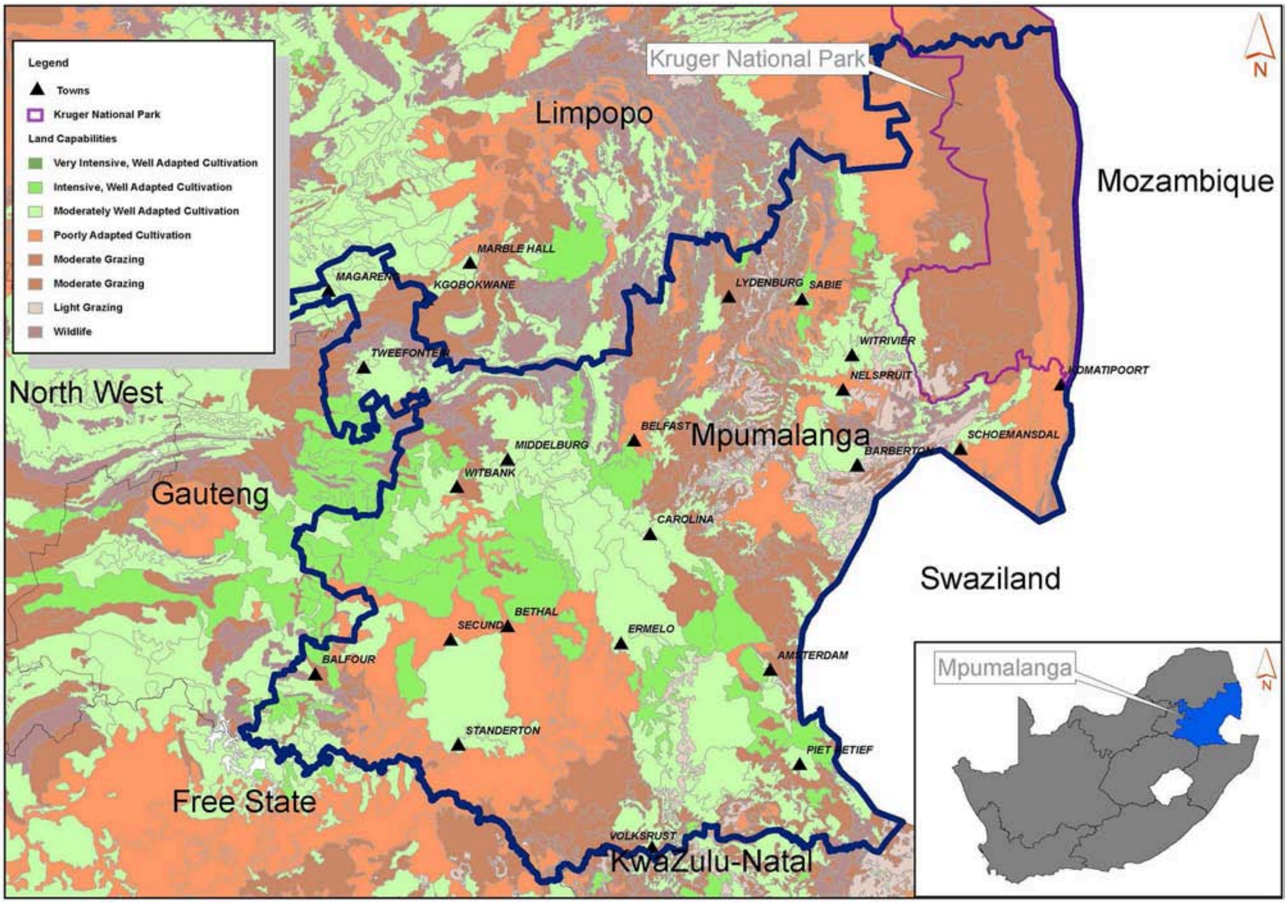

FIGURE 3 | Map of the Mpumalanga Province indicating the land capability classes (Lotter, 2010).

TABLE 2 | Loss of high-value agricultural land due to mining activities in Mpumalanga (ha) (Collett, 2013).

Land capability class	I	II
Available	872,007	2,058,727
Existing mining	18,378 (2.1%)	34,868 (1.7%)
Mining and prospecting applications	751,326 (86.2%)	1,404,224 (68.2%)

to food is primarily a problem related to poverty than actual food production.

Improved land management strategies and policies, as well as increased resource efficiency, will be required to produce more food with the same area of available land. The option of simply planting more food and expanding agriculture to satisfy the increasing demand, due to population growth and changing consumption patterns, is not feasible since all soils are not equal from an agricultural cultivation perspective. Further, rainfall, evaporation, topography and other factors (e.g., distance to market) that cultivated land depend on are not equally available throughout Mpumalanga. The use of degraded land will present an opportunity for renewable energy generation, specifically bioenergy production (Wicke, 2011). However, it is critical to implement efficient water use strategies if bioenergy generation is to be sustainable, e.g., irrigation of bioenergy crops with mine-affected water (if this is successfully trialed and approved by the Department of Water and Sanitation).

TABLE 3 | Six ratios appertaining to the WEF nexus in the Mpumalanga Province.

Sector indicator	Ratio	Source
Mpumalanga households with access to improved drinking water	0.914	Stats SA, 2016a
Average Mpumalanga municipal revenue water (system input minus non-revenue water and unbilled authorized water)	0.566	Mckenzie et al., 2012
Mpumalanga households with connections to mains electricity supply	0.898	Stats SA, 2015
Share of renewables in electricity production in South Africa	0.033	Enerdata, 2016
Mpumalanga households with adequate access to food	0.726	Stats SA, 2015
Cereal import in-dependency for South Africa	0.972	FAO, 2016

NEXUS ASSESSMENT

Having presented various details relating to the three resource sectors, together with selected interactions and trade-offs, the WEF nexus is tabulated and presented graphically for the province of Mpumalanga in **Table 3** and **Figure 4**, respectively. Six indicators appertaining to the Mpumalanga Province are presented. Two of these ratios have been selected for each of the three resource sectors, one representing human vulnerability and the other resource security on a provincial or national level. These values can be tabulated and graphically represented together since they each represent different facets of Mpumalanga's WEF nexus resource security. For example, by presenting both the proportion of people with connections to national grid electricity supply (which provides an indication of infrastructural development) and the share of renewables in electricity production, an indication of progress toward SDG 7 is obtained. Similarly, the proportion of non-revenue water provides an indication of municipal governance standards, while access to improved drinking water provides an indication of progress toward SDG 6.

The reason for presenting the cereal import dependency ratio and the share of renewables as national values is that these ratios are equally applicable to all provinces in South Africa. Some ratios, such as the cereal import dependency ratio, can be greater than unity. This is the case for countries that produce cereal crops in excess of their domestic requirements, such as Argentina, Canada and Bulgaria.

The radar chart in **Figure 4** indicates that South Africa is currently largely self-sufficient in terms of cereal production. A significantly large proportion of the households in the Mpumalanga Province have access to improved drinking water and mains electricity supply, especially when the backlog in the provision of basic services to the majority of the population in South Africa, post-Apartheid, is considered. What is concerning is that just over a quarter of this province's population has inadequate or severely inadequate access to food.

South Africa's dependency on coal for power generation, which in turn requires land for the development of mines—which in Mpumalanga is often high potential arable land—means that food security is being threatened by the pursuit of coal-based energy security. This may in time negatively impact the cereal import dependency ratio, which will raise food prices, resulting in increased pressure on the vulnerable members of society.

The radar chart also presents the average revenue water associated with municipalities in Mpumalanga Province. The non-revenue water values ranged from 33.6 to 51.3% in the assessment undertaken in this province (Mckenzie et al., 2012). These values indicate that much can be achieved at a local government level to reduce water leaks and improve cost recovery. When water losses are considered in conjunction with the 16.5% of households in the province who experience water pollution (Stats SA, 2016a), it is evident that water security is being threatened by not only poor governance but also by the pursuit of energy and food security. This is because much of the water pollution results from AMD, contaminated runoff from

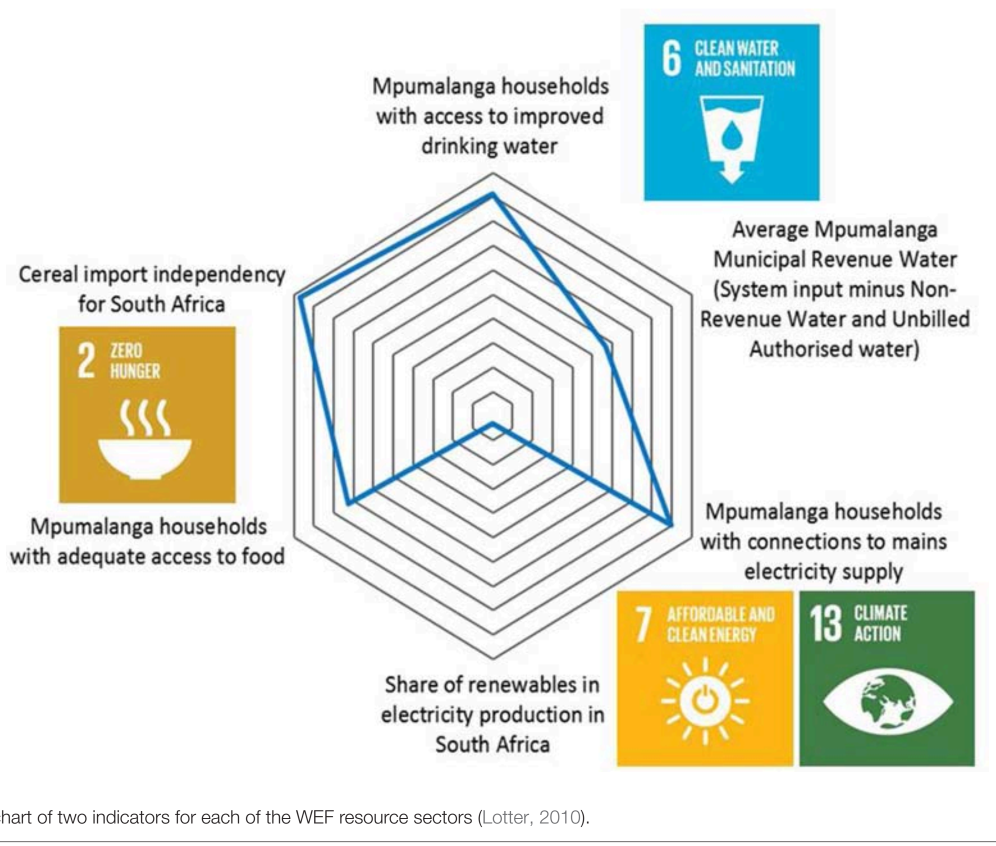

FIGURE 4 | Radar chart of two indicators for each of the WEF resource sectors (Lotter, 2010).

mines, agricultural chemical fertilizers, and the generally poor management of municipal sewerage treatment works.

CONCLUSIONS AND RECOMMENDATIONS

This semi-quantitative WEF nexus assessment of the Mpumalanga Province yields several interconnections between the three constituent sectors. When considering the importance of the region for coal mining and agriculture, and the cross-cutting relevance of water to both, this analysis has shown that an integrated approach is necessary to facilitate any movement toward resource management and the attainment of SDGs 2, 6, and 7.

When sensitive natural systems are considered in parallel with conservation areas such as the Kruger National Park, trans-boundary water considerations, decreasing arable hectarages, and the need to continue mining coal for the medium to long-term, it is essential that regional planning and policies be developed to balance the competing sectors, and to introduce an element of sustainability to this potentially volatile situation. One such effort from DAFF is the *Preservation and Development of Agricultural Land Bill*, which aims, amongst others, to promote the preservation and sustainable development of agricultural land.

The integration of several key regulatory departments associated with the WEF nexus, together with industry, NGOs and the public, in a regional planning initiative is imperative to enable this region to balance its, and the nation's, competing requirements. Ideally, this effort should be integrated with a regional land use and mine closure strategy. The WWF already stated this in 2011, when they wrote that the National Planning Commission and Departments of Water and Sanitation, Environmental Affairs and Mineral Resources must agree at the highest level to restrict mining in critical water source areas in order to mitigate the impacts of water pollution (Colvin et al., 2011). Further, the WWF also emphasized that spatially explicit development plans are needed at a provincial level that take into account high yield catchment areas, critical biodiversity areas and high-value agricultural areas.

Because of the continued dependence on coal in South Africa for the foreseeable future, it is imperative that any policy and planning initiatives be accompanied by mitigation measures. Such mitigation measures could include retrofits to the existing coal-fired power plants to increase their efficiencies and flexibility, thereby reducing their coal consumption and CO_2 emissions. Flexibility does not make coal clean, but making existing coal-fired plants more flexible enables the integration of more wind and solar power in the system (Agora Energiewende, 2017).

Alternative solutions, such as a significantly increased share of electricity from renewable sources, must be accelerated. This could be achieved if the implementation of the 55 000 MW renewable component of the Department of Energy's *Integrated Resource Plan Update* (DOE, 2016) is brought forward. This will not only decrease the reliance on coal-fired power generation but can also be an accelerator for innovation and a provider of so-called "clean jobs" (including the manufacture of components of renewable energy systems), thus not only yielding environmental but also socio-economic benefits.

Many studies and much monitoring has taken place in the Mpumalanga Province (Colvin et al., 2011; McCarthy, 2011; BFAP, 2012; Collett, 2013; Lodewijks et al., 2013; Delport et al., 2015; CER, 2016; Solomons, 2016; Stats SA, 2016a; Agora Energiewende, 2017; Simpson and Berchner, 2017). Many of these calls for change have fallen on deaf ears due to the energy security, jobs, and economic benefit that fossil-fuel based energy production delivers. There is however a need for WEF nexus science and data to influence integrated public policy in order to promote the long-term sustainability of this resource-rich province.

AUTHOR CONTRIBUTIONS

GS conceived and led the research, while GJ supervised the project. JB, MB, and ED participated as researchers.

FUNDING

This work is based on the research supported in part by the National Research Foundation of South Africa (Grant Number: 114692). This research falls under the WEF Nexus Lighthouse of South Africa's Water Research Commission (WRC), and workshops organized and supported by the WRC have contributed to the development of this study.

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Conflict of Interest Statement: GS and JB are employed by company Jones & Wagener (Pty) Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Environmental Science

ORIGINAL RESEARCH
published: 19 June 2019
doi: 10.3389/fenvs.2019.00085

Explaining National Trends in Terrestrial Water Storage

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Access to fresh water is critical for human well-being, economic activity and, in some cases, political stability. Data from the Gravity Recovery and Climate Experiment (GRACE) has been used to monitor variability and trends in total water storage. This makes it possible to associate changes in water storage with both climate variability and large scale water management. Recent research has shown that these trends can be associated, globally, with rainfall, irrigation, and climate model predictions. This research indicates a need for further investigation into specific human predictors of trends in terrestrial water storage. This paper presents the first global scale analysis of GRACE trends focused on national scale socio-economic predictors of terrestrial water storage. We show that rainfall, irrigation, agricultural characteristics, and energy practices all contribute to GRACE trends, and the importance of each differs by country and region. Additionally, this work suggests that other factors such as GDP, population density, urbanization, and forest cover do not explain GRACE trends at a national level. Identifying these key predictors aids in understanding trends in water availability and for informing water management policy in a changing climate.

Keywords: terrestrial water stress, GRACE satellite data, global water storage variability, irrigated agriculture, crop-choice

OPEN ACCESS

Edited by:
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Reviewed by:
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Specialty section:
This article was submitted to Freshwater Science, a section of the journal Frontiers in Environmental Science

Received: *25 June 2018*
Accepted: *27 May 2019*
Published: *19 June 2019*

Citation:
Bruss CB, Nateghi R and Zaitchik BF (2019) Explaining National Trends in Terrestrial Water Storage. Front. Environ. Sci. 7:85. doi: 10.3389/fenvs.2019.00085

1. INTRODUCTION

The global distribution of accessible fresh water resource is in flux. Rising temperatures affect the extent and seasonality of water storage in snow and glaciers. Changes in the distribution and intensity of precipitation influence the reliability of river flows and recharge to shallow aquifers. Construction or removal of major dams alters human ability to appropriate surface water flows. Perhaps most significantly, extensive exploitation of groundwater reserves is rapidly depleting aquifers in some of the world's most important food basket regions (Liu et al., 2011; Kumar et al., 2012; Scanlon et al., 2012). Against this backdrop, the need to monitor, understand, and, when possible, project the future distribution of water resources is a recognized research priority.

One area that has seen dramatic progress in the past decade is our ability to monitor changes in water resources using satellite-derived observations. Global monitoring of rainfall, soil moisture, snow cover, and even evapotranspiration is now possible, albeit with significant uncertainties that are the subject of active research (Greatrex et al., 2014; Wanders et al., 2014). The Gravity Recovery and Climate Experiment (GRACE) satellite mission has been instrumental in providing data that allows us to monitor total fresh water resources. With GRACE observations, estimates of anomalies in total terrestrial water storage can be computed. This has allowed for remote monitoring of water storage change—particularly groundwater storage change—in a manner never before possible.

Using this data researchers have investigated the global scale relationships between GRACE trends, climate models, precipitation, and irrigation. They show that once these signals are removed, irrigation, and potentially other human causes may explain, in part, GRACE observed TWS trends (Rodell et al., 2018). At a basin scale, GRACE has been applied to quantify trends in water storage in critical breadbasket regions around the world (Tiwari et al., 2009; Voss et al., 2013; Richey et al., 2015; Li and Rodell, 2016; Lo et al., 2016; Girotto et al., 2017; Nie et al., 2017). This research indicates that common terrestrial water storage components do not explain these trends, suggesting that they may be caused by unsustainable human use (Rodell et al., 2009; Famiglietti et al., 2011).

Globally, irrigated agriculture continues to be the largest user of surface water and groundwater resources. However, all irrigated agriculture is not equal. This is true hydrologically—different crops require different amounts of water, and some regions have greater access to renewable irrigation water resource than others—and it is also true economically. The value of crops differs dramatically, as was repeatedly emphasized during the recent California drought (e.g., high value almond vs. low value alfalfa), and the drivers of production differ as well (Swegal, 2017). The percentage of agricultural production sent to international markets has increased significantly in recent decades (Kastner et al., 2014), such that domestic water resources are now strongly influenced by international virtual water flow for many countries. This influences local economic opportunities, national trade strategies, and risks to water resources. Beyond agriculture, urban and industrial activity have a smaller but growing influence on surface water and groundwater resources.

Given these multiple drivers of water use, it is important to investigate observed trends in terms of their climatic and societal drivers. Doing so can help to characterize and map diverse human influences on water resources, distinguishing between regions in which water shortages are a function of climate variability and those in which particular economic or demographic activities might be most directly responsible for changing water availability. In this paper, we compile extensive data on climatic and socio-economic variables that have been shown in the literature to influence water storage and leverage statistical learning theory to identify the key predictors of observed GRACE trends at a national scale.

2. DATA PREPARATION AND PROCESSING

In order to explore drivers of GRACE trends at a country level we compiled a dataset with 47 covariates. Covariates were chosen for their potential to impact groundwater use in a country. Specifically, the covariates were selected based on a review of existing literature of potential drivers of groundwater storage trends as well as data availability at a national level over the time period of the GRACE observations. These included annual or monthly metrics for precipitation data, agricultural data (e.g., irrigation, crop yields, area under cultivation), economic and trade data (e.g., imports, exports, GDP, employment), population data (e.g., population density, percent urbanized population), and land-use data (e.g., forested area, agricultural land, urban land). A full list and data sources of country level indicators can be found in Appendix **Table A1**.

GPCC and GRACE data are made available by NOAA and NASA respectively. Other data was gathered from the World Bank's "World Development Indicators" and the United Nations Food and Agriculture Organization's "FAOSTAT" database. This analysis was conducted on 88 countries. Country inclusion was limited according to the following criteria.

- Latitude: This study does not address high latitude cryospheric effects, so analysis was limited to the latitudes 50°S–50°N. Countries that lie entirely below 50°S or above 50°N were excluded from analysis. For countries that lie partially outside this latitude range the GRACE and GPCC variables were extracted only for the portion of the country below 50°N (or above 50°S). While there are cryospheric trends between 50°S and 50°N, limiting our analysis to these latitudes excludes Greenland and Antarctica, where GRACE trends are dominated by ice sheet dynamics. Excluding high latitude regions of countries that cross the 50th parallel introduces some inconsistency with national-scale covariates, but it is consistent with the fact that most major water use activities in these countries occurs at lower latitudes.
- Area: Accuracy for GRACE is known to diminish at smaller scales, such as smaller countries. Therefore, countries smaller than 100,000 km^2 were not included. Additionally, significant coastline can also affect the accuracy of GRACE measurements therefore small island nations and peninsular countries were excluded.
- Data Availability: Some countries lacked the measures for several of the other covariates. These countries were also excluded.

Raw source data from the World Development Indicators and FAOSTAT are provided as time series with varying time-steps for each variable and for each country. To transform the data the raw data was processed in two distinct ways:

- Trends: calculating a historic average for each country for the years available prior to 2002 (corresponding to the first year of the GRACE data), then that number was subtracted from each year between 2002 and 2015. A simple linear regression was fit to those deviations from the historic average and this was deemed the trend over that time period.
- Averages: averaging the values between 2002 and 2015, the time period roughly corresponding to the GRACE observations.

Data Visualization

GRACE trends were calculated in 88 countries at national scale and depicted in **Figure 1** (top graph). As has been reported in previous studies (Rodell et al., 2009; Voss et al., 2013) strong negative trends in the Middle East and Central Asia are evident in the top graph in **Figure 1**. Additionally, positive trends can be seen in Equatorial West Africa and the northern regions of South America. Precipitation trends were also depicted in

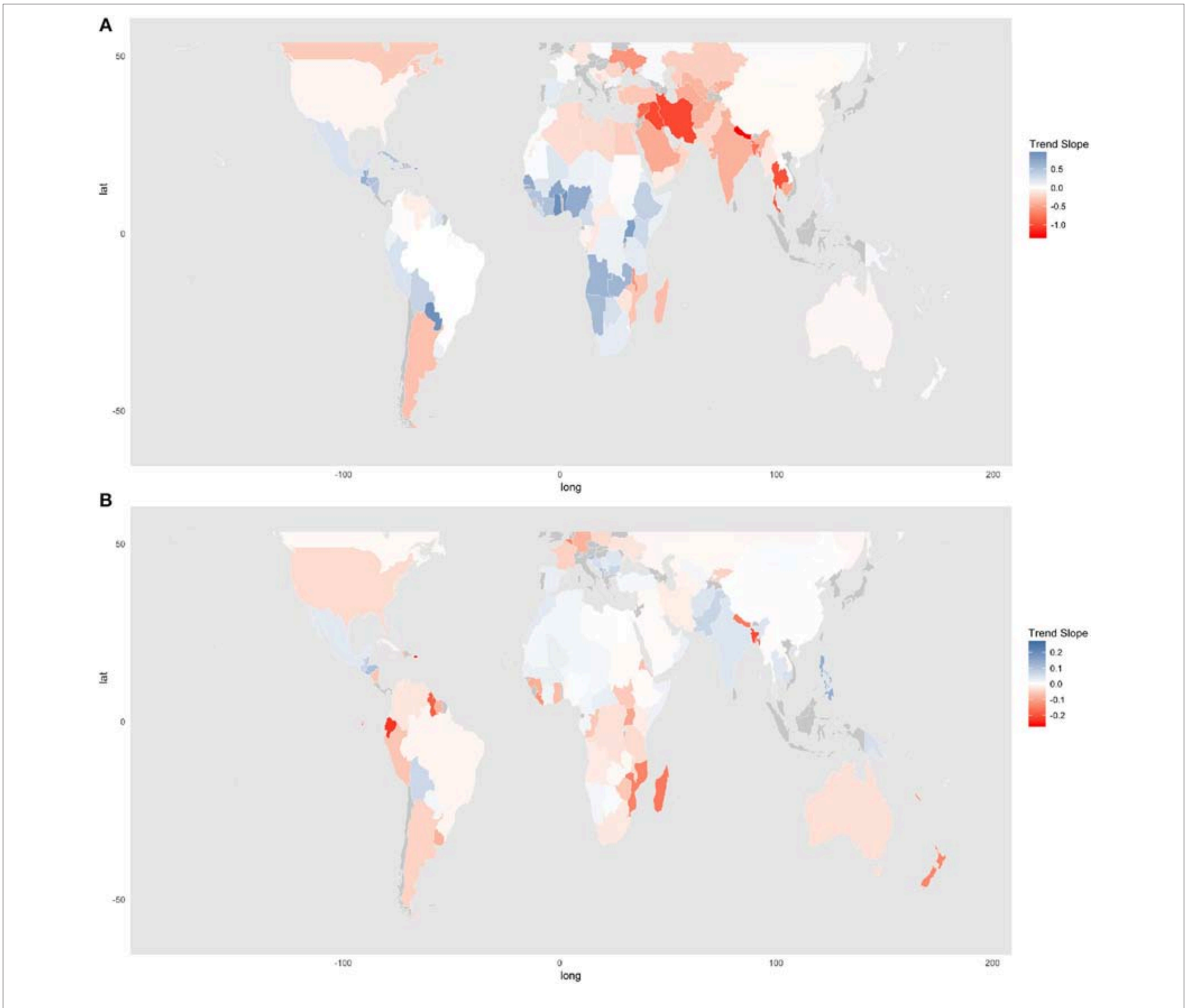

FIGURE 1 | (A) Seasonally Adjusted Country Level GRACE Trends (top), **(B)** Seasonally Adjusted Country Level GPCC Trends (bottom).

Figure 1 (bottom graph). Trends in precipitation over the period of GRACE record align with the GRACE trends in some regions, but in many regions there is no clear association between water storage trend and precipitation trend.

As another exploratory analysis of the input data we leveraged Principal component analysis (PCA)-biplot which is a powerful visualization technique for high dimensional multivariate data (Gower et al., 2011). A PCA-biplot can help create a low-dimensional representation of multivariate data using the first two principle components. In a PCA-biplot, vector lengths approximate standard deviations, and the cosines of their angles are proportional to the correlation between the variables. It can be seen in the biplot of the first two principal components of leading predictor variables, **Figure 2A**, that countries generally cluster by continent, with expected economic outliers, and there is a tendency for countries with negative GRACE water storage trends to cluster relative to countries with positive trends (**Figure 2B**). For instance, it is interesting to note from **Figure 2** (top) that the African countries (in red) tend to cluster around the increasing trends in land equipped for irrigation; while some of those countries (such as Republic of Congo) are already experiencing negative GRACE anomalies (**Figure 2**, bottom). Of additional note, in the first two principal components, Land Equipped for Irrigation (Average) and GPCC have nearly opposite vector directions. Suggesting that these two indicators may be inversely related to one another.

3. METHODOLOGY

Supervised machine learning is used to approximate an unknown function f to predict the response variable Y as a function of independent variables x. Mathematically, it be summarized as $Y = f(X) + \epsilon$; where ϵ is referred to as "irreducible error."

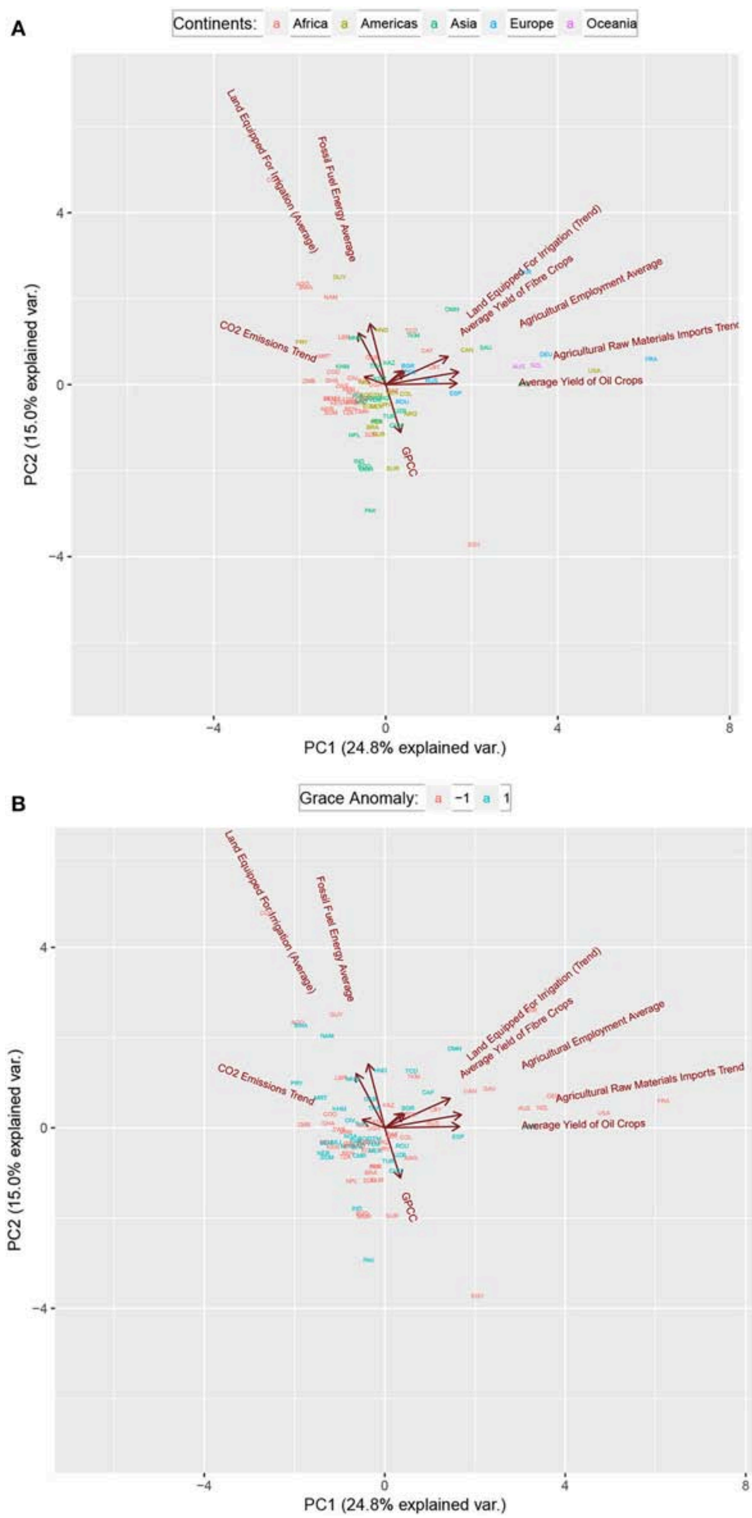

FIGURE 2 | (A) PCA-Biplot of input data, the countries are color-coded by continents, **(B)** PCA Biplots of input data, with color red indicating negative and blue indicating positive GRACE anomalies.

The goal of supervised learning is to use the training data to approximate the function $\hat{f}(X)$ such that the loss function of interest $L = \int \omega(X)\Delta[f(\hat{x}), f(X)]dX$ is minimized over the entire domain of input data; where $\omega(X)$ stands for a weight function and Δ denotes a measure of distance (Friedman, 1991; Hastie et al., 2001). Global parametric modeling—such as GLM—has been the most widely used technique for approximating $f(X)$. Global parametric models are popular due to their ease of computation and interpretability. However, such an approach is "rigid" (due to assumptions such as linearity, etc.). Its limited flexibility means that it often fails to approximate the true function accurately (Hastie et al., 2001).

To estimate GRACE anomalies and identify the most important predictors of global ground water storage trends, we tested the predictive performance of several classes of models such as generalized linear models (GLM) (McCullagh, 1984), generalized additive models (GAM) (Hastie and Tibshirani, 1990), artificial neural network (ANN) (Hastie et al., 2001), multivariate adaptive regression splines (MARS), support vector machines (SVM) (Drucker et al., 1997) and ensemble tree-based approaches such as Random Forest (RF) (Breiman, 2001), and Bayesian Additive Regression Trees (BART) (Chipman et al., 2010; Kapelner and Bleich, 2013). BART (Chipman et al., 2010; Kapelner and Bleich, 2013) was selected as our final best model due to its robust predictive performance. More specifically, the predictive models developed based on the BART algorithm outperformed the other models (i.e., GLM, GAM, MARS, RF, SVM, and ANN) in terms of both out-of-sample performance (i.e., based on 30-fold random holdout cross-validation tests on the data) and goodness-of-fit (i.e., based on in-sample errors and R^2 values). Each model was compared in terms of mean squared error on a held out set of data for each of the 30-folds of the cross-validation. The BART model had a Bonferroni corrected statistically significant mean squared error lower than the rest of the models. Moreover, BART's ability to yield probabilistic inferences and adequately characterize the uncertainties was another attribute of the algorithm that made it desirable for this analysis.

Bayesian Additive Regression Trees (BART)

BART is a Bayesian, ensemble, tree-based approach, capable of capturing complex interactions and non-linearities (Chipman et al., 2010). A BART model can be represented as the summation of the estimate from M small(shallow) trees:

$$Y = \Sigma_{j=1}^{m} g(X, T_j, M_j) + \epsilon \quad \text{where} \quad \epsilon \sim (0, \sigma^2) \tag{1}$$

Where Y represents the response variable, $g()$ denotes a regression tree. For each of the tree structures denoted by T_j, and its associated terminal node parameter denoted by $M_j = (\mu_1, \mu_2, ..., \mu_j)$. The function g assigns the conditional mean value μ to the vector of covariates, where μ can represents the main effects or interaction effects depending on the number of covariate(s). The trees are fitted via an MCMC algorithm (Chipman et al., 2010; Kapelner and Bleich, 2013). What makes BART different from other ensemble, tree-based methods is the Bayesian component; where prior probabilities are imposed on each tree such that all individual trees are "weak learner." This means that no one tree will dominate the final estimate. The application of a regularization prior prohibits the trees from growing too deep and over-fitting the data.

Model Inference

To conduct model inferencing based on BART, variable importance ranking (to facilitate variable selection) and partial dependence plots (PDP) can be generated. The ranking of the most important variable in BART can be identified by tracking the number of times a predictor has been used in a given tree and therefore contributing to the final prediction. Moreover, since BART is a non-parametric model, the relationship between the response and the predictors can be depicted via partial dependence plots (PDP). PDPs show the influence of the predictor of interest on the response, while the effect of all other variables are averaged as shown in the equation below.

$$\hat{f}_j(x_j) = \frac{1}{n} \Sigma \hat{f}(x_j, x_{-j,i}) \tag{2}$$

Where x_j is the predictor of interest and $x_{-j,i}$ are all the predictors in the model other than x_j and $\hat{f}_j$ represents the BART model. Partial dependence plots provide the effect of the predictors at different quantiles and provide a 95% confidence interval at each quantile. PDPs show the overall picture of how the predictor contributes to the model as it increases in quantile.

4. RESULTS

We developed predictive models of GRACE trends—using the BART algorithm described above—to identify the key predictors of water storage trends a national scale. The response variable in all models is a linear trend computed from GRACE Terrestrial Water Storage anomalies. This data was extracted from the 0.5x 0.5 degree gridded RL05 Mascon solutions from the Center for Space Research (Himanshu et al., 2016), downloaded from http://www.csr.utexas.edu/grace.

Given the stochastic nature of the BART algorithm, to achieve stability and convergence, The predictive models OF GRACE trends were fitted over 3,000 times, and in each instance the variable importance for the model was calculated. Analyses were repeated with Spherical Harmonics GRACE solutions and the character of results did not change. The features that consistently demonstrated high importance in these 3000 models are as follows:

- Rainfall (Trend): monthly total rainfall derived from the Global Precipitation Climatology Centre (GPCC) 0.5 x 0.5 degree monthly Full Data Product (V7). The Full Data Product is considered to be the most reliable GPCC product, and is available from 1901 to 2013. Gridded fields are generated using quality-controlled data from 67,200 stations with records of 10 years/longer (Schneider et al., 2016). GPCC Precipitation data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado from their website[1].
- Land Equipped for Irrigation (Trend and Average): This is the % agricultural land in a country that is equipped for irrigating crops. This does not mean that the entire area is actually irrigated at any point in time.

[1]https://www.esrl.noaa.gov/psd/ (accessed November 30, 2017).

- Agricultural Raw Material Imports (Trend): This represents the percentage of imports to a country comprised primarily of crude agricultural products such as vegetable oils, wood, cotton, raw animal, and vegetable products as defined in Standard International Trade Classification (SITC) section 2. Of note, it excludes crude fertilizers and minerals.
- Fiber Crops Yield (Average): This consists of the total land used in fibre crop production and the annual yield of fibre crop per country. Fibre crops include cotton, jute and kenaf, hemp, flax, coir, sisal, henequen, and abaca. It has been estimated that per ton of fibre crop produced 3,837 cubic meters of water are used, nearly 10 times higher than that required for one ton of vegetables (Van Dam and Bos, 2004).
- Oil Crops Yield (Average): This includes the yields and total land area in production of oil crops. The most important of these crops are oil-palm, soybean, sunflower, and rapeseed. Oil-crops are known to have a very high water footprint (2,400 m^3/ton).
- Agricultural Employment (% Average): This indicator represents the percent of employed persons who work in the agricultural sector. Employment here means people of working age working to earn money. Agricultural sector includes farming, hunting, fishing, and forestry.
- CO_2 Emissions (Trend): This indicator measures changes in CO_2 emissions within a country during the time period in question. CO_2 emissions are measured in KiloTons. The World Bank collects this data from the Carbon Dioxide Information Analysis Center, Environmental Sciences Division, at Oak Ridge National Laboratory.
- Fossil Fuel Energy Use (% Average): This indicator represents the average percent of total energy comprised of Fossil Fuels. Fossil fuels here refer to coal, petroleum, natural gas, and oil products. Total energy, according to the World Bank "refers to the use of primary energy before transformation to other end-use fuels (such as electricity and refined petroleum products)."

These consistently most important variables can be clustered into four main groups: Climate, Irrigation, Agriculture, and Energy. These groupings and the variables associated are:

Climate	1) The trend in monthly total rainfall derived from the Global Precipitation and Climatology Centre (GPCC)
Irrigation	2) The decadal average of land equipped for irrigation expressed as a percentage
	3) The trend in the percent of land equipped for irrigation
Agriculture	4) The trend in agricultural raw material imports as a percent of merchandise
	5) The Average Annual Yield of Oil Crops (Soybeans, Coconuts, Oil Palm, Olives, etc.) in hectograms/hectare
	6) The Average Annual Yield of Fibre Crops (cotton, hemp, flax, etc.) in hectograms/hectare
	7) The percent of the population employed in the agricultural sector
Energy	8) Percent of energy consumption generated by fossil fuels
	9) Trend in CO_2 emissions

Investigating the partial dependence plots for these variables in **Figure 3** provides further insight into the relationship between these variables and GRACE trends.

GPCC: Intuitively, countries that experienced an increase in precipitation over the period of GRACE record tend to show increases in total water storage. It is a reasonably symmetric relationship, in which increased (decreased) precipitation is associated with increased (decreased) water storage up to a threshold, beyond which additional precipitation increase (decrease) has no significant impact. Another rainfall measure, the Tropical Rainfall Measurement Mission (TRMM) Multisensor Precipitation Analysis (TMPA) (Huffman et al., 2007), was also tested with consistent results.

Average Land Equipped for Irrigation: The negative relationship between land equipped for irrigation and water storage indicates that the capability to irrigate is associated with reductions in water storage. The relationship indicates that countries with a low percentage of irrigated land have positive water storage trends. However, countries where greater percentages of agricultural land relies on irrigation, have increasingly negative water storage trends.

Trend in Land Equipped for Irrigation: Interestingly, increases in irrigated area over the GRACE record are associated with an increase in total water storage. This is counter-intuitive, and could reflect the presence of time lags between the implementation of irrigation and potential long-term impacts on water resources. Countries that are actively adding irrigation infrastructure currently have adequate water resources to supply them in the short term.

Trend in Agricultural Raw Material Imports: Countries with rapid growth in their agricultural sectors see increases in the amount of agricultural raw materials required to maintain this growth. This variable distinguishes between countries that are rapidly decreasing raw materials imports (near zero on partial dependence) with those in the more normal range. Within this normal range the more a country increases its agricultural raw materials imports the more likely it is to be experiencing water storage declines. This can be seen as an indicator of how fast a country is growing its agricultural sector or how much a country is decreasing its reliance on domestic agriculture.

Average Yield of Major Crop Types: Interestingly, there are systematic differences in the relationship between water storage trend and yield of various crop types. For oil crops the relationship is positive, where higher yields occur in countries with positive water storage trends, possibly because high yielding

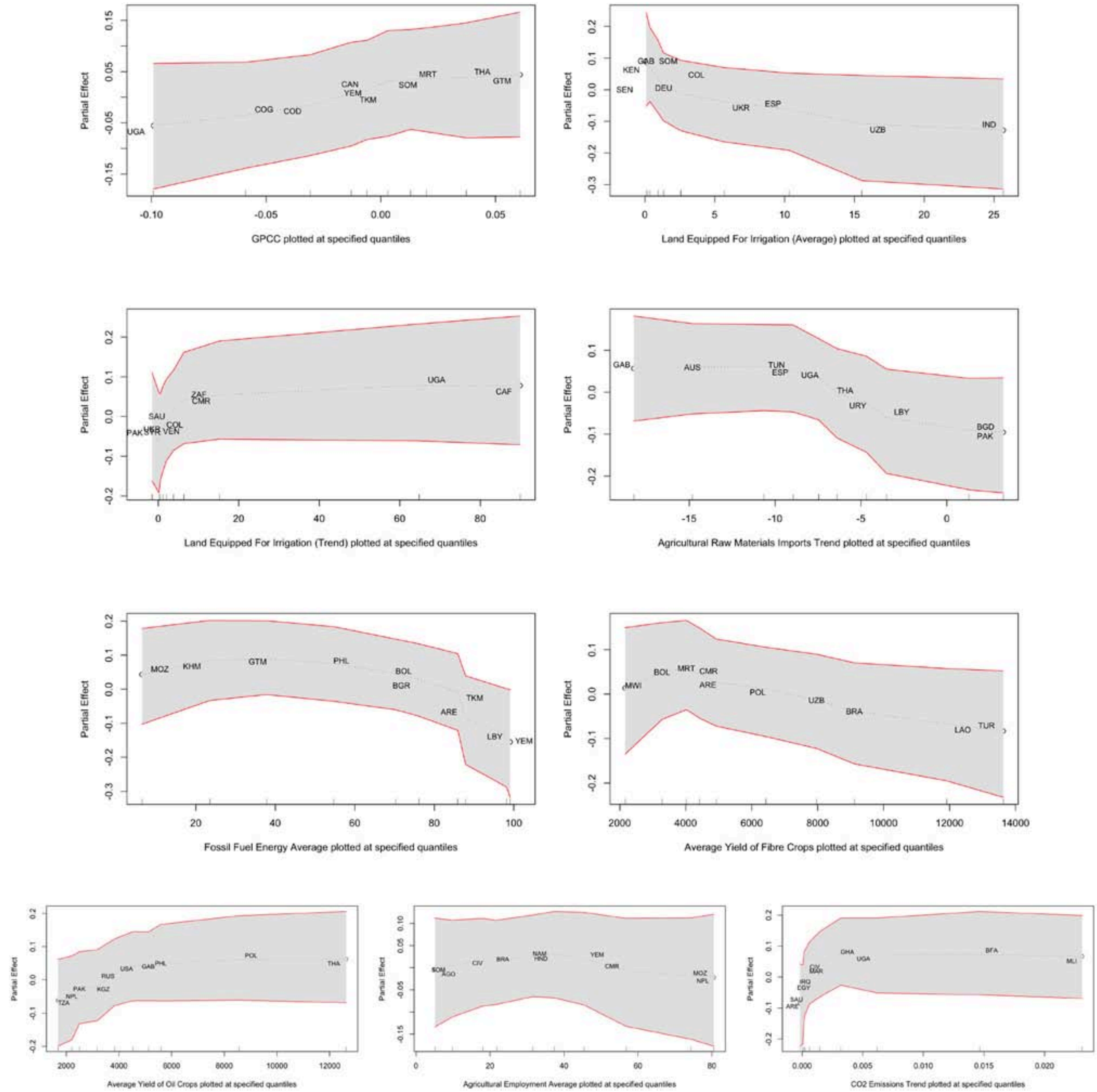

FIGURE 3 | Partial dependence plots for most important predictors. Country codes appearing on the plots relate to which countries have a value closest to that particular quintile.

oil crops are planted in humid areas that are not prone to water deficit. For fibre, higher yield is associated with water depletion. This could be because fibre crops tend to be irrigated and are very water intensive.

Fossil Fuel Use: This variable indicates that countries that are heavily reliant (greater than 80%) on fossil fuel as a sole source of energy for example, United Arab Emirates (ARE) and Khazakstan (KAZ) are more likely to be experiencing ground water storage declines. For the rest of the countries there isn't a clear relationship. Intuitively there should be no direct relationship between fossil fuel use and groundwater depletion. However, countries that have high percent of energy from fossil fuels might be have a lower cost of fossil fuels than other countries (e.g., fossil fuel providers) therefore it could be cheaper to use said fossil fuels in water pumping systems. Further investigation into the local economies would be required to show this effect more precisely.

Average Percent Agricultural Employment: Countries with low percent and high percent of their workforce in the agricultural sector tend to have negative GRACE trends. However, the effect is not great in any of the quintiles. Nonetheless this feature is consistently important across model iterations. One possible explanation is that this feature is interacting with other features in a meaningful manner. Perhaps this is because this feature is a proxy for several indicators. On the one hand it can be a sign of the net agricultural capacity of a country. If a country has little agricultural capacity, very few people will be employed in agriculture. At the same time, highly technological countries can also have low agricultural employment even if its net output is high.

CO_2 Emissions Trend: This variable may indicate a growth in industry and development over the period of GRACE observations. Particularly, this was highest in countries where there was little CO_2 emissions at the beginning of period of observation. Those countries appear to be in places where water resources have been increasing. This appears to be the case for countries in West Africa that both experienced a rapid economic growth and an increase in rainfall during this same period. However, effect is fairly limited across all quintiles and it is likely that this feature is interacting with other features more than it is directly contributing to explaining GRACE trends.

5. DISCUSSION

Changes in climate, population growth, urbanization, and industrialization have made fresh water access a global concern. Countries are increasingly relying on groundwater for population and agricultural needs. However, given groundwater storage system complexity, it has been difficult to ascertain the impacts of these withdrawals. Data from the Gravitational Recovery and Climate Experiment satellites have been used at local scales (individual countries and watersheds) to demonstrate that subsurface groundwater can be effectively monitored. Researchers had long hypothesized that where groundwater shortages had been identified, human use played a large role (Rodell et al., 2009). Recent research using GRACE data has shown that land equipped for irrigation helps to explain variability in GRACE observed trends not explained exclusively by rainfall and climate model predictions (Rodell et al., 2018). The work presented here extends this research, confirms the impact of these human factors and further defines the specific anthropogenic factors that contribute the most to these trends.

The food-water-energy nexus is a valuable paradigm through which to view the inter-relatedness of these human and environmental systems[2]. Within this paradigm, water access, energy prices, and crop choice play a significant and highly interconnected role. Our research further demonstrates this approach. Of the top most important anthropogenic variables used to predict water storage trends, crop choice, fossil fuel energy use and irrigation play the biggest role. Not surprisingly, irrigation leads these factors, as agricultural and irrigation accounts for 69% percent of global water withdrawals, with higher percentages in countries with limited surface water[3]. Additionally, with fossil fuel energy, deep groundwater extraction requires significant energy as pumps are largely driven by electricity or fossil fuels. Water scarce countries that also rely on fossil fuels for a significant portion of their electricity may be more likely to have energy subsidies in place and therefore it can be theorized that there is a lower barrier for the extraction of deep aquifers (Zhu et al., 2007) to enable economic development in their agricultural sectors.

Due to different water requirements, crop choice plays a logical role in how much water is required by a nation's agricultural system (Mekonnen and Hoekstra, 2011). Furthermore, specific crops show a generally negative relationship with water storage trends, such as fibre crop yields. Fibre crops are resource intensive, and farmers may switch to fibre crops if they command higher market prices than alternatives (Yang et al., 2017). Furthermore, we show that commonly thought drivers such as population density, forested land and GDP do not contribute significantly to models predicting terrestrial water storage trends. These variables might show correlation with water storage when considered independently, but they do not offer explanatory power when variables related to agriculture and energy are also taken into account.

While this study provides good evidence for the anthropogenic factors in water storage trends, there are several limitations. First, the country level statistics used for covariates could contain errors or inconsistencies due to collection methods as well as missing data due to geopolitical changes. Second, there is an obvious mismatch between the gridded scale of the GRACE and GPCC data with the country level statistics. This was resolved by taking the average GRACE and GPCC signal at the country level across grid-cells. This is particularly problematic for large countries with internal variance of water storage trends (i.e., USA, Russia, and China). Third, the means by which variables are selected by the BART model favors those variables which give the cleanest lift to the overall model. This means if two variables are correlated to one another, the one with the stronger signal will be overweighed while the other will be dampened. This impacts interpretation of variable importance. While the top variables are consistent, it's important to avoid over-attributing meaning or policy decisions to some of the features with lower effects. Fourth, we were limited in taking a truly global view because we had to avoid high latitude countries due to cryosphere effects. It is known that snow and mountain glaciers can affect TWS and snow melt was not addressed by this study. Fifth, while data-driven models do not directly account for physical processes, they can be complementary to dynamical systems models. This is because data driven models—such as the one proposed in this study—are more computationally efficient; and by mining dependency mechanisms between highly-dimensional complex data, they can help formulate additional hypotheses to be tested

[2]http://www.unwater.org/water-facts/water-food-and-energy/ (accessed December 04, 2017).

[3]http://www.fao.org/nr/water/aquastat/water_use/index.stm (accessed December 04, 2017).

through dynamical systems modeling frameworks. Lastly, while the number of covariates was extensive, we do not rule out that there are other significant drivers of water storage not explored here.

Further research is needed to explore additional variables and their impact on water storage trends. For instance, livestock data was not included in this analysis, as their direct consumption of water is limited. However, the virtual water required per pound of meat is much higher than per pound of plant matter. Additionally, incorporating hydrological information and downscaling from country level to watershed levels would help researchers get an even better understanding of how climate, hydrology and human-landscape interactions affect water storage. While this is difficult given the lack of granular data on local agriculture, other remote sensing techniques could be combined with the GRACE satellite data to estimate agricultural production and irrigation at finer grid scales and move away from country level statistics.

In brief, this work extends existing research into the observable changes in groundwater storage trends globally by bridging the gap between global scale analysis and local basin scale. By looking at national trends we are able to utilize commonly collected statistics by non-Governmental Organizations. Using the statistical methods outlined above we are able to model the complex relationship between different types of human factors related to groundwater trends and show that certain human factors related to the food-water-energy nexus have a stronger relationship to groundwater storage trend than others. This effort lays a foundation for additional follow-up case studies in specific countries with the appropriate data available that would both validate the statistical results laid out here as well as provide more detail required for resource management decisions.

AUTHOR CONTRIBUTIONS

CB completed data collection, preprocessing, analysis, and inferencing. BZ implemented data collection, guided the study, and assisted in result analysis. RN contributed to the analysis. All authors reviewed and edited the manuscript.

ACKNOWLEDGMENTS

The authors would like to acknowledge NSF (#1555582), NSF HDBE (#1826161), NASA (NNX16AF12G), Purdue Climate Change Research Center (PCCRC), and Purdue University Libraries Open Access Publishing Fund.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2019.00085/full#supplementary-material

Table A1 | Complete list and data sources of country level indicators used as inputs to BART model.

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Conflict of Interest Statement: CB was employed by company Capital One.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Environmental Science

POLICY AND PRACTICE REVIEWS
published: 02 July 2019
doi: 10.3389/fenvs.2019.00084

Can the Implementation of the Water-Energy-Food Nexus Support Economic Growth in the Mediterranean Region? The Current Status and the Way Forward

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OPEN ACCESS

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Specialty section:
This article was submitted to Freshwater Science, a section of the journal Frontiers in Environmental Science

Received: 23 June 2018
Accepted: 27 May 2019
Published: 02 July 2019

Citation:
Markantonis V, Reynaud A, Karabulut A, El Hajj R, Altinbilek D, Awad IM, Bruggeman A, Constantianos V, Mysiak J, Lamaddalena N, Matoussi MS, Monteiro H, Pistocchi A, Pretato U, Tahboub N, Tunçok IK, Ünver O, Van Ek R, Willaarts B, Bülent S, Zakir T and Bidoglio G (2019) (2019) Can the Implementation of the Water-Energy-Food Nexus Support Economic Growth in the Mediterranean Region? The Current Status and the Way Forward. Front. Environ. Sci. 7:84. doi: 10.3389/fenvs.2019.00084

Water resources is a crucial environmental good for the function of the human societies and the ecosystems. Moreover, water is an important input for the economy and an indispensable factor for economic growth. Especially in regions that are facing water scarcity, the adoption of water management policies and approaches fostering the sustainable use of resources while promoting economic growth becomes an emerging issue. The Mediterranean region is one of the most vulnerable regions regarding the availability of water resources due to climate change and human activities. The Water-Energy-Food (WEF) Nexus offers an integrated approach analyzing the synergies and trade-offs between the different sectors in order to maximize the efficiency of using the resources, whereas adapting optimum policies and institutional arrangements. The Mediterranean is a region where we observe a large spectrum of issues emanating from water pollution and natural resource degradation to water scarcity, large amounts of food loss and waste and increasing demand for energy and food. Agricultural practices, urban development, demand management for water, and protection of ecosystems, particularly aquatic ecosystems, are areas of particular intervention available to the decision-makers in enhancing availability of water for the various water using sectors. In this context, the current policy note paper aims to address a major issue: how can the implementation of the WEF

Nexus support the economic growth in the Mediterranean? Based on the outcome of an experts and stakeholders regional workshop, this paper presents the current status, including the opportunities and the practices of applying the WEF Nexus in the Mediterranean and draws specific recommendations for the way forward. Regarding the later, the strengthening of WEF Nexus in the Mediterranean requires a set of interventions to strengthen the institutional capacities, to enhance the finance mechanisms, to support the intra-regional dialogue as well, to enhance data collection and management, as well as to implement economic instruments and integrated economic approaches to measure the impact of Nexus into economy and employment.

Keywords: economic growth, Water-Energy-Food Nexus, Mediterranean, water policy, economic instruments, recommendations, opportunities, integrated approach

INTRODUCTION

Water is inextricably linked to energy and food production. Energy depends on water for power generation, the extraction, transport and processing of fossil fuels, and the irrigation of biofuel crops [International Energy Agency (IEA), 2012]. At the same time, water provision depends on energy for its abstraction, purification and distribution (Copeland, 2014). Food production needs water, productive land and energy to grow crops, maintain livestock, and process food. Food waste can also be used to generate energy via anaerobic digestion. Such bi-directional links are further complicated by the sector-specific externalities that modify the physical or chemical characteristics of water and alter water flows. The structural modification of water courses resulting from their use for energy can impair their integrity, alter water flows and negatively affect the health of rivers. Farming byproducts that are released into surface and groundwater bodies lead to the contamination of water resources and the degradation of ecosystems.

This web of mutual interlinkages defines the Water-Energy-Food (WEF) Nexus. Given that societal changes drive the growth WEF demand, and that ongoing environmental changes are likely to alter the availability or accessibility of water, the WEF Nexus is central to natural resource management and climate change policies. Coping with the WEF Nexus requires that the multi-sectoral use of water be reconciled and brought into line with the restoration and/or preservation of river (basin) integrity. Compared to integrated water resources management (IWRM), the WEF-Nexus puts emphasis on non-linear system analysis and dynamic feedbacks across water-intensive sectors (**Figure 1**). Over the past decade, the body of knowledge positioning water in the WEF Nexus has increased substantially.

Several concepts, frameworks and methodologies have looked at the interlinkages between water, energy and food (Mohtar and Daher, 2012; Bizikova et al., 2013; Benson et al., 2015) using a Nexus approach. Scott et al. (2015) provide a comprehensive definition of the WEF Nexus, including the basic interactions as well as institutional and policy implementation issues. The Food and Agriculture Organization of the United Nations (Food Agriculture Organization of the United Nations, 2014) developed a conceptual approach to the WEF Nexus, balancing different user goals and interests in support of food security, sustainable agriculture and human development. In addition to the importance of welfare in the Nexus approach, Ringler et al. (2013) include the environmental impact when analyzing the interactions and balance between water, energy, land and food. In an effort to explore the green economic growth potential of a Nexus approach, the paper of Hoff (2011) presents initial evidence on how a nexus approach can enhance water, energy and food security by increasing efficiency, reducing trade-offs, building synergies and improving governance across sectors.

While integrated, holistic approaches to resource management and sectoral planning have been largely embraced by stakeholders and decision makers, and although the benefits of the WEF approach may appear obvious to its advocates, the Nexus concept still needs to be appropriated beyond the academic domain. At the EU policy level, the WEF Nexus is considered in the Renewable Energy Directive, the Green Infrastructure Communication, and (arguably) the Common Agricultural Policy (CAP). Indeed, most studies and papers have focused on assessments and analyses of the WEF Nexus, reaffirming the importance of the concept, but there is still a lack of concrete examples of the actual implementation of such an approach. In that context, a number of organizations, including the JRC, the FAO, the United Nations Economic Commission for Europe (UNECE), the Centre International de Hautes Études Agronomiques Méditerranéennes (CIHEAM), Plan Bleu, Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), Global Water Partnership (GWP) have recently been piloting Nexus approaches through modeling, assessment, dialogue, assistance to policy making, and technical applications, testing new methodologies; most of these are work-in-progress, with actual results and lessons learned pending. Importantly, key regional and sub-regional multilateral institutions have been addressing or have expressed an interest in exploring the Nexus approach, including the European Union (EU), the Regional Cooperation Council (RCC), the League of Arab States (LAS), Union for the Mediterranean (UfM), and the Barcelona Convention (MAP UNEP). Some highlights from these initiatives and programs are presented in **Table 1**.

In order to move from concepts to implementation, it is necessary to identify the economic sectors of the Nexus that

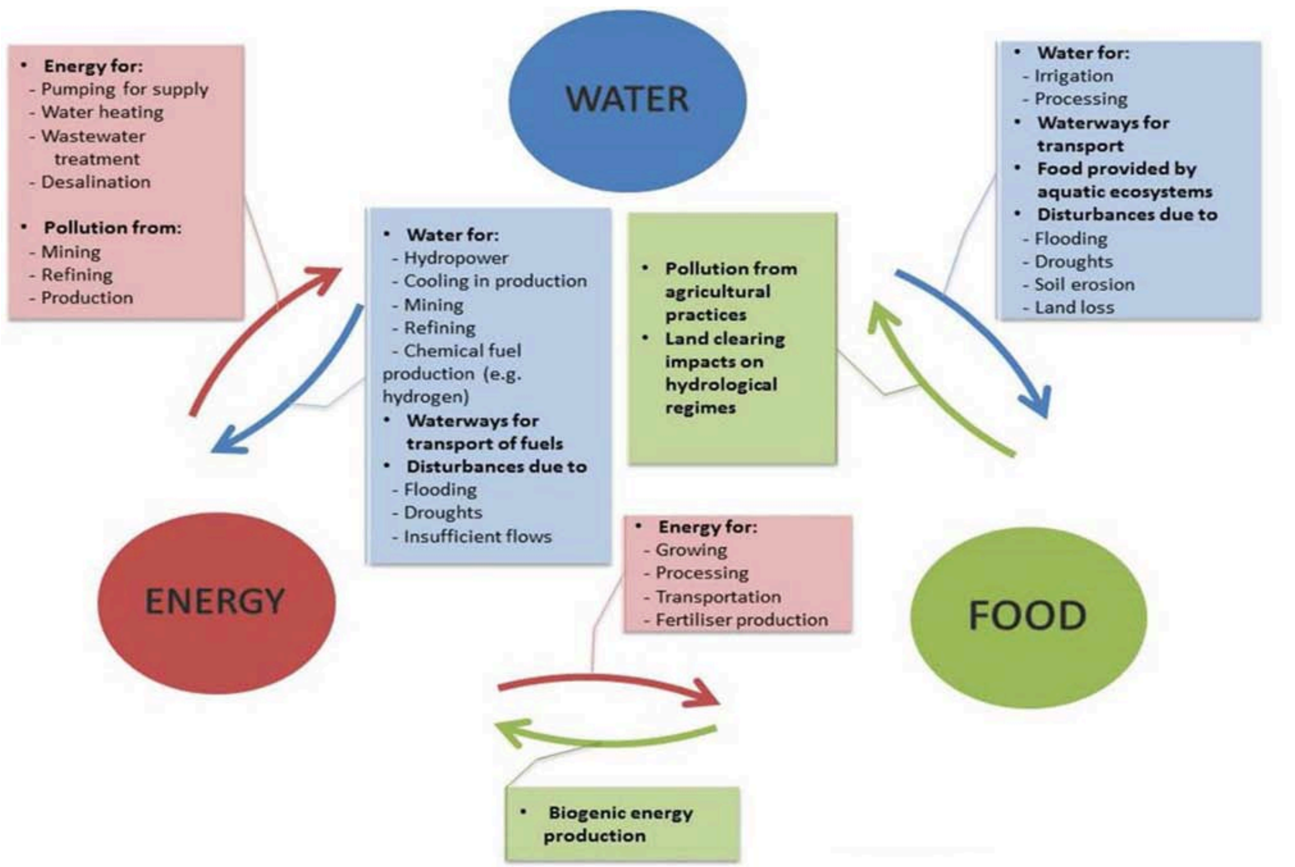

FIGURE 1 | The WEF Nexus concept. Source: IW: LEARN, Germany and GWP-Med, 2014.

can benefit from a change in the planning process. This is the main topic of the present policy note, which aims to analyze the potential of a WEF Nexus approach to create economic growth. The focus is on the Mediterranean region, an area under threat of water scarcity due to climate variability and change, population growth, developmental pressures and consequent imbalanced water allocations by different sectoral water users, and where demand for food and energy is expected to increase in the coming decades. We analyze specific economic options, policy setting and institutional arrangements that, if incorporated into a WEF Nexus approach, could contribute to sustainable economic growth in this region. The content of this paper is based on the outcomes of the Workshop "Can implementation of the Water Nexus support economic growth in the Mediterranean region?" held in Ankara, Turkey, on 12–13 February 2015.

In the first section, we gather evidence on the opportunities for adopting the WEF Nexus in the Mediterranean region. Water resources are particularly limited and vulnerable to pollution and weather extremes in the Mediterranean countries. Despite water scarcity and land degradation, agricultural practices do not represent sound, sustainable practices, and a significant proportion of food remains lost or wasted in the food value chain. Moreover, environmental protection is occasionally in conflict with economic growth. The integrated perspective provided by the WEF Nexus may help to meet the needs of different water uses and ecosystem protection, by stimulating appropriate investments in the Mediterranean region, based on consistent and effective cross-cutting water, energy and food policies. Nexus interdependencies should also be taken into account for improved designs of water tariffs for domestic, agricultural, and industrial water uses in the region. In the second section, we discuss the barriers hampering the adoption of a cross-sectoral perspective for integrated water management. The discussion focuses on administrative, legislative and market-related barriers (transaction costs, interest groups, constraints due to limited water property rights, tariffs, subsidies etc.). "Good" and "bad" practices linking water-energy-food security and ecosystem protection to investments, jobs creation, innovation, and competitiveness in the Mediterranean region are identified, taking account of feasibility in terms of the presence or absence of an enabling environment, potential for growth, implementation and transaction costs, actors involved, and financial risks. The final section of this paper provides specific recommendations and suggests a way forward for implementing the WEF Nexus in the Mediterranean area. This section explicitly covers institutional, economic and policy aspects that would facilitate a better

TABLE 1 | International WEF nexus initiatives and programs.

Organization	Initiative/Program	Source
European Union	Partnership for Research and Innovation in the Mediterranean Area (PRIMA)	http://ec.europa.eu/research/environment/index.cfm?pg=prima
JRC—European Commission	Monitoring tool linking the Water-Energy-Food Nexus and Sustainable Development Indicators for the Mediterranean Region	https://ec.europa.eu/jrc/en/science-update/new-monitoring-tool-developed
FAO	The Nexus Assessment	http://www.fao.org/3/a-i3959e.pdf
	WEF Nexus rapid Appraisal tool	http://www.fao.org/energy/water-food-energy-nexus/water-energy-food-nexus-ra/en/
CIHEAM	Various research and education programs and tools	http://www.iamb.it/about/bari_institute/l&w
Plan Bleu	Various activities	http://planbleu.org/en/1st-edition-avitem-workshops-resources-and-urban-development-mediterranean-nexus-water-energy-food
GWP	Country-level pilots	https://www.gwp.org/en/we-act/themesprogrammes/Nexus-Water-Food-Energy-Ecosystems/
GIZ	Nexus Dialogue Programme	https://www.nexus-dialogue-programme.eu/

implementation of the WEF Nexus. We discuss in particular how to improve governance and collaboration among stakeholders and between stakeholders and governments, in order to optimally tap the potential added value that the Nexus can bring to the economic growth of the Mediterranean region.

WEF NEXUS OPPORTUNITIES IN THE MEDITERRANEAN REGION

The Mediterranean is a diverse geographical area of different economic, social, political and environmental conditions. In recent decades, several policies and programs have striven for the more efficient use of natural resources and enhanced sustainability in agricultural production and food systems at country, sub-regional and regional levels. In general, however, as in most other regions in the world, water, energy and food production have historically been managed separately, with little consideration of cross-sectoral interactions. During the past decade, there has been an effort to introduce IWRM in regional, sub-regional and national policies, with a certain level of success. Overall, although the terms and provisions of the IWRM were introduced into laws and policies, practices have not advanced accordingly. At the same time, integrated approaches in the food sector have advanced, including toward more "crop per drop" and more "crop per Kwh." Much of the new investment in the region was put into the energy sector, as an engine for development. Although such cross-sectoral approaches are currently not systemically incorporated in decision making, strong opportunities in this direction are being made available at the level of economic, public policy and institutional arrangements.

For instance, Daccache et al. (2014) modeled, mapped and quantified the links between irrigation demand, crop production and energy consumption in Mediterranean irrigated agriculture. Garrido et al. (2010) explored opportunities to alleviate water scarcity and increase water productivity of Spanish agriculture by reallocating agricultural water toward more productive crops. Siddiqi and Anadon (2011) developed a Water-Energy Nexus approach to estimate the energy demands for freshwater supply in the Middle East and North Africa. In their review paper addressing water desalination in a Nexus perspective, Bazilian et al. (2011) concluded that the benefits of a holistic WEF Nexus would include better economic development conditions and overall welfare optimization of society in the Middle East and North Africa.

A WEF Nexus at the Mediterranean could be developed within multiple frameworks, such as the Post-2015 development agenda, the United Nations Framework Convention on Climate Change (UNFCCC), Union for the Mediterranean (UfM), Barcelona Convention (MAP UNEP), Regional Cooperation Council (RCC) contexts. In such cases, the Nexus can provide an analytical and innovative framework (complementing a new policy perspective) and a design principle for water, energy and food security policy. Research and development (R&D) could be an initial step in applying a WEF Nexus agenda, building on future planned actions, such as Horizon 2020 and the COST Action, and including the active involvement of the private sector.

A number of regional partners of various backgrounds, constituencies, and areas of focus, have launched and/or advanced regional programmes and initiatives that contribute to building mechanisms that support the Nexus approach at various levels. For instance, UfM, International Center for Advanced Mediterranean Agronomic Studies (CIHEAM), Center for Mediterranean Integration (CMI), Global Water Partnership-Mediterranean (GWP-Med), Association of Agricultural Research Institutions in the Near East & North Africa (AARINENA), and Plan Blue are some of these partners with various strategies to support Nexus perspectives toward sustainable development in the Mediterranean region. Further opportunities emerge in building cooperative agreements and dialogue platforms (established already by Plan Blue and UfM). In this context, Plan Blue has initiated a dialogue with many partners, which is already meeting the multi-disciplinarily perspective of the Nexus framework. As a starting point, a

Nexus-oriented platform for dialogue requires a road map and action plan supported by governments and stakeholders, which can be applied at regional, sub-regional, national, basin, or transboundary level. In this dialogue platform, all relevant actors (the public and private sectors, knowledge institutes and NGOs) should be included through a participatory approach. The Nexus dialogue can be also a strategic starting point for capacity-building activities and agreements to share data and information systems, as already set up in the Blue plan-SIMEDD database (the Mediterranean Information System on Environment and Development). However, due to the specific conditions of the region/sub-regions, it may be difficult to involve all the countries and establish a dialogue network along the lines of WEF sectors.

Food waste and changing dietary habits have large effects on the Nexus, which as yet have not been accounted for (Vanham et al., 2015). Lundqvist and Unver (2018) argue that commitments, such as those through SDGs cannot be treated in isolation from one another and alternative pathways chosen to attain them, as in the water and food systems, can take us to different, unintended ends. Throughout the Mediterranean region, ongoing dietary shifts are mostly translating into a move from vegetables, fruits, and legumes toward increased consumption of animal protein and sugar products. Such a movement away from the healthy Mediterranean diet has significant implications for water and energy use. As López-Gunn et al. (2012) described, dietary shifts of Spanish consumers have led to an increase in water consumption by 8%, while a shift to a Mediterranean diet could potentially lead to a saving of 750 liters/person/day in Spain (Blas et al., 2019). Such an increase not only adds to the pressure on existing water and land resources, but also poses a challenge from a health perspective. It is estimated that around 30% of food is wasted along the production, processing and consumption chain. FAO (http://www.fao.org/fileadmin/user_upload/newsroom/docs/water_facts.pdf) provides a rough, average figure of one liter of water to produce one Kcal of food energy. The following is an example of a simple computation of water consumption in the Apulia region (southern Italy), which has a population of around four million people: considering that every person needs around 2,000 Kcal/day, and 30% of food is wasted, we have:

$$2,000 \text{l/person/day} \times 0.30 = 600 \text{l/person/d}$$
$$600 \times 4,000,000 : 1,000 = 2,400,000 \text{m}^3/\text{d}$$
$$2,400,000 \times 365 = 876,000,000 \text{m}^3/\text{year}$$

Hence, around 875 million m^3 of water are lost every year, which corresponds to the total annual irrigation requirements for all the crops in the region.

Footprint assessments of natural resources, including water (Garrido et al., 2010; Dumont et al., 2013), have proven to be an effective tool for exploring options for their reallocation among sectors and promoting economic development. Also, such accounting for water facilitates exploration of the impacts of policy measures on water resources and the environment. For instance, Salmoral et al. (2011) showed that agricultural subsidies that aim to promote the productivity of woody crops, such as olive trees in southern Spain, have led to increased groundwater abstractions for olive irrigation (an historically rain-fed crop) and increased pressure on local groundwater resources. Wichelns (2003) studied the role of public policy in motivating virtual water trade, stating that "countries in water-short regions may gain from trade by importing water-intensive crops, while using their limited water supply for activities that generate greater incremental values." In the case of Egypt, he tried to identify the best policy to fit Egypt's water-scarce yet highly productive agriculture sector. When planning which crops to invest in, farmers will most likely favor crops that give a high return on land value rather than on water value, irrespective of a better national option to import virtual water. Consequently, an understanding of the impacts of agricultural/food security and macro policies at the farm level can help to better formulate virtual water policies.

Novo et al. (2015) explored existing barriers and the government's reluctance to take action to halt illegal groundwater use and adopt a Nexus approach to conciliate agricultural and environmental water use in the Upper Guadiana Region of Portugal and Spain. Their study showed that the largest share of the agricultural water footprint in the area is due to illegal groundwater use, which is contributing to unbalance the aquifer dynamics and causing large environmental trade-offs in a nearby wetland. Actions to halt this illegal water use, however, have been scarce, to a large extent because this region generates the largest farm revenues and is a major source of local employment. This situation largely explains the complexities surrounding the illegal use of groundwater resources and the reluctance of regional managers to take action in promoting a Nexus approach. Considering the energy dimension in groundwater pumping and transfer for irrigation aiming at optimizing uses, is within the Nexus approach pursues.

GLOBAL NEXUS PROGRAMS AND EXAMPLES FROM OTHER REGIONS

A glimpse of the developments both globally and in regions provide the interest by the stakeholders and the potential for implementation. A recent review commissioned by Nexus Regional Dialogue Programme (Aboelnga et al., 2018) identifies a number of frameworks into which Nexus approaches can be incorporated as well as case implementations from various regions. The opportunities include Sustainable Energy for All (SEforALL, 2018) initiative launched by the former UN Secretary General Ban Ki-Moon to facilitate the achievement of SDG 7 (Ensure access to affordable, reliable, sustainable and modern energy for all), which uses a Nexus approach in its High Impact Opportunities platform to engage multiple stakeholders. The World Bank Group's Thirsty Energy Initiative (World Bank Group, 2018), United Nations Economic Commission for Europe's (UNECE, 2018) transboundary basin assessments, and United States Agency for International Development's Grand Challenges for Development initiative (USAID, 2018) each uses a Nexus approach in assessing co-benefits and trade-offs and engaging stakeholders in selected implementation projects in different regions. The current portfolios include

South Africa, China and Morocco in the World Bank initiative; Alazani/Ganykh, Sava, Syr Darya, Isonzo/Soča, and Drina river basins in UNECE transboundary assessments; and two of the ten grand challenges of the USAID programme. The United Nations Economic and Social Commission for West Africa [United Nations Economic Social Commission for Western Asia (UN-ESCWA), 2017] lists a number of initiatives and arrangements in the Middle East and North Africa (MENA) region that use a Nexus approach, under the frameworks of the League of Arab States, the Arab Ministerial Water Council, and Arab Ministerial Council for Electricity.

Providing more evidence on global practices a recent JRC report (Barchiesi et al., 2018) presents examples of implementing the Water-Energy-Food-Ecosystems (WEFE) in various geographical regions: Africa, MENA and the Arab region, Central Asia, Latin America and the Caribbean. The paper of Gulati et al. (2013) explores the impacts of energy and water costs on food security in South Africa. Flachsbarth et al. (2015) explore the interlinkages between food production, water use and ecosystem services trade-offs in Latin America. In a similar way, Rasul (2014) developed a WEF Nexus approach for sustaining water, energy and food resources in South Asia, while preserving upstream river basin ecosystem services. Providing a different spatial view, Lawford et al. (2013) analyze the potential for advancing water sustainability, increasing understanding and collaborative governance approaches. Recently, Karabulut et al. (2016) evaluated the water provisioning services in the Danube, giving a spatially explicit quantification of the amounts and economic values of water used by the food, environment and energy sectors, with the aim of better understanding the trade-offs between the water needs of the different sectors.

PRACTICES IN AND BARRIERS TO IMPLEMENTING A WEF NEXUS APPROACH IN THE MEDITERRANEAN

In this section, we analyze the emerging practices and conditions that either enhance or hamper the adoption of a cross-sectoral perspective for natural resource management as a particular sector of the WEF Nexus. In this context, we study the Mediterranean region with a focus on the Water perspective, including water market functions, technical considerations on the available data, trade-offs within the product supply chain, institutional barriers and governance arrangements. We then present specific "good" and "bad" practices that can influence the adoption of the WEF Nexus.

In economic terms, water is characterized as a common good that has no substitutes. The fair distribution of this particular resource is governed by social equity and efficient allocation. In the Mediterranean region, where freshwater resources are scarce and need to be allocated efficiently to supply the domestic, agricultural, energy and industrial sectors, the Nexus can provide ways forward through trade-offs and an understanding of the different stakes involved. Addressing productive sectors and related natural resources separately leads to high opportunity costs across different uses as well as increased transaction costs between the Nexus sectors. Hence, when implementing (or developing) a WEF Nexus approach, the minimization of high transaction costs should be at the core of the considered economic measures. Furthermore, water provision and energy distribution have the characteristics of monopolies, which are highly regulated and produce both positive and negative externalities. Positive externalities may exist for water provision in terms of benefits to public health, while negative externalities may exist in energy and food production (point and diffuse pollution). With regard to water management, the pricing of water should include social, environmental and cultural values that are difficult to estimate or to translate into monetary terms. Water services are strongly subsidized in most regions of the Mediterranean, and water prices mostly reflect investment and maintenance costs but do not include the opportunity cost or scarcity of the resource. Although water pricing is a necessary instrument, it is not sufficient due to the inelastic nature of water demand (increasing prices cannot substantially decrease consumption) and the need to provide sufficient subsidies to lower the costs to households and farmers.

In general, the WEF Nexus has the potential to create new employment opportunities in the Mediterranean. However, there is some skepticism that the new jobs that can be created in the medium term will only be for a limited number of skilled workers, while unemployment might be created in other competitive sectors (e.g., agriculture).

A significant barrier to the technical implementation of the WEF Nexus is the absence of precise and uniform data for the whole Mediterranean region. The Shared Environmental Information System (SEIS) and the Mediterranean Information System on Environment and Development (SIMEDD) that have been provided by the European Environment Agency (EEA) to set up a uniform database and provide links to water related initiatives, papers, events, etc., require greater contributions from Mediterranean countries. Several countries have only low levels of data availability and accuracy, while detailed socio-economic and climate data are necessary to conduct a sectoral and intersectoral WEF Nexus analysis. Furthermore, some countries may be unwilling to share certain types of required data, as they could be considered nationally strategic.

Regarding the potential WEF trade-offs, as product systems are closely interrelated, actions at the local scale that aim to improve a certain area of the WEF Nexus may cause a shifting of burdens to other areas, ultimately leading to negative consequences for water, energy or food security. To prevent this, a lifecycle perspective should be applied when assessing the different policy options. Lifecycle approaches and methods are, for instance, widely used by industry to manage water risks. Impacts on water security are not only limited to production sites, but extend over the entire supply chain, especially in the case of agricultural products that often require large amounts of water and energy for their management and harvesting. The virtual water content of traded products may be a suitable indicator for measuring the trade-offs related to the supply chain. The lack of available lifecycle-based data to complement local databases for the Mediterranean region is a challenging issue that would need to be extensively improved in national accounting systems. Similar considerations apply to the other elements of the WEF Nexus. Regarding energy, for instance, activities along the product supply chain, such as manufacturing operations and product transportation, strongly contribute to the energy and carbon footprints of the whole system.

Considerable institutional barriers also exist. The varying levels of engagement of, and trust in, some stakeholders in the Mediterranean region, including civil society, hampers the development of a Nexus approach that demands a high level of cooperation and mutual trust. The responsibility for water, food and energy domains is often assigned to different ministries, which hampers the close communication and coordination that is needed to deal with the WEF Nexus. Innovative partnerships (such as in Plan Blue) need to be improved at the pan-Mediterranean level, although this may be a challenge due to geographical, political and social differences within the region. Science and policy should cooperate to initiate and support the sound planning of solutions for addressing challenges through the WEF Nexus. However, there is traditionally a low level of cooperation between science and policy, which often express different goals, agendas and priorities. There is also some skepticism on the role of governments, which do not seem to be ready and fit to build a WEF Nexus approach. In such cases, R&D may help advance the Nexus dialogue, with national governments following on their interest and readiness.

Furthermore, the WEF Nexus would require the close involvement of the private sector. The private sector has specific knowledge about production processes, their management and the markets they operate in. As people in the private sector make use of natural resources or are in the business of producing or processing them, it imperative that they be included in the dialogue on the WEF Nexus. As business depends on the availability of resources, such as water, it is also in their economic interest to be involved. In addition, they can also provide equipment and personnel, and contribute to funding R&D on Nexus solutions. Although many enterprises understand the need to innovate in order to maintain sustainable growth, they are slow to make the required connections with other relevant parties, such as the public sector and knowledge institutes. Many barriers can be identified, such as the lack of communication, poor mutual understanding or differences in the dynamics between the different sectors. Special effort is required to overcome these barriers in order to start a constructive discussion on how the different interests can be aligned into a project or program that will simultaneously enhance the business model of the entrepreneur and help to significantly reduce the WEF Nexus challenge. The conditions, bottlenecks and opportunities for the effective engagement of the private sector in fostering the Nexus should be analyzed, and ways forward should be suggested.

An example is provided by wastewater reuse. Different approaches and legislation can be found in the Mediterranean countries. The Italian legislation imposes very strict limits to the use of waste water in irrigation. This makes very difficult such use as costs for treatments are too high to be afforded by farmers. As a result, two different phenomena occur: (i) waste water is releases to the sea without any use, (ii) waste water is used illegally by farmers without any control.

Research can play an important role in better understanding the most appropriate limits to be respected, the types of irrigation systems that can be used and the types of crops that can be irrigated by wastewater without creating any health problems to the population. Overall, research results should better orient policy makers.

Bringing the analysis a step further, we have identified current "good" and "bad" practices that link water/energy/food security and ecosystem protection to investments, job creation, innovation and competitiveness in the Mediterranean region. It is recognized that some of these practices may not be applicable to or preferred by some countries; however, this does not diminish their added value as "food for thought." These practices are summarized in **Table 2**, for practices with positive and negative/adverse consequences.

Practices with unintended and/or negative consequences often emanate from common, underlying origins. These include the complexities of setting and implementing different prices for different sectors that use the same resources; lack of cooperation between science, policy and the business sectors; lack of coherence and cooperation between various levels of government; limited number of success stories and guidelines to help promote innovative partnerships; and the level of public awareness and support for innovation.

RECOMMENDATIONS AND THE WAY FORWARD

Although there is evidence that the WEF Nexus approach brings added value in terms of sustainable development, and that it is generating emerging interest, or even demand, from a number of countries and institutions, the most crucial step to be taken currently is to analyze and debate the related conditions, bottlenecks, opportunities and ways forward through structured dialogues that lead to action plans, including the identification of investments and pilot demonstrations. In our analysis, we reviewed the economic, institutional and policy aspects of the implementation of the Nexus, particularly from a Water perspective, that could help promote the economic growth potential of the Mediterranean region.

Water Pricing

Currently often underestimated, water pricing is an important economic issue that affects the implementation of the Nexus, especially with regard to the agricultural sector, which is the main water user. Pricing is a necessary economic instrument whose efficiency depends on how it is conceived, designed and implemented, and which should be adapted within the WEF Nexus framework. Different water valuation and pricing approaches are in use in the Mediterranean with varying levels of success, corresponding to policy choices based on to socio-economic perceptions and realities. Among others, the Water Framework Directive provides a range of water-pricing tools that are applied by law in the EU Member States and have

TABLE 2 | Practices with positive and negative/adverse consequences.

Intervention positive or negative	Country	Practice	Source
De green deals (positive)	Netherlands. Government program that has been in effect since 2011.	Contracts involving coalition of companies, civil society organizations and local and regional government to stimulate innovative investments	https://www.greendeals.nl/english
PPP for Nexus (positive)	United Kingdom. Research in Innovative public-private cross-sector multi- stakeholder partnerships.	Innovative partnership models, and developing, testing, and applying an innovative framework for the appraisal and evaluation of partnerships in food-energy-water-environment Nexus domains, with a particular focus on infrastructure projects.	https://www.innovativeppp.org/ Study with project-level implementation, funded by UK Research and Innovation.
Mediterranean research centers			
Support for water efficiency (positive)	Government support program with grants and zero interest credits.	Turkish farmers receive support from the Government on the condition that they use innovative irrigation and farming systems that increase the efficiency of irrigation water use and reduce the agricultural pollution of water resources.	https://www.tarimorman.gov.tr/Belgeler/ButceSunumlari/ButceSunumu_2018.pdf Support extended to 108,000 ha in grants and 670,000 ha in credits between 2006 and 2016.
Full cost pricing and extra service-based fees (positive)	Various	Environmental fees (e.g., in Israel, Greece, Portugal). Escalating irrigation fees (France)	
WEF in practice (positive)	Portugal	(1) Water-use-efficiency labeling on household appliances	(1) Potential water savings of up to 45% with additional energy savings in water heating and water supply;
		(2) Association of textile and clothing firms	(2) Promotes water and energy use optimization;
		(3) IBET, a private non-profit research introduced the WEF nexus as an important research topic.	(3) Links universities and firms for nexus research-implementation.
Willingness to pay, WTP (positive)	Academic study in West Bank of the Palestinian territories	Efficient allocation mechanisms based on WTP with key socio-economic variables suggested by economic theory are non-existent in Palestine.	https://www.sciencedirect.com/science/article/pii/S1053535712000546 Possible input for reforming allocation mechanisms.
Nexus in Government structure (positive)	Lebanon	Lebanon has the potential to lead nexus implementation given its integrated Ministry for Water and Energy.	
Support for water efficiency (adverse)	Turkey	Subsidies to farmers for reducing fertilizer and chemicals use and subsequently reducing water pollution in some cases decreased agricultural productivity and farm income.	Negative effects of internalizing the external costs. Input for policy revision.
Gradual quotas and prices (negative)	Israel	Scheme of gradual quotas and prices linking water consumption to price stipulates that if farmers do not use all of their quotas, their future quotas are reduced. This poor design is an obstacle for efficient water use.	The actual situation behind reduced quotas is more complicated as the country is severely water scarce.
Solar power for irrigation (positive)	Lebanon	A farm-level case study was carried out in Lebanon of a 120,000 m^2 organic farm in the western Bekaa valley, where the owner would spend $200,000 annually on upkeep and maintenance. Nearly a quarter of that went toward electricity expenses, the bulk of which was for the irrigation system. He introduced 64 solar panels measuring 1.5 m2 for solar-powered irrigation. By switching to solar power, the farm became self-sustaining and profitable.	Anderson (2009)

been voluntarily adopted in south-east Europe; other countries may be interested in exploring and adapting such tools to their national needs. Although the implementation of efficient water prices among sectors is a complicated affair, it also provides an opportunity for the WEF Nexus to incorporate externalities (environmental, social, cultural costs, opportunity costs) in a full-cost manner and apply a total economic value. In this context, we can go beyond abstraction costs, and include environmental costs, wastewater treatment, and the preservation of resources and ecosystems. Moreover, prices have to be connected to specific uses and levels of use, introducing block tariffs and supplementary fixed tariffs. Additionally, water prices should reflect not only the cost of providing the service but also the opportunity costs, which will define the foregone benefits of those not using the water resources. In this context, water pricing based on economic principles can support political decisions and policy making, and at the same time provide crucial information and incentives for businesses to invest in the water supply.

Market Economic Instruments

Additional appropriate economic instruments (taxes, property rights, subsidies, etc.) can be selected as a toolbox that addresses various specific needs in the Mediterranean in order to promote allocation efficiency, the transfer of advanced technology and equity. Prior to applying any instrument, it is first necessary to identify the market structures, technological dimensions and the involved stakeholders. For example, although subsidies can lead to inefficient water management and use if applied to water consumption, they could prove useful in promoting WEF technology investments and could be combined with other mechanisms, such as lowering taxes on those investments. Economic efficiency or Pareto efficiency can be achieved when the marginal cost-pricing rule, which means the incremental cost of supplying an additional unit (marginal cost) equals the incremental amount that will be paid for a volume of water (marginal willingness to pay). In other words, Rogers et al. (2002) states that when water is priced at its real marginal cost, including environmental costs, it is put to its highest economically valued use. As an extra tool, awareness campaigns should be promoted since they can have very good results concerning water and energy savings by inducing advanced technologies.

Integrated Evaluation Approaches

Regarding specific integrated methods for evaluating the economic effects of the WEF Nexus, in complement to the Cost Benefit Analysis, Cost Effectiveness with clearly defined objectives can be used as a tool to choose the optimal choices in the WEF Nexus. Alternatively, stated preference methods (Contingent Valuation and Choice Experiments) and "Benefit Transfer" methods can be further and more widely used to assess the specific welfare effects of the WEF Nexus application.

Financing the WEF Nexus

Financing the WEF Nexus is another considerable component of economic growth. The public sector is the appropriate institutional body for providing a holistic orientation and long term perspective of the WEF Nexus, as well as for appropriating funds to support the initiation and establishment of a WEF Nexus approach. In this case the use of public funds should be justified with a specific investment plan that incorporates reduced opportunity costs to other public investments. Generally, Nexus investments can potentially be justified when they are profitable and low risk in terms of economic and social welfare, regulated by the state. However, the participation of the private sector is indispensable, involved already at the planning phase and the R&D process. Overall, it is essential to encourage the involvement of the private sector from the beginning in the planning phase, because its knowledge is important for providing sustainable market solutions, innovations, and better operational arrangements. Public-Private Partnerships, although debatable, should be fostered in a consistent manner providing a factor for either further increasing welfare or achieving the same goal more efficiently and cost effectively. If there are no obstacles and uncertainties and profitability emerges, then firms will invest without public involvement. However, when market conditions are not conducive to investments by private firms, government, universities and knowledge institutes should still invest for public welfare, and market-related shortcomings and share funding uncertainties should be corrected through the appropriate policies. An example of financing Nexuses are the investments in multiple-use water supply systems that support different user needs (water for Water, Sanitation and Hygiene (WASH), water for irrigation, water for small-scale hydropower, water storage for climate change mitigation, healthy wetlands, and aquatic ecosystems), improving people's access to and effective use of water resources. However, this should also be accompanied by training sessions, capacity and trust building, and most importantly, in dialogue with the people eventually benefitting or losing from these investments.

WEF Contributing to New Job Opportunities

Regarding the emergence of new employment opportunities, there is a need to accelerate the process of water management in that direction. Investment at R&D on Nexus approaches could also on its own induce a positive economic effect by creating more jobs while providing solutions. Investing in new efficient technologies (e.g., renewable energy for water-related activities and innovative farming practices for water and energy efficiency in agriculture) within a Nexus approach can create job opportunities, or at the least prevent job losses for several sectors in a region. In defining the right focus for R&D it is important to have good links between the knowledge parties and the technology users. To prevent purely academic exercises, research linked to viable business cases is needed and real life demonstrations, adopting a bottom-up approach before upscaling, can be considered. Further development of and innovation in the agricultural sector can play a central role in enhancing Nexuses, while in parallel mainstreaming and coordinating across sectorial policies. Other sectors could be further developed, attracting additional investments and producing new jobs within a Nexus framework, such as monitoring and auditing. Furthermore, desalination technologies and the smart use of ecosystems (wetlands) to collect and store water and carbon could also provide positive economic opportunities. The role of governments is of great importance for the Nexus implementation, since they can speed up the process by providing funding or subsidies for new technologies that contribute to the welfare of society which otherwise would not easily reach the markets.

The creation of jobs depends on the sector to which water is allocated (e.g., water for irrigation can provide more jobs than hydropower energy production). However, there should be a balance between efficiency and equity in the employment opportunities created. Promoting a better policy for water resource allocation through the use of the Nexus approach could also have a negative impact on employment. Given that at present in the Mediterranean countries, especially those in the south, the water sector receives substantial public subsidies in order to maintain the well-being of users, any attempt toward rationalization, which requires a reduction in subsidies, will lead to a direct deterioration in the employment situation. The implementation of the Nexus should explicitly take account of this and do everything possible to alleviate it.

Data Availability and Management

Concerning the data issue, which should be a priority for policy-makers, a WEF Nexus based on a holistic economic and environmental perspective should use consistent, reliable and comprehensive data as well as sound scientific references. It is also imperative that data across the nexus sectors are comparable in terms of accuracy and resolution. Accurate economic databases could further support the setting of efficient water prices. Moreover, precise data needs to be collected and maintained for agricultural and energy production and technology at various levels, including throughout the supply chains of goods and services concerned. Research and scientific institutions can initiate the collection of open data and other stakeholders can join the process, in order to build a sustainable database for analyzing the Nexus. It is imperative to invest in collecting highly disaggregated micro data, with the distinction for example between farmers benefiting from highly subsidized water in terms of price and famers who mobilize their water supplies themselves, bearing all the costs related to water pumping. The collection of such data would substantially improve the estimation of the price elasticity of water demand, and thus serve as a solid basis on which to define tariff policy.

Institutional Settings

Analyzing the institutional arrangements, partners could further support the establishment of a Nexus framework by sharing experiences, utilizing regional Institutions, promoting stakeholder involvement (including civil society), networking and strengthening trust and capacity building. Supporting the WEF Nexus is not a matter of defining new institutions, but more of how existing institutions are managed and interlinked. The human resources capacity sometimes limits the most representative and sustainable lines of action. Therefore, it is important to structure institutions around efficient management frameworks and allow integration of the concept "sustainable ownership." It is necessary to promote innovation as one of the key topics in establishing solutions to the WEF Nexus. The participation of regional institutions in global forums on innovation and Nexus dialogues is essential. Fostering linkages between science and policy is necessary for good governance and management, where institutions coordinate at a national level and participate in capacity building and cooperative activities at a regional level. To this end, institutions from all sectors involved should set a common WEF Nexus policy, which will be integrated into universities' research agendas. Furthermore, civil society could support two strategic measures: awareness and monitoring for enforcement; governments should have the central role in evaluating and enforcing the agreed WEF Nexus provisions.

Dialogue

Organized dialogue is another keystone of the WEF Nexus framework. Added value can be generated only through partnerships between the public sector, the private sector, knowledge institutes, NGOs and regional stakeholders. A Nexus dialogue process can start at the macro-regional level and then continue at higher levels. Dialogue at the macro-regional level can be organized by existing regional institutions, concentrating on success stories to promote greater use of these applications and/or to scale them up. The Mediterranean countries can then transfer this expertise through their reviewed internal national dialogue to their regional institutions to complete the dialogue chain. Initiating the dialogue between countries and introducing the Nexus at a macro-regional level first is more representative of the conditions and less clouded by conflicts. In this context, dialogue capacities can be built through regional and national activities and can be targeted to both national and regional partners/stakeholders.

AUTHOR CONTRIBUTIONS

The research presented in this paper is a product of a Workshop held in Ankara in February 2015. All the authors participated in the Workshop and jointly developed the workshop findings which were included in the present paper. During the writing of the paper, all the authors contributed in reviewing it and adding specific parts and comments.

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Conflict of Interest Statement: UP was employed by company Studio Fieschi & Soci Srl. IT was employed by company Solaris. RV was employed by company Deltares.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Environmental Science

ORIGINAL RESEARCH
published: 01 November 2019
doi: 10.3389/fenvs.2019.00146

Energy and Climate Change Mitigation Benefits of *Faidherbia albida* Agroforestry in Ethiopia

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Agriculture must raise productivity while addressing climate change in order to ensure the food security of a growing population. Adding fossil fuel energy to the agricultural system can increase productivity through the use of manufactured fertilizer but creates greenhouse gas emissions. This study quantifies an alternative in which energy is added to the agricultural system through a substitution of solar energy for fossil fuel energy by the tree species *Faidherbia albida*. This substitution can be quantified as an avoided emission of greenhouse gas, a climate benefit. *F. albida* trees have unusual phenology, leafing out during the dry season and shedding leaves in the rainy season. In agroforestry systems, *F. albida* adds nutrients and organic matter to the soil through leaf drop, and these are beneficial to the crop growing under the tree canopy. Dormant during the cropping season, they do not compete for light, water or nutrients, and contribute nitrogen to the soil under their canopy. This nitrogen benefit is analyzed in relation to an equivalent quantity of urea fertilizer. This is a substitution of solar energy that the trees use to obtain nitrogen from the atmosphere, for the fossil fuels used in the manufacture and transport of urea fertilizer. This energy contribution by the tree, within the food energy and water system, enhances the food production, and resilience of the system, as soil organic matter increases available water for the plants. This energy contribution to the Ethiopian farming system is estimated as 3.48 GJ ha^{-1} $year^{-1}$, based on the nitrogen contribution. Greenhouse gas emissions are avoided by the substitution of solar energy for fossil fuel energy, a climate change mitigation benefit estimated as 0.116 tons CO_2 ha^{-1} $year^{-1}$. This mitigation is fundamentally different from sequestration of carbon in biomass or soil organic matter. It is a permanently avoided emission of carbon dioxide into the atmosphere, associated with a particular cropping year, and is not reversible, unlike carbon stored in biomass or soil organic matter that could return to the atmosphere. The potential extent of *F. albida* agroforestry is substantial and its potential climate change mitigation benefits are great.

Keywords: food energy water nexus, climate change adaptation and mitigation, *Faidherbia albida*, agroforestry, Ethiopia, evergreen agriculture, nitrogen fertilization, avoided emissions

OPEN ACCESS

Edited by:
Richard George Lawford, Morgan State University, United States

Reviewed by:
Xander Wang, University of Prince Edward Island, Canada
Sushel Unninayar, Morgan State University, United States

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Specialty section:
This article was submitted to Interdisciplinary Climate Studies, a section of the journal Frontiers in Environmental Science

Received: *31 August 2018*
Accepted: *17 September 2019*
Published: *01 November 2019*

Citation:
Haskett JD, Simane B and Smith C (2019) Energy and Climate Change Mitigation Benefits of Faidherbia albida Agroforestry in Ethiopia. Front. Environ. Sci. 7:146. doi: 10.3389/fenvs.2019.00146

INTRODUCTION

The relationship between energy inputs and agricultural productivity is a critical aspect of the food-energy-water nexus. An agroforestry production system based on the acacia species *Faidherbia albida* has shown great promise to provide an energy input by adding nitrogen to some agricultural systems. In effect, a *F. albida* agroforestry production system captures solar energy and converts it to a nitrogen fertilization input, through symbiotic nitrogen fixation in root nodules. This is quantified in the current study as equivalent to an amount of urea nitrogen fertilizer and the energy that would be required to manufacture and transport that amount of fertilizer to the field. The marked increases in crop yield, especially in maize associated with Faidherbia agroforestry (Saka et al., 1994), illustrate a direct link between this tree-based energy input and the potential for enhanced food security, especially since Faidherbia is well-adapted to challenging dryland regions such as the Sahel. *F. albida* has long been viewed as one of the most important acacia species due to the roles it plays in improving small-holder agriculture in developing countries and in recovering the degraded lands of some of the most difficult dryland landscapes, including in large areas of the Sahel (Barnes and Fagg, 2003). The species is an integral part of a highly successful development strategy known as Evergreen Agriculture (Garrity et al., 2010). The Evergreen Agriculture system is based on the integration of trees, into annual food production and cropping systems, and incorporates mutually supporting strategies that are applied in various combinations at different locations. In addition to cultivating beneficial trees, the Evergreen Agriculture system includes soil conservation structures, water collection, and targeted fertilizer and manure applications. The adoption of Evergreen Agriculture often associated with *F. albida* is becoming widespread in Africa, with demonstrated success in improving farmer livelihoods and agricultural sustainability in Ethiopia, Zambia, Malawi, Burkina Faso, and Niger (Garrity et al., 2010) and *F. albida* is one of the principle species incorporated into this approach.

Distribution and Biophysical Characteristics

Faidherbia albida can achieve heights of 30 m, with trunk diameters up to 2 m. It has a taproot that can reach a depth of 20 m to access ground water, pull nutrients from the deeper layers of the soil, and cycle these nutrients to the surface layers of the soil (Barnes and Fagg, 2003; Sileshi, 2016). Additionally, because *F. albida* pods fall at the end of the dry season, they become nutritious forage for livestock when other pastures and foraging sources are typically scarce (Barnes and Fagg, 2003).

The species has an extremely wide natural distribution across large areas of semi-arid Africa, from Senegal to Ethiopia and south through Kenya and Malawi into the Transvaal (Umar et al., 2013). In Ethiopia, it is predominantly grown in the agroforestry systems for fodder, mulch, soil improvement, and soil conservation.The species is highly unusual in that it exhibits "reverse" phenology, meaning that, unlike most other plant species that grow in areas with a distinct rainy season, *F. albida* sheds its leaves and goes dormant at the start of the rainy season, and only goes to full leaf during the dry season (Barnes and Fagg, 2003). Reverse phenology is an unusual trait that may have arisen as adaptation to competition from other tree species. Faidherbia is a poor competitor with other species of trees and this restricts its natural occurrence (Barnes and Fagg, 2003). Reverse phenology is a trait that gives the species a competitive advantage in colonizing and growing in alluvial soils on river banks, floodplains or in the river bed itself (Barnes and Fagg, 2003). Faidherbia becomes dormant during periodic flooding and is thus able to survive the inundation that kills other species of trees. This reverse phenology means that the species is out of phase with field crops growing nearby and under its canopy, so it does not compete with these crops for water, light, or nutrients. The tree uses a symbiotic relationship with nitrogen fixing bacteria living in nodules in its roots to pull nitrogen from the atmosphere. A portion of this nitrogen is translocated from the point of fixation in the nodules to the growing leaves in the canopy, throughout the period of leaf growth. This nitrogen enters the agricultural system primarily when the tree drops its leaves. The leaves may be incorporated into the soil and as decomposition proceeds the nitrogen in the leafy biomass enters the soil and becomes available to crops. This process provides numerous benefits to the crops beneath the canopy and within the area of influence of the tree. These benefits include enhanced availability of nitrogen, phosphorus[1], and soil moisture, plus increased quantities of soil organic matter in the vicinity of the trees (Hadgu et al., 2009; Sileshi, 2016).

Effect on Crop Yields

These characteristics of the tree frequently increase crop yields and help to account for the popularity of the species with farmers (Wahl and Bland, 2013). Indeed, there is an extensive literature showing significant yield increases associated with *F. albida* for many crops including maize, millet, sorghum, and groundnut (Barnes and Fagg, 2003). Hadgu et al. (2009) found increases in yields of barley in Tigray Ethiopia tied to the impacts of *F. albida*. In Malawi, Saka et al. (1994) reported a 280% increase in maize yields under the canopy of these trees. Shitumbanuma (2012) reported consistent increases in yields of maize, soybeans, and groundnuts when these were grown with Faidherbia, but also found concurrently observed decreases in cotton yields. Boffa (1999) reported substantial increases in cereal grain production associated with *F. albida*, including increases in millet and sorghum that were observed when production under the Faidherbia canopy was compared with production outside of the area of influence of the trees, and these relative increases were often quite pronounced in years with below average rainfall. Faidherbia is easily incorporated into smallholder farming systems in which hand cultivation facilitates tillage activity around the tree's base. It has been incorporated into mechanized systems planted on a grid pattern with spacing measured to allow the passage of tillage equipment.

[1] Sileshi (2016) proposes that the phosphorus is provided beneath the tree canopy in part by deep capture and recycling of nutrients by *Faidherbia albida*.

One of *F. albida*'s greatest benefits is the addition of nitrogen to the soil in the area around the tree, primarily through the addition and subsequent decomposition of leaves to the soil surface (Barnes and Fagg, 2003). This quantity of nitrogen can be substantial and a major factor in the increased crop productivity that occurs in proximity to the tree (Rhoades, 1995; Sileshi, 2016). A recent study by Yengwe et al. (2018), sampled the total addition of nitrogen in leaf fall over two growing seasons and determined the addition on a per hectare basis, for three age classes of Faidherbia trees. The average value for this addition is used in the current study to provide a realistic baseline for determining the energy and climate mitigation contribution of Faidherbia in agricultural systems.

Energy Input to the Farming System

Although the addition of nitrogen and its benefits for soil fertility and crop growth are widely recognized, *F. albida*'s corresponding energy input to the farming systems in which they are integrated, has not yet been explored. A part of this contribution can be quantified through the equivalent nitrogen benefit that the trees provide. This nitrogen benefit can be evaluated as an input equal to the energy expended in manufacturing, transporting, and applying the same amount of urea to the field. Viewing nitrogen fertilizer as a quantifiable energy input to agricultural production is well-established in the context of an energy analysis of agriculture, in the United States (Patzek, 2005; Pimental, 2009), including Pimental's definition of the term "energy," but that analysis has neither been applied to the nitrogen contribution of *F. albida* nor been performed in relation to an energy equivalent substitution for urea fertilizer, prior to the current study, based on a review of the literature.

The current study performs these analyses and is part of an ongoing research effort examining the likely response of Ethiopian agricultural to climate change and potential climate shocks (Bakker et al., 2018). The current framework of this research examines the potential responses of the Ethiopian agricultural system in the interconnected Food-Energy-Water (FEWS) meta-system (Leck et al., 2015) in which it is embedded. The current study looks at one energy component of this meta-system and uses an Ethiopian case study as the starting point, consistent with the other aspects of the research effort.

Agriculture in Ethiopia

Agriculture in Ethiopia is a core component of the economy. Productivity in this sector is increasingly challenged by depletion of soil nutrients, high levels of livestock grazing pressure, loss of forest cover, population increases, and land use practices that do not ensure long term sustainability [IFDC (International Fertilizer Development Center), 2012]. The wide ranges of topographic, climatic factors, parent material, and land use have resulted in extreme variability of soils in Ethiopia. *F. albida*'s contribution to Ethiopian agriculture needs to be understood in the context of Ethiopian soil nutrient status and nutrient depletion. Assessments of nutrient status of Ethiopian soils indicate ranges of 0.9–2.9 g N kg^{-1} soil and 0.4–1.10 g P kg^{-1} soil. The calculated national nutrient balances were on average: 47 kg N ha^{-1}, 15 kg P_20_5 ha^{-1}, and 38 kg K_2O ha^{-1} for the year 2000 (Haileslassie et al., 2005). At the national level, full nutrient balance results indicate a depletion rate of 122 kg N ha^{-1} yr^{-1}, 13 kg P ha^{-1} yr^{-1}, and 82 kg K ha^{-1} yr^{-1}. The soil nutrient stocks are decreasing except in areas under permanent and vegetable crops. These challenges are exacerbated by the semi-arid climate of the region, which is subject to periodic droughts. The combined impact of these factors compromises Ethiopia's economic productivity and puts parts of the Ethiopian population at risk of food insecurity, malnutrition, and poor health outcomes [IFDC (International Fertilizer Development Center), 2012]. Reversing these trends, halting soil degradation, and boosting soil fertility, are top priorities of the Government of Ethiopia [IFDC (International Fertilizer Development Center), 2012].

Ethiopian farmers primarily use urea and diammonium phosphate (DAP) as fertilizers, but only 30–40% of Ethiopian small farmers apply fertilizers to their fields and often at rates below the recommended rates of application (Abdulkadi et al., 2017). Other sources of added plant nutrition may also be limited as, in some communities, 80% of animal manure is used as cooking fuel (Abdulkadi et al., 2017). *F. albida*, which is native to Ethiopia, can help reverse these trends in soil depletion by providing additional plant nutrition and soil amendment benefits to smallholder agricultural systems. The distribution of *F. albida* populations in Ethiopia is not uniform as *F. albida* tree populations are lower in the Northern regions of Tigray and Gonder than in the central highlands. The highest populations of *F. albida* trees are commonly found along Southern Ethiopia's Great Rift Valley lakes and Awassa, Koka, and Arba Minch drainage systems, as well as in the heavy vertisols around Debre Zeit (Barnes and Fagg, 2003).

DETERMINATION OF ENERGY SAVINGS OF *FAIDHERBIA ALBIDA* IN FERTILIZER EQUIVALENTS

Faidherbia albida makes significant additions of nitrogen to the soil annually and these additions can be expressed in terms of an equivalent quantity of urea fertilizer [CTFT (Centre Technique Forestier Tropical), 1989]. This nitrogen addition is valuable both as a nutrient and as an energy contribution, because the nitrogen provided by the trees substitutes for the energy required to manufacture and transport an equal amount of urea to the field where it would be applied. Yengwe et al. (2018) collected data on the total leaf fall added to the soil surface in maize plots in Zambia and analyzed the nitrogen content over two annual growing seasons. This study converts their value for nitrogen addition to an equivalent amount of nitrogen in the form of urea and uses this value as the basis for calculating both the energy input to the system and the climate mitigation benefit (**Figures 1**, **2**).

Energetics of Fertilizer Manufacture

To determine this energy equivalent, it is first necessary to calculate the energy required to manufacture the ammonia, as ammonia is a necessary precursor to manufactured urea. A study by the U.S. Environmental Protection Agency [EPA

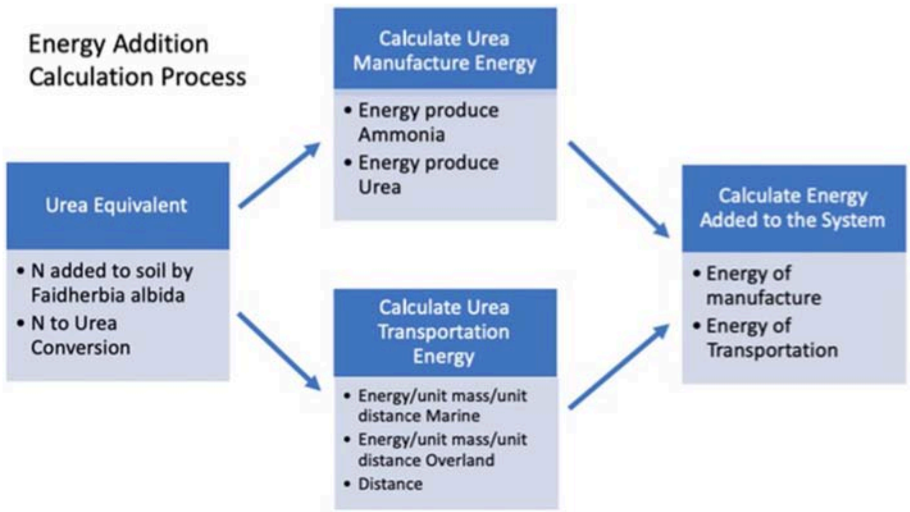

FIGURE 1 | *Faidherbia albida* energy addition calculation process.

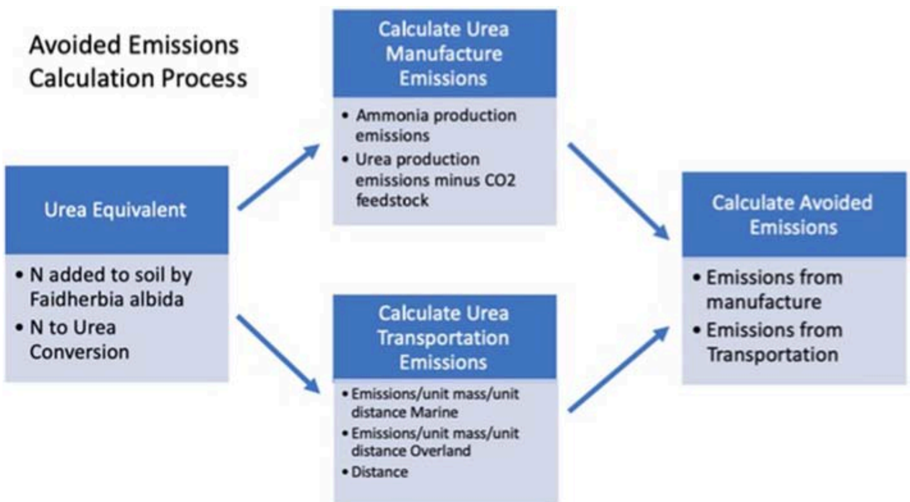

FIGURE 2 | *Faidherbia albida* avoided emissions calculation process.

(United States Environmental Protection Agency), 2017], indicated that producing each metric ton of ammonia in a typical fertilizer plant required between 30.9 GJ and 39.1 GJ of natural gas. Taking the average of these two values as representative, this study uses 35.0 GJ as the energy used to produce ammonia.

The ammonia produced is then used as a feedstock to produce urea. According to the same EPA study [EPA (United States Environmental Protection Agency), 2017], the energy intensity of urea production in a conventional total recycling plant, can be estimated as 6.0 GJ per ton of urea produced. The lower energy requirement for the production of urea as compared with that for ammonia is due, in part, to the energy required to break the triple chemical bond of atmospheric dinitrogen, during the production of ammonia.

To determine the total energy requirement of urea manufacture, the energy intensity of the urea production is added to the energy required to produce the ammonia feedstock used to manufacture urea. This ammonia energy input must be adjusted for the stoichiometric amount of ammonia used in the production of urea, which is 0.567 tons ammonia per ton of urea (Fertilizer Europe, 2000). The total energy used to produce urea is then the sum of the energy used in the production of urea and the energy used in the production of the ammonia feedstock (Equation 1).

$$E_{manufacture,\ urea} = 6.0\frac{GJ}{ton\ urea} + (0.567\frac{ton\ NH_3}{ton\ urea} * 35.0\ \frac{GJ}{ton\ NH_3})$$
$$E_{manufacture,\ urea} = 25.9\ \frac{GJ}{ton\ urea} \quad (1)$$

Nitrogen Contribution and Urea Energy Equivalence

This energy value needs to be related to the nitrogen contribution of *F. albida*, so it can be appropriately adjusted to capture the energy contribution of the trees to the agricultural system. Yengwe et al. (2018) sampled leaf litter drop in three age classes of Faidherbia trees over two cropping seasons and then used this to determine the litter fall on a per hectare basis. By analyzing the nitrogen content of the leaf litter, they were able to estimate the nitrogen addition in the leaf drop (**Table 1**). The authors of the study discuss the possibility that variability in litterfall across seasons and age classes could be due to differences in rainfall distribution and amount, but they were not able to confirm this.

The current study uses the averages of these values to determine the average amount of nitrogen returned to the soil in a typical growing season. Using the average of the nitrogen returned by the three age classes, the average Faidherbia Albida tree returned 59.59 total N (kg ha^{-1}) for the 2014/15 season and 45.92 total N (kg ha^{-1}) for the 2015/16. The average of these two values is 52.76 kg total *N* per hectare and this value is used in the current study as the representative value of nitrogen returned by *F. albida* trees to the soil in an annual growing season.

To obtain an equivalent amount of urea fertilizer, the current study used a stoichiometric value of 46% percent nitrogen in urea (CH_4N_2O)[2] to convert the nitrogen value of 52.76 kg N ha^{-1} to a mass-based value of urea fertilizer. Equation (2) below, multiplies the nitrogen value by a factor of 2.17 (1/0.46) to obtain an equivalent amount of urea fertilizer equal to 114.48 Urea (kg ha^{-1}).

$$114.48\,\frac{kg\ urea}{ha} = 52.76\frac{kg\ N}{ha} *1\,\frac{kg\ urea}{0.46\ kg\ N} \tag{2}$$

To calculate the energy that would be required to manufacture this same amount of urea, Equation (3) below, multiplies this calculated urea equivalent in Equation (2) by the energy required to produce manufactured urea from Equation (1). The energy equivalent of the *F. albida* contribution in terms of the manufacture of urea is calculated as 2.91 GJ/ha-year (Equation 3).

$$\begin{aligned} E_{FA,energy,manufacture,equivalent} &= 25.49\,\frac{GJ}{ton\ urea} *0.114\,\frac{ton\ urea}{ha-year} \\ E_{FA,energy,manufacture,equivalent} &= 2.91\,\frac{GJ}{ha-year} \end{aligned} \tag{3}$$

A realistic estimate of the energy equivalent contribution of the *F. albida* trees with respect to urea also needs to take into account that the nitrogen from the trees is applied directly to the farm field, but manufactured urea must be transported to the farm for application. This study assumes that the urea will be applied in Ethiopia, in which urea fertilizer is applied at significant rates [IFDC (International Fertilizer Development Center), 2012] and *F. albida* is deeply integrated into some of its agricultural system (Hadgu et al., 2011). China is a primary source for urea shipped to Ethiopia [IFDC/AFAP (International Fertilizer Development Center/African Fertilizer Agribusiness Partnership), 2015], and typically, the urea is offloaded at the port of Djibouti and trucked to distribution warehouses in Ethiopia [IFDC (International Fertilizer Development Center), 2012].

[2]PubChem at https://pubchem.ncbi.nlm.nih.gov/compound/urea#section=Top

TABLE 1 | Foliar litterfall quantity and nitrogen return for three age classes of *Faidherbia albida* trees for two growing seasons (average ± SE; *n* = 3).

Age of tree	2014/15 season		2015/16 season	
	Litterfall (t DM ha^{-1})	Total *N* (kg ha^{-1})	Litterfall (t DM ha^{-1})	Total *N* (kg ha^{-1})
8	2.0 ± 0.2	49.41 ± 0.19	1.3 ± 0.1	31.49 ± 0.12
15	2.4 ± 0.4	49.13 ± 0.57	0.9 ± 0.1	19.67 ± 0.23
22	3.6 ± 0.5	80.24 ± 0.92	3.9 ± 0.6	86.50 ± 0.99

Data as reported by Yengwe et al. (2018).

Energetics of Urea Transport

To calculate the energy required to transport manufactured urea, this study assumes that the fertilizer is transported first by ship from the Chinese port of Shanghai to the port of Djibouti and next driven by truck from the port of Djibouti to a distribution warehouse in Addis Ababa. Further distribution within Ethiopia is not included in the calculation of the distribution from the warehouse to the individual fields would be prohibitive. Although other fertilizer routes and sources are possible, this route is realistic and captures a significant portion of the fertilizer import supply chain, allowing for a realistic and conservative calculation of the energy used to transport urea from China to Ethiopia.

The online shipping distance calculating tool found at sea-distances.org, estimates this ocean voyageto be 5,973 nautical miles. Although routes may vary, this estimate is within ∼50 nautical miles of those obtained from other online commercial shipping distance calculating tools. For example, MarineTraffic.com estimated the most direct route of this voyage to be 6,000 nautical miles.

For purposes of calculation, 5,973 nautical miles was converted to 11,062 km and used in Equation (4) to calculate the energy expended to ship the 0.114 ton of urea equivalent provided by *F. albida*. Simonsen and Walnum (2011) estimate that 0.172 MJ/ton-km is the energy expended per ton-km of cargo sent by ocean shipping routes.

$$\begin{aligned} E_{FA,marine,transport,equivalent} &= 0.114\,\frac{ton\ urea}{ha-year} *11062\ km \\ &\quad *0.172\,\frac{MJ}{ton-km} \\ E_{FA,marine,transport,equivalent} &= 0.217\,\frac{GJ}{ha-year} \end{aligned} \tag{4}$$

Equation (5) calculates the energy required to transport the manufactured urea by road from the port of Djibouti to distribution warehouses in Ethiopia. For overland transport by truck, the distance from the Djibouti Container Terminal to Addis Ababa, was estimated, using the online distance estimator

Distanceto.com, to be 891 km. The International Energy Agency (IEA) (2009) has estimated the energy required for truck road freight transport in Africa at slightly more than 3.5 MJ ton-km^{-1}. This study uses a conservative value of 3.5 MJ ton-km^{-1}

$$\begin{aligned} E_{FA,\ road\ freight\ transport\ equivalent} &= \left(0.114\ \frac{ton\ urea}{ha-year}*891\ km\right) *3.5\ \frac{MJ}{ton-km} \\ E_{FA,\ road\ freight\ transport\ equivalent} &= 0.355\ \frac{GJ}{ha-year} \end{aligned} \tag{5}$$

The total energy of transportation is the sum of the energy used for marine and road transport (Equation 6).

$$\begin{aligned} E_{Total,\ transport,\ energy,\ equivalent} &= 0.217\ \frac{GJ}{ha-year} + 0.355\ \frac{GJ}{ha-year} \\ E_{Total,\ transport,\ energy,\ equivalent} &= 0.572\ \frac{GJ}{ha-year} \end{aligned} \tag{6}$$

Total Energy Contribution of *F. albida*

Thus, the equivalent energy contribution of *F. albida* to each hectare of the agricultural system, can be calculated by summing the energy used to manufacture urea fertilizer and the energy used to transport that fertilizer (Equation 7). Equation (7) estimates the total energy equivalent of *F. albida* fertilizer contribution to be 3.48 GJ per hectare per year.

$$\begin{aligned} E_{Total,FA,\ energy,equivalent} &= 2.91\frac{GJ}{ha-year} + 0.572\frac{GJ}{ha-year} \\ E_{Total,FA,\ energy,equivalent} &= \mathbf{3.48}\frac{GJ}{ha-year} \end{aligned} \tag{7}$$

Calculation of Emissions From Manufacture of Urea

The contribution of *F. albida* can also be quantified in terms of avoided CO_2 emissions, or the emissions that would have occurred in manufacturing and transporting the equivalent urea fertilizer (**Figure 2**). With respect to the CO_2 emissions involved in the manufacture of urea, it must be acknowledged that carbon dioxide is a feedstock for the manufacturing process, so some offsetting of CO_2 occurs. On a stoichiometric basis, each ton of urea produced consumes 0.733 tons of CO_2 (Fertilizer Europe, 2000). The emissions per Giga Joule are 56.0 kg CO_2 [EPA (United States Environmental Protection Agency), 2017] and the adjusted emissions from a year of manufacturing are then the total emissions minus the CO_2 recovered as feedstock (Equation 8) or 0.079 ton CO_2 per ha-year.

$$\begin{aligned} Em_{FA,\ emissions,equivalent,\ urea} &= \left(2.91\frac{GJ}{ha-year}*0.056\ \frac{ton\ CO_2}{GJ}\right) - \left(0.114\ ton\ urea^{*}0.733\ \frac{ton\ CO_2 absorbed}{ton\ urea}\right) \\ Em_{FA,emissions,equivalent,\ urea} &= 0.079\ \frac{ton\ CO_2}{ha-year} \end{aligned} \tag{8}$$

Calculation of Emissions From Transportation of Urea

To obtain the total avoided CO_2 emissions, the emissions from manufacturing must be added to the emissions produced by transporting the fertilizer. A corresponding estimate of the per-km emissions from deep water ocean transport (Equation 9) is 8.4 g CO_2 per ton-km (McKinnon and Piecyk, 2010), and the total emissions from shipping 0.114 tons of urea from China to Djibouti are calculated in Equation (9). Equation (10) calculates the total emissions of trucking 0.114 tons of urea from the Port of Djibouti to the warehouses in Ethiopia. Transport of that quantity of urea for that distance is 101.5 ton-km, while the International Energy Agency (IEA) (2009) value for road freight energy usage of 3.5 MJ/ton-km, and Edwards et al. (2004) estimate that the value to relate energy expenditure for diesel fuel to CO_2 emissions is 73.54 kg CO_2/MJ. Thus, as shown in Equation (11), the total CO_2 emissions from transporting the *F. albida* equivalent quantity of urea fertilizer is the sum of emissions from marine and road.

$$\begin{aligned} Em_{FA,emissions,marine,transport,equivalent} &= \left(0.114\ \frac{ton\ urea}{ha-year} *\ 11062\ km\right)*\left(8.4\ \frac{g\ CO_2}{ton-km}\right) \\ Em_{FA,emissions,marine,transport,equivalent} &= 10.59\ \frac{kg\ CO_2}{ha-year} \end{aligned} \tag{9}$$

$$\begin{aligned} Em_{FA,emissions,road\ freight,\ transport,equivalent} &= \left(891\ km*0.114\ \frac{ton\ urea}{ha-year}\right) *3.5\ \frac{MJ}{ton-km} *73.54\ \frac{g\ CO_2}{MJ} \\ Em_{FA,emissions,road\ freight,\ transport,equivalent} &= 26.1\ \frac{kg\ CO_2}{ha-year} \end{aligned} \tag{10}$$

$$\begin{aligned} Em_{FA,emissions,total\ transportation,equivalent} &= 10.59\ \frac{kg\ CO_2}{ha-year} + 26.1\ \frac{kg\ CO_2}{ha-year} \\ Em_{FA,emissons,total\ transportation,equivalent} &= 36.69\ \frac{kg\ CO_2}{ha-year} \end{aligned} \tag{11}$$

Calculation of Total Emissions

Finally, the emissions avoided by gaining the nitrogen input from the Faidherbia trees rather than from the application of manufactured urea can be calculated by adding the emissions from the urea manufacturing process to the emissions from transporting the urea. The annual total avoided emissions from the nitrogen provided by *F. albida* is 0.116 tons CO_2 per hectare, as shown in Equation (12).

$$\begin{aligned} Em_{FA,emissions,total,equivalent} &= 79.4\ \frac{kg\ CO_2}{ha-year} + 36.69\ \frac{kg\ CO_2}{ha-year} \\ Em_{FA,emissions,total,equivalent} &= \mathbf{0.116}\frac{ton\ CO_2}{ha-year} \end{aligned} \tag{12}$$

DISCUSSION

On a per hectare basis through the contribution of nitrogen alone, *F. albida* could make an annual equivalent energy contribution of 3.48 GJ/ha in Ethiopia. Such a contribution can facilitate significant improvements in agricultural development such as enhanced productivity, enhanced crop nutrition, and adaptation to climate change for farming systems, as well as a contribution to climate change mitigation. These aspects are discussed further below. It is important to note that in different regions and under different climate and environmental circumstances, there may be significant variation in the nitrogen additions of *F. albida* to cropping systems. The values arrived at in this study, while based on sound research, and likely to have broad application, should not be regarded as precisely prescriptive in each instance, inside or outside of Ethiopia. Future research can build on the principles described in the current study to arrive at accurate assessments of the energy and climate contributions of *F. albida* in other regions and circumstances.

Soil Nitrogen Additions

A crucial factor for this study is the quantity of nitrogen added to the soil by the leaf litter from the *F. albida* trees. Earlier research has provided estimates that were far higher than the value used in the current study. One such estimate by the Centre Technique Forestier Tropical [CTFT (Centre Technique Forestier Tropical), 1989] estimated an annual addition of 480 Kg N ha^{-1} and linked this to an equivalent addition of 1.15 tons of urea nitrogen fertilizer. (Dancette and Poulain, 1969), cited in Umar et al. (2013) provide an estimate of 300 kg N ha^{-1} added by Faidherbia trees annually. A study in Zambia by Yengwe et al. (2017) estimated that, over a 35-year time span, a *F. albida* tree contributed between 61 and 78 kg N ha^{-1} year $^{-1}$, with mature trees contributing an estimated 100 Kg N ha^{-1} year $^{-1}$. By contrast, Umar et al. (2013), in another study in Zambia, estimated that a Faidherbia tree would provide 39 kg N ha^{-1} annually. Umar et al. (2013) also stated that, for small holders, this nitrogen addition could be viewed as a direct substitute for purchased mineral fertilizer. The value used for calculation in the current study is a conservative estimate that is consistent with the range of values reported in recent work on nitrogen additions from Faidherbia trees and based on data from direct measurements using more recent investigative techniques.

MANUFACTURING ENERGY CALCULATIONS

The current study uses the values set out by the EPA (United States Environmental Protection Agency) (2017) to calculate the energy expended to manufacture urea. The range of values for the production of ammonia was 30.9–39.1 GJ/ton of ammonia depending on the age and practices of the manufacturing facility. The current study used the average of this range, 35.0 GJ/ton of ammonia as representative on the recommendation of one of the EPA study's authors (EPA (United States Environmental Protection Agency), 2017). The same EPA (United States Environmental Protection Agency) (2017) study provided a value of 6.0 GJ per ton of urea produced that is used in the current study. Earlier studies of energy consumption for ammonia production cited by Patzek (2005) found a value of 34.5 GJ/ton for modern NH_3 production, and Patzek (2005) found values ranging from 35.6 to 58 GJ/ton reported in the pre-1986 literature with values as high as 65 GJ/ton reported in the literature of small pre-1969 plants. The energy required to produce urea, citing the values of 35.6 GJ/ton value for the production of ammonia and 7.5 GJ/ton for urea from the same source, is reported in the existing literature as 42 GJ/ton of urea. However, this assumes that on a per ton basis the energy expenditures are directly additive and does not account for the stoichiometric relationship that occurs in the actual consumption of ammonia in the urea manufacturing process.

The current study, however, accounts for this stoichiometric relationship by adjusting the energy consumed in urea production by 0.567 ton of ammonia, which is the ammonia consumed per ton of urea produced (Fertilizer Europe, 2000; EPA (United States Environmental Protection Agency), 2017). When this relationship is included in calculations based on the values presented by Patzek, the energy value for the ammonia used in the production of a ton of urea is 20.2 GJ/ton urea. When this 20.2 GH/ton urea is added to the 7.5 GJ/ton urea used in the manufacturing process, this study obtains a value of 27.7 GJ/ton urea manufactured. This calculated value is much closer to the value of 25.49 GJ/ton derived from the values reported by EPA (United States Environmental Protection Agency) (2017).

TRANSPORTATION ENERGY CALCULATIONS

The values used in this study to calculate the energy used in transporting urea fertilizer are not identical to those found in other sources. Standard values for energy consumption for freight transport were reported by Deutsche Bahn (2017). For truck freight energy consumption, the value of 1.31 MJ/ton-km closely matches the value of 1.33 MJ/ton-km published by Simonsen and Walnum (2011) but both are far below the >3.5 MJ/ton-km for Africa found in the International Energy Agency (IEA) (2009). The International Energy Agency (IEA) (2009) value was specific to Africa and it was used in the current study.

The value for ocean freight provided by Deutsche Bahn was 0.09 MJ/ton-km and substantially lower than the 0.172 MJ/ton-km published by Simonsen and Walnum (2011). Values reported in Gleick et al. (2012) are substantially higher than either of these values, and Gleick cites DOE and Natural Resources Canada with values of 0.37 MJ/ton-km for ocean freight transport and 3.5 MJ/ton-km for heavy truck transport (also consistent with the International Energy Agency (IEA) (2009). In this study we use the values of Simonsen and Walnum (2011) because they are more conservative than those cited by Gleick and likely to underestimate, not overestimate, the equivalent energy input benefit to the farming system. Further, these values were selected over the more conservative values of Deutsche Bahn because sourcing from Simonsen and Walnum includes explicit external peer review. Evidently further research on this energy expenditure will be needed in the future, focused specifically on the transportation of urea fertilizer and specifying both the typical type and displacement of the ship transport and the likely energy expenditure of the typical trucking journey from the port of Djibouti to Addis Ababa.

ENERGY ANALYSIS OF THE FERTILIZER CONTRIBUTION TO THE FARMING SYSTEM

One of the factors that separates agriculture in the developing world from agriculture in the industrialized world is the difference in energy inputted to the farming systems and the crop yields, per unit of energy invested, from each system. Using corn as a comparison crop, Pimental (2009) found that corn production in India and Indonesia had an energy input to output ratio of 1:1.08 but corn production in the United States had an energy input to output ratio of 1:4.11 with a corresponding 5-fold increase in crop yield. The energy input, occurring through mechanization and the very large application of fertilizers in the United States, is responsible for much of this massive increase in crop yield (Warren, 1998). In the energetics of this study, part of the increase in yield comes from what is essentially an increase in efficiency, where energy in the form of animal traction and human labor that is less productive in cultivating and harvesting, is substituted for by more productive mechanical and fossil fuel energy, in the United States. However, with respect to nutrient inputs, the energy contribution of nitrogen virtually doubles between the two systems, with the energy value of nitrogen in India and Indonesia reported as 1,200 kCal $\times$ 1,000 $ha^{-1}$and as 2,480 kCal $\times$ 1,000 $ha^{-1}$for the United States (Pimental, 2009). This is an energy input increase achieved through significant additions of fossil fuel, in the form of natural gas, used to produce nitrogen fertilizer.

While a corresponding input of fertilizer energy would probably also increase yields in the developing world, there are several obstacles to realizing this benefit. One such obstacle is the lack of farmer financial resources, or sometimes shortages of foreign exchange on a national level, to buy fertilizer. This is compounded by the logistical difficulty in transporting and distributing fertilizer to the small farmers who need it. In addition, the heavy reliance of nitrogen fertilizer production on fossil fuel, which is a primary energy input into this production system, means that there will be significant emissions of greenhouse gases, which have negative consequences for the earth's climate. Given the energetics of breaking the triple atomic bond of diatomic Nitrogen, it is currently not cost-effective to use renewable energy, and not natural gas, in the nitrogen fertilizer production system (Pimental, 2009).

Nevertheless, the agricultural benefits to be gained from adding nitrogen fertilization are so substantial that an alternative method of bringing this energy into the Ethiopian agricultural system would be quite useful. This study shows that incorporating *F. albida* into the Ethiopian farming systems can provide this energy input in a manner that is effective and environmentally beneficial, from a climate change point of view. Due to its reverse phenology, Faidherbia is out of phase with the planted crops, so is able to harvest what would otherwise be agriculturally unused photosynthetically active radiation incident from the cropping area during the unplanted dry season and use parts of this energy to fix nitrogen from the atmosphere. This occurs as Faidherbia provides part of the resulting photosynthate to the symbiotic bacteria in the roots. These roots then break the energy-intensive nitrogen triple bond in ammonia, without using fossil fuels and provide the resulting nitrogen to the tree. The tree is not unique in this ability to obtain nitrogen from the atmosphere but is unique in that it can take advantage of this nitrogen fixation in areas where alternatives such as "green manure," or nitrogen-fixing crops would be infeasible because these methods can provide nitrogen by depleting the soil of moisture and sacrificing an entire cropping cycle. *F. albida* trees, conversely, are able to expand the net quantity of energy entering the system by converting it into a usable form, rather than letting it escape from the system as radiant heat. This increase in energy input is equivalent to the additional energy of fertilizer that is often made available through large investment of fossil fuel, but without the expense or climate consequences of fossil fuel consumption.

A process of adding energy to the agricultural system through the addition of nitrogen via biological nitrogen fixation, through the integration of *F. albida* into the agricultural system, could increase yields in large areas of Africa (and elsewhere) in the developing world but without the need to develop corresponding manufacturing and transportation infrastructure to support this increase and without the corresponding greenhouse gas emissions. This increase might also be enhanced by the development of other components of the agricultural system, such as the development of locally adapted, dryland crop varieties that could withstand the restricted quantity and variability of rainfall, while taking advantage of the increased nutrient availability due to introduction of this agroforestry system. The combination of more productive and adaptive varieties could be further enhanced by the adoption of water capture and soil conservation methods (Reij et al., 2009a), as well as highly targeted, locally-appropriate fertilizer application technologies for other limiting nutrients, once the fundamental nutrient base for crop production has been provided, by the Faidherbia trees. In these ways there is the potential for *F. albida* to provide the energy/nutrient foundation for a marked, discontinuous increase in crop yields.

THE ENERGY SUBSTITUTION OF *FAIDHERBIA* PRODUCES ADDITIONAL BENEFITS BEYOND N FERTILIZATION

In addition to the avoided emissions, there are significant differences between the nitrogen energy expenditures that provide manufactured nitrogen fertilizer to the agricultural system and those used by *F. albida* to add nitrogen to the system. The nitrogen from Faidherbia enters the agricultural system when the trees lose their leaves at the beginning of the rainy season and the decomposing leaves deposit both the fixed nitrogen that was used to grow the leaves and the leaves' carbon component into the soil, leading to increases in soil organic matter in proximity to the tree (Hadgu et al., 2009; Sileshi, 2016). This increase in soil organic matter has significant implications for crop productivity, agricultural system food security and climate change adaptation. The net increase in organic matter, especially in agricultural systems from which it has been depleted, both greatly enhances the effectiveness of added nitrogen fertilizer (Marenya and Barret, 2009) and improves other soil properties, such as plant available water and cation exchange capacity. The increase in soil organic matter also favors increased plant productivity and crop resistance to drought (Bot and Benites, 2005), both of which are critical components to maintaining sustainable yields for food security and to facilitating adaptation to climate change, which is projected to result in greater variability in rainfall and increased instances of drought (Kandji et al., 2006).

The energy input of the Faidherbia tree thus provides multiple system-wide benefits[3] beyond the addition of nitrogen that cannot be matched by the equivalent energy input provided by chemical nitrogen fertilizer. These additional systemic benefits are more difficult to quantify than the fertilizer energy use equivalence but should be considered when assessing the potential of *F. albida* to improve agricultural systems in the context of rural development.

THE FERTILIZER SUBSTITUTION OF *FAIDHERBIA* PROVIDES CLIMATE CHANGE MITIGATION BENEFITS

As illustrated in Equations (8)–(12), above, there are significant avoided carbon dioxide emissions associated with using nitrogen provided by Faidherbia instead of nitrogen from manufactured urea. This study calculates avoided CO_2 emissions of 0.116 tons per hectare per year. Where large-scale integration of Faidherbia takes place as a strategy for agricultural development, this contribution to climate change mitigation could be significant. For example, the late Prime Minister Meles Zenawi of Ethiopia announced at the Durban Climate Change Convention in December 2011, that the Ethiopian government would work to establish a 100 million *F. albida* trees Ethiopia through engagement with smallholder agriculture (https://allafrica.com/stories/201211190086.html, site accessed 8/15/2018). Achieving this level of integration would result in real contributions to Ethiopia's pledge in its Nationally Determined Contribution to reduce emissions by 64% below business-as-usual projections by 2030. Such a contribution would be significant in both ensuring agricultural productivity continues to rise to meet a growing human population and in showing that climate mitigation can also support the achievement other national development benefits.

[3]By increasing the soil organic matter, the tree provides multiple benefits to the cropping system including, increased plant available water, increased fertilizer use efficiency, increased water use efficiency, increased cation exchange capacity, and improved ease of cultivation.

The increasing yields achieved in industrialized agriculture have come at a price of increased emissions of greenhouse gases, especially CO_2 and methane (CH_4), making agriculture a major contributor to climate change [IPCC (Intergovernmental Panel on Climate Change), 2014]. Nitrogen fixation by human chemical means has now altered the global nitrogen cycle (Steffen et al., 2005). At the same time, there is a need to increase agricultural productivity to feed the growing human population in an environmentally sustainable way in part by closing the yield gap, between the potential productivity of the agricultural system and its current productivity (Foley et al., 2011). *F. albida* can help accomplish these dual goals, as it provides nitrogen fertilization, without any additions of heat-trapping gases to the atmosphere. As such, *F. albida* provides an alternative development pathway to closing of the yield gap, while having a positive effect on the climate. As this closing would otherwise need to be accomplished, in part, by the addition of fossil fuel produced nitrogen fertilizer, the contribution of Faidherbia effectively substitutes for the chemical fertilizer input (Umar et al., 2013). Thus, the emissions associated with the manufacture and transportation of the fertilizer to the point of application can legitimately be counted as an avoided emission that helps mitigate climate change in combination with the carbon sequestered in the trees' biomass and in the increases in soil organic matter associated in the trees' areas of influence. Indeed, increases in carbon sequestered above and below ground in Evergreen Agriculture systems that include Faidherbia, or other tree species that provide a fertilizer benefit, can be as much as an order of magnitude greater than that of conservation farming alone (Garrity et al., 2010).

Faidherbia also sequesters carbon in its biomass and increases the levels of soil organic matter within its area of influence. These benefits of sequestration are fundamentally different from avoided emissions, as carbon sequestered in soil is released if the tree is cut or burned or if the soil brought under more intensive tillage. Conversely, the avoided emissions resulting from fertilizer substitution are permanent, as they are associated with a specific fertilizer application in a specific cropping cycle in a particular year. They are thus equivalent to avoided emissions on par with an increase in energy efficiency at a factory that reduces emissions in a given year. As such any tradable carbon credits associated with the trees' avoided emissions should be considered as permanent, fully fungible credits and thus different from other land use credits.

Case Studies in Niger and Zambia

Farmer Managed Natural Regeneration (FMNR)[4], is a highly successful approach to the regeneration of degraded land and to generating productivity increases centered on the cultivation of trees in small-holder agricultural systems (Reij et al., 2009a). The set of methods was introduced and promoted in Niger in the 1970s and 1980s with key adoption occurring during the drought of 1983–1984 (Reij et al., 2009b). By 2009 the methods had spread widely in areas of Niger, largely by spontaneous adoption among farmers and communities. Since *F. albida* is a key species used

[4]See Reij et al. (2009a) for a more complete description of the method, adoption and impact of Farmer Managed Natural Regeneration.

in this approach, the area of FMNR on a landscape can provide some insight into the potential scale that could be achieved through the integration of *F. albida* into smallholder agricultural landscapes. Based on the analysis of high-resolution, remote sensing imagery for the Maradi-Zinder region of Niger, Reij et al. (2009a) estimate that FMNR was practiced over 4,828,500 ha. Using this figure as a starting point in a thought experiment, it is assumed, conservatively, that Faidherbia is present in half of this area and that the Faidherbia tree cover is half of that of the Yengwe et al. (2018) study. The energy for transportation will likely be greater to this area than for typical areas of Ethiopia, but for purposes of this thought experiment, the same value is used to produce a conservative estimate. Based on the calculations suggested in the current study, *F. albida* covering half the FMNR land used in Niger would result in an annual injection of energy equal to 4.2 million GJ and 0.28 million tons of avoided CO_2 emissions.

$$4.2\ million\ \frac{GJ}{year} = (2,414,250\ ha*3.48\frac{GJ}{ha-year})/2$$
$$0.28\ million\ \frac{ton\ CO_2}{year} = (2,414,250\ ha*0.116\frac{ton\ CO_2}{ha-year})/2$$

The avoided emissions are at a significant scale such that they could help Niger fulfill the pledges in its Nationally Determined Contribution plan to both reduce GHG emissions by at least 3.5% by 2030 and to scale up sustainable land management practices over all agroecological areas[5] (INDC, Niger, 2015). At the scale of adoption of *F. albida* that is already occurring in large areas of the Sahel and elsewhere in Sub-Saharan Africa, it seems reasonable to propose that the avoided emissions produced by the trees could also potentially make contributions to the climate mitigation efforts of some countries including, Ethiopia.

Similarly, the Zambian Conservation Farming Unit (CFU) estimates that *F. albida* is now cultivated on 300,000 ha of farmland with recommended planting rates likely providing full canopy cover (Garrity et al., 2010). As in the Niger example, the energy for transportation will likely be greater to this area than for Ethiopia, but to be consistent, the same value is used to produce a conservative estimate. Based on the current study figures, the energy input of the *F. albida* trees cultivated on the 300,000 ha in Zambia is estimated in this thought experiment to be 1.04 million GJ per year and the avoided emissions to be 50,400 tons of CO_2 per year.

$$1.04\ million\ \frac{GJ}{year} = 300,000\ ha*3.48\frac{GJ}{ha-year}$$
$$34,800\ \frac{ton\ CO_2}{year} = 300,000\ ha*0.116\frac{ton\ CO_2}{ha-year}$$

Further, the Faidherbia nitrogen is estimated to substitute for 34,200 tons of manufactured urea annually. A full economic analysis of this substitution is beyond the scope of the current study, however a simple price comparison is provided to show the possible scale of the monetary value of the substitution. It is assumed that Faidherbia nitrogen is directly interconvertible with manufactured urea nitrogen and that Faidherbia nitrogen substitutes directly for urea nitrogen. The price is for urea as purchased in bulk from a distributor and does not include transportation, handling, or application costs. The addition of these costs could potentially raise the value of the substitution. At a price urea fertilizer of $200[6] per ton of urea fertilizer the Faidherbia leads to savings of $6.8 million USD in fertilizer that would not need to be purchased.

$$6.8\ \frac{million\ USD}{year} = 300,000\ ha*0.114\ \frac{ton\ urea}{ha-year}*200\ \frac{USD}{ton-urea}$$

THE CONTRIBUTION OF *FAIDHERBIA ALBIDA* WOULD ALSO HAVE MULTIPLE ECONOMIC BENEFITS

Finally, it is important to note that adding nitrogen from *F. albida* is likely to have multiple economic benefits, some of which are specific to integrating trees into the agricultural system. In addition to the positive impacts on crop productivity, food security, and decreases in vulnerability to drought impacts that are discussed throughout this study, *F. albida* provides tangible financial savings to the farmers, governments, and other stakeholders in the economic system. Governments in Sub-Saharan Africa sometimes subsidize manufactured fertilizer, so procuring the nitrogen fertilizer by cultivating *F. albida* instead of from imported manufactured urea would reduce government's foreign exchange expenditures. The use of the trees would also avoid an unstable economic dynamic in which farmers are dependent on government subsidies to use nitrogen fertilizers to a degree such that the curtailment of said subsidies would lead to abrupt drop in fertilizer use, crop productivity, and potentially, a severe economic shock. By contrast, Faidherbia trees are long lived, provide a consistent and reliable source of nutrients, and are decoupled from both the world price of fertilizer and the economic policies of the government. Malawi has adopted policies that reflect the benefits of substituting tree-based sources of nitrogen for subsidized chemical fertilizer (Garrity et al., 2010) and other governments in the region may also recognize these benefits.

RELEVANCE AND APPLICABILITY TO OTHER AREAS IN AFRICA

The native range of Faidherbia in Africa extends over vast areas of Africa (**Figure 3**) and includes over 20 African countries. In addition to its current application in Ethiopia (Hadgu et al., 2009), Faidherbia has demonstrated potential to contribute to agriculture in Zambia (Yengwe et al., 2017), Malawi (Beedy et al., 2016), Niger (Kho et al., 2001), and Burkina Faso (Reij et al., 2009b). The benefits of *F. albida* for crop production

[5] Agriculture Forestry and Other Land Use (AFOLU) is a priority sector for climate mitigation under the Intended Nationally Determined Contribution plan of Niger (INDC, Niger, 2015).

[6] International Raw Materials Ltd. reported a global granular urea price of $263 per metric ton on July 26, 2018. https://www.irmteam.com/

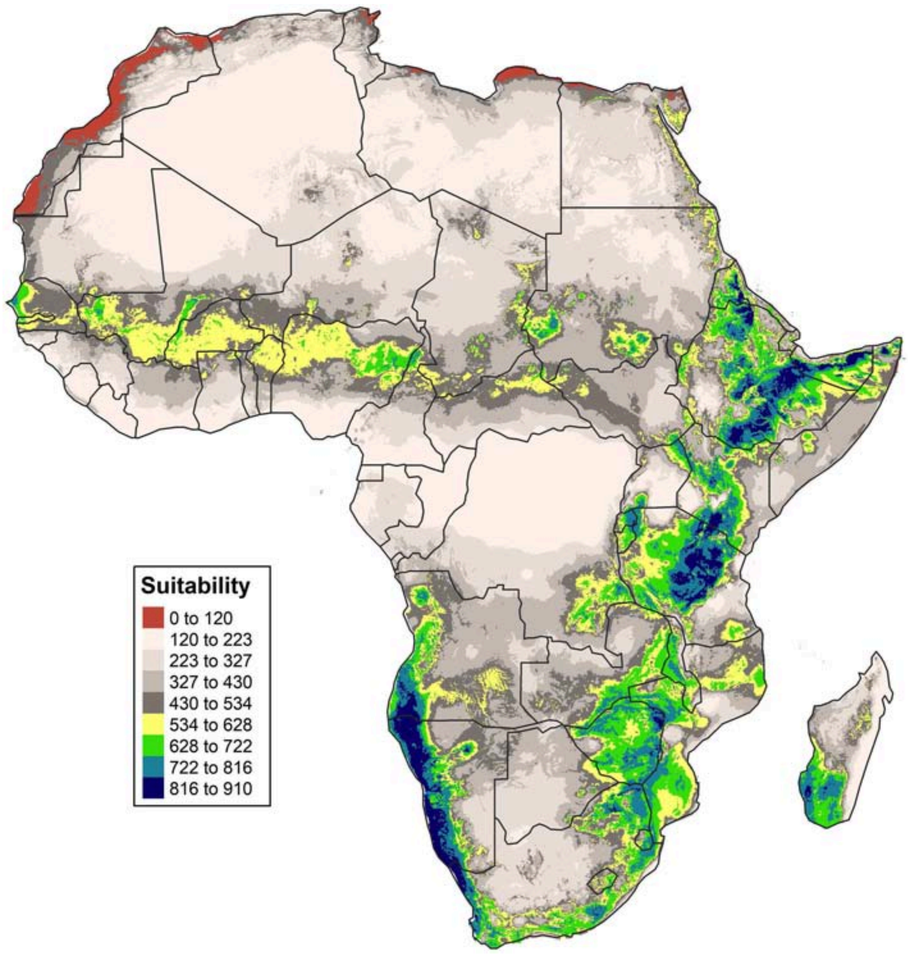

FIGURE 3 | Estimated distribution of *Faidherbia albida* in Africa, obtained by ensemble suitability modeling with *BiodiversityR* (Kindt, 2018). In the map, the green-blue colors show where the species is expected to be suitable, the gray areas where the species is not suitable and the orange areas where the species was predicted to be suitable but where those latter areas were outside a buffer around the known presence observations. Suitability values above 534 correspond to likely presence of the species with increasing values associated with higher likelihood of species presence. The suitability index is unitless can be understood as the probability of the species occurring at a given location (de Sousa et al., 2019). Country boundaries were obtained from the *tmap* package [*data(World)*, (Tennekes, 2018; de Sousa et al., 2019)].

include the addition of nitrogen to the soil (Yengwe et al., 2017), increasing soil organic matter (Kamara and Haque, 1992), and improving crop micro-climate (Sida et al., 2017). These benefits are associated with the tree species and are not specific to a particular crop. It is very likely that the potential beneficial effects of the tree are available for many crops. Yield increases associated with Faidherbia have been reported for millet, maize, sorghum, teff grown with wheat, sunflower (Barnes and Fagg, 2003), wheat alone (Sida et al., 2018), and barely (Hadgu et al., 2009). All of these crops have benefited when grown in association with Faidherbia and their production systems have received an energy input. To the extent that Faidherbia nitrogen inputs substitute for manufactured fertilizer these systems can also provide quantified avoided emissions as a climate change benefit and where they are implemented at scale could contribute to African countries meeting their Nationally Determined Contributions under the international climate accords. The methods described here and associated with Faidherbia agroforestry have wide application beyond Ethiopia in many countries and landscapes.

LARGE SCALE IMPACT SCENARIOS

To illustrate the potential large-scale contribution of the avoided emissions provided by *F. albida* in an Ethiopian context, the following scenarios are provided. It is well understood that this is an illustrative exercise and that actual implementation would be far more complex and could produce different results. The aggregated suitability analysis which integrates the environmental factors determining the range of Faidherbia indicates that very large areas of Ethiopia are highly suitable for Faidherbia adoption (**Figure 3**), other factors that could influence adoption include the presence of existing viable rootstock and potential policy interventions such as provision of seedlings, extension support and secure land tenure. However, while taking the uncertainty of these factors into account, this analysis does provide an initial comparison, at scale, of selection between policy alternatives that include large-scale adoption of *F. albida* agroforestry on uncultivated and unproductive lands, no action or intervention to improve productivity on uncultivated and unproductive lands, and the addition of an equivalent amount of nitrogen in the form of urea fertilizer to increase productivity on uncultivated and unproductive lands. *F. albida* has been a key part of the Farmer Managed Natural Regeneration (FMNR) approach which has been adopted over millions of hectares of Niger and Burkina Faso and has been successful in reversing land degradation and rehabilitating barren agricultural landscapes, bringing them to high levels of agricultural production (Reij et al., 2009b).

In the first scenario *F. albida* is used to fully transform that land in Ethiopia which has been degraded or is currently unproductive, into productive agricultural land, following some aspects of the Sahelian FMNR model including cultivation from existing rootstock and cultivation from seedlings. As of 2013 unproductive land in Ethiopia accounted for 12,457,975 ha, while for uncultivated land accounted for 1,400,565 ha (**Table 2**, **Figure 4**).

The area available for *F. albida* agroforestry crop production, without changing practices on land currently in production, was the sum of the unproductive and uncultivated land, 13,858,540 ha. Based on the value of 0.116 t CO_2e/ha/yr, if this area was converted to *F. albida* based production, the avoided emissions would be 1.6 Mt CO_2e per year or 104 Mt CO_2e over the 65-year productive life of the trees. The Intended National Determined Contribution (INDC) plan presented by Ethiopia, specifies emissions reductions for all major sectors of the economy. The proposed annual emission reduction for the building sector is 5 Mt CO_2e per year. In this scenario avoided emissions gained from *F. albida* agroforestry would be equivalent to achieving ∼32% of this goal.

For comparison two business—as—usual scenarios are presented. In the first business—as—usual scenario there is no cultivation or promotion of Faidherbia and no effort to bring uncultivated or unproductive lands into cultivation. This would mean forgoing the Faidherbia mediated productive capacity of this land area, which could be substantial. Sida et al. (2018) reports average wheat yield under Faidherbia in the rift valley of Ethiopia, as 6.7 t/ha, yield levels of this kind, over the scenario area, could mean a foregoing access to 94 Mt of wheat annually. Alternatively, in the second business as usual scenario, if the scenario area was brought under cultivation using additions of urea fertilizer this would mean additional emissions of 1.6 Mt CO_2. As this would be a net addition to existing emissions levels, under this business—as—usual scenario Ethiopia would have to decrease emissions by 3.2 Mt CO_2e per year to achieve the same levels of emissions produced by the 1.6 Mt CO_2e avoided emissions provided by the first Faidherbia scenario. It should be noted that in the chemical fertilizer scenario, the organic matter additions provided by Faidherbia do not occur. On the weathered soils of Africa this is a critical deficiency because the without organic matter in the soil the yield increases obtained by the addition of chemical fertilizer cannot be maintained and yields begin to fall off despite ongoing additions of chemical fertilizer (Pieri, 1992). Ultimately this business—as—usual scenario is most likely to produce declining yields without a climate benefit and with emissions that add to the reductions needed to attain the INDC.

A second scenario with a somewhat more conservative approach is as follows. Between 2007 and 2013 the estimated area of unproductive land went from 4,467,485 to 12,457,975 ha, a net increase of 7,990,490 ha. As productive land is at a premium, it is assumed that this increase in unproductive land in this brief period of time was due largely land degradation. The primary cause of land degradation is soil erosion driven by excessive cultivation using poor tillage practices, excessive livestock grazing and stocking rates, and deforestation (Taddese, 2001). If Faidherbia agroforestry were used to bring all of this land back into production the avoided emissions per year would be, again based on a value of 0.116 t CO_2e/ha/yr, 0.93 Mt CO_2e per year. This would equivalent to achieving ∼18% of the emissions reductions proposed for the building sector in Ethiopia's INDC. As with the scenario covering both unproductive and uncultivated land, there are two corresponding business—as—usual scenarios for this area. The first business as usual scenario involves leaving the land in an unproductive state and forgoes the potential productivity achieved through Faidherbia agroforestry. In this instance that could include substantial harvests of wheat, again at the level of 6.7 t/ha and forgoing 53 Mt of wheat annually. In the second business—as—usual scenario the nitrogen benefit of Faidherbia is replaced by equivalent additions of urea. As in the large area scenario, this would be a net addition to emissions and would require net emission reductions of 1.9 Mt CO_2e to achieve the same level of emissions as that provided by the 0.93 Mt CO_2e contributed by the Faidherbia scenario. Ultimately, as with the large area scenario, fertilizer additions in the absence of soil organic matter maintenance will result in declining yields while emissions remain constant an increasing carbon footprint per unit of yield.

The same two scenarios can be used to calculate potential energy inputs to Ethiopian agriculture that Faidherbia could provide in in these areas. With this urea equivalent urea addition there is an input of 3.48 MJ per hectare per year. For the first scenario with 13,858,540 ha, that combines uncultivated and unproductive land, this is equivalent to an input of 48,227,719 GJ/ha/yr. For the second scenario in which the net addition of unproductive land, 7,990,490, is brought under Faidherbia agroforestry, this is equivalent to an input of 27,806,905 GJ/ha/yr. These are equivalent to the energy in 1,645,548 and 948,782 tons of coal, respectively (National Research Council, 2007). Under business—as—usual, if no equivalent urea fertilizer additions are made there is no energy addition made to the agricultural system and no corresponding increase in productivity. In the scenario where an equivalent addition of urea is made without maintaining soil organic matter, there is an initial increase in productivity for an equivalent input of energy to the agricultural system, however over time as yields decline the energy use efficiency, that is, the yield increase per unit of energy input decreases.

TABLE 2 | Estimated area and net area change of land use land cover types (Simane Personal Communication, 2019).

Land use and land cover types	Estimated area 2007		Estimated area 2013		Net area changes 2007–2013	
	Ha	%	Ha	%	Ha	%
Annual cropland	15,401,065	13.1	21,372,910	18.18	5,971,845	38.78
Perennial crops	1,998,612	1.7	4,390,664	3.73	2,392,052	119.69
Grazing land	59,958,344	51	13,288,994	11.30	−46,669,350	−77.84
Currently unproductive land	4,467,485	3.8	12,457,975	10.60	7,990,490	178.8
Currently uncultivated land	21,984,726	18.7	1,400,565	1.19	−20,584,161	−93.63
Forest	4,232,354	3.6	16,156,166	13.74	11,923,812	281.73
Wood land and shrub land	9,522,796	8.1	48,498,108	41.22	38,975,312	409.28
Total	117,565,382	100	117,565,382			

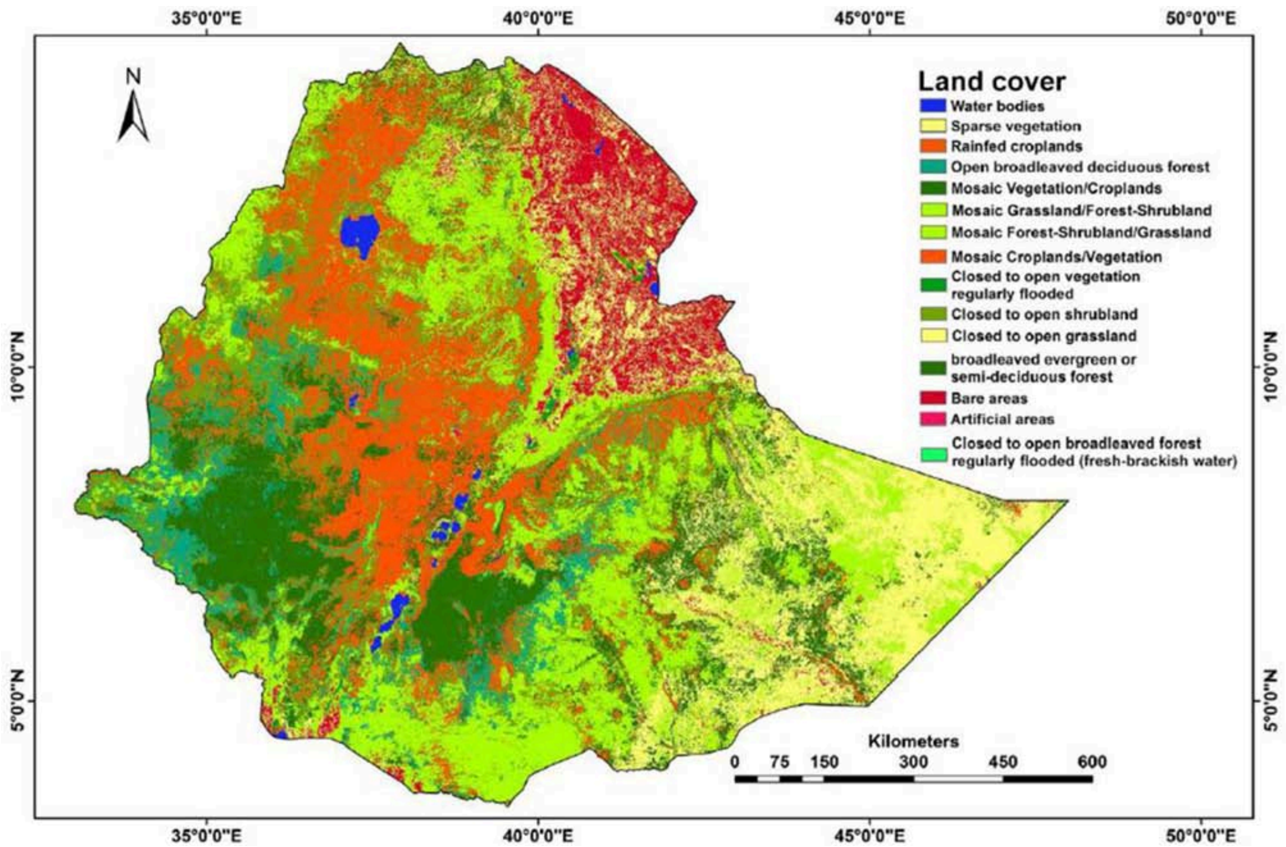

FIGURE 4 | Landcover map of Ethiopia (FAO, 2009 cited in Hailu et al., 2015).

CONCLUSION

F. albida's reverse phenology enables it to provide nitrogen nutrition and soil organic matter additions to farming systems that function as a significant contribution of useable energy to these same systems. The trees' energy input also provides a vehicle to ramp up agricultural productivity, similar to the way in which agriculture productivity increased in the industrialized world through increased energy inputs. In Ethiopia, this additional energy benefit occurs as the trees' decomposing leaves add nitrogen equivalent to the nitrogen contained in a substantial quantity of urea fertilizer and increase water availability to the crops. The development benefits, in terms of increased agricultural productivity and adaptation to climate change, are substantial. Additionally, the trees use solar radiation as their energy input, and this solar energy displaces the natural gas used to both manufacture urea and the fossil fuels used to transport the manufactured fertilizer to the point of use. The trees thus lead to substantial avoided greenhouse gas emissions, meaning that if *F. albida* trees were cultivated over large areas their avoided emissions could make a significant annual contribution to national efforts to mitigate climate change.

AUTHOR CONTRIBUTIONS

JH developed the original concepts, elaborated the concepts, performed a literature review, performed the mathematical calculations, wrote language included in the article, and found references supporting the research. BS provided discussion and important analysis of the concepts, provided information from the field that ensured the rigor and correctness of the work, wrote language included in the article, and found references supporting the research. CS provided discussion and important analysis of the concepts, wrote language included in the article, and found references supporting the research.

FUNDING

This research was support by National Science Foundation award BCS-1639214.

ACKNOWLEDGMENTS

Benjamin Zaitchik whose encouragement and support helped in execution of the research and the preparation of the manuscript. Roeland Kindt who helped us to access the most current understanding of the range and extent of *Faidherbia albida*.

Irving Mintzer whose comments and suggestion were a great help in refining and preparing the manuscript.

John Byrne whose feedback and suggestions from the energy point of view were very helpful in putting the work into perspective.

The National Science Foundation whose financial support made this research and scientific collaboration possible.

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