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REPORT

Better Forests, Better Cities

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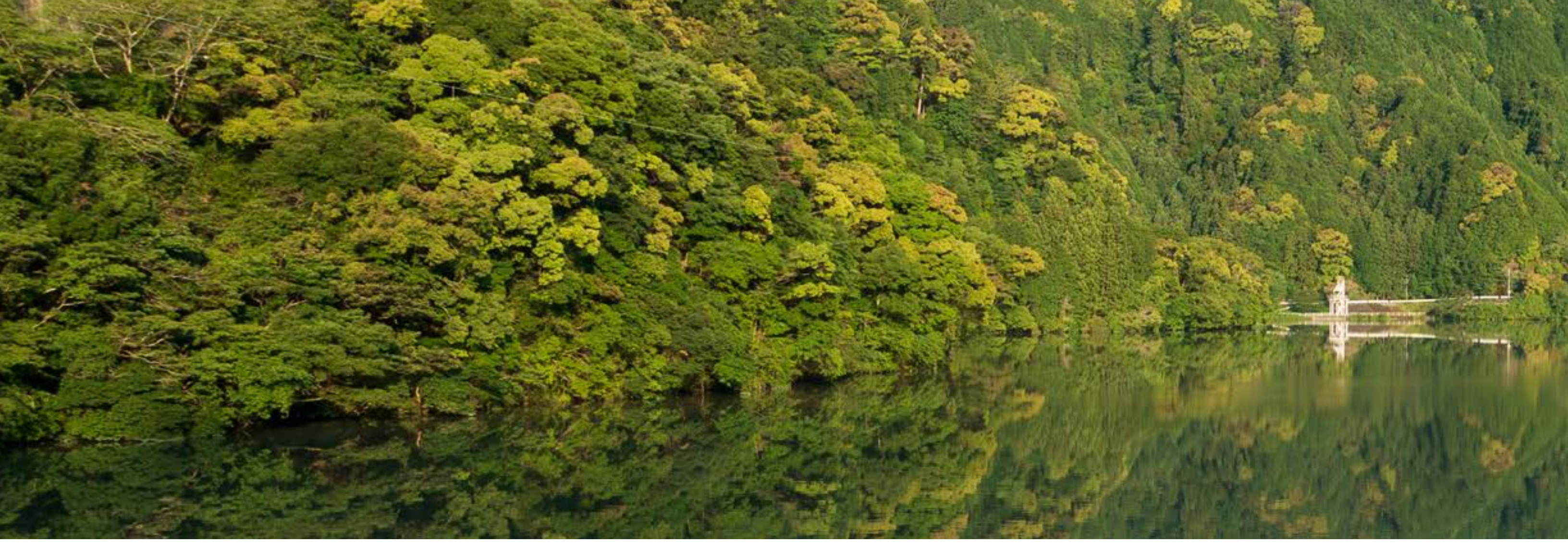

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Foreword

Cities across the world are reeling from the direct impacts of deforestation and forest degradation. In neighborhoods with low tree cover, higher mortality rates from extreme heat are on the rise, disproportionately affecting poor and marginalized communities. Meanwhile, deforestation and other disturbances to the world's forests emit an average of 8.1 billion metric tonnes of carbon dioxide every year, contributing to devastating climate impacts in cities across the world.

At the same time, cities are the ones shaping forests around the world. Although cities cover only a small proportion of the earth's surface area, their carbon footprints are large and extend far beyond their limits. Ongoing consumption of globally traded agricultural commodities – the vast majority of which are consumed by urban residents – is the leading driver of tropical deforestation. For example, 80 percent of permanent deforestation in South-East Asia is the result of land conversion to grow commodities such as oil palm.

The fates of cities and forests are deeply intertwined—which also offers us an opportunity to change course. Cities can redefine the role of nature within and outside of their boundaries. By taking action to protect, restore and sustainably manage forests at all scales, cities can tackle the global climate and biodiversity crises while promoting the well-being of their residents. The public policies and procurement practices of cities have enormous potential to support the rejuvenation of the world's forests—with huge benefits in return.

Until now, there has been a lack of clarity on how forests directly benefit cities and their residents. This report synthesizes hundreds of research articles to characterize the wealth of benefits that forests offer to cities in terms of human well-being, water security, climate mitigation, and biodiversity. The report evaluates the full range of benefits that cities receive from forests, whether they are inside, nearby, or far away from their boundaries, highlighting innovative examples from cities who are already leading the way. For example, the *Green Cadaster* in Skopje, North Macedonia offers a comprehensive map and catalog of every single tree and shrub in all public green zones within the city, making it easier for city officials to manage and track the benefits of green spaces. In Quito, Ecuador, a multi-stakeholder water fund known as *FONAG* has protected and restored over 40,000 hectares of forests with the support of over 400 local families. These are shining innovations and examples that decision makers across the world can learn from and seek to replicate in their own cities.

The report also echoes the *Cities4Forests Call to Action on Forests and Climate* that more than 50 mayors issued in 2021, calling for accelerated national and subnational action to support forests. As the first of its kind, this report provides city leaders with a new authoritative source to develop and expedite their efforts to protect forests worldwide.

As centers of political, economic, and cultural clout, city leaders have an increasingly important role to play. Mayoral voices are not yet tapped to their full potential in support of the world's forests. This needs to change, and soon. After all, the battle on climate change will be won or lost in cities. We cannot afford to lose any more time. By 2050, an estimated 70 percent of the world's population will live in cities. City leaders must act decisively in order to secure a green future for their growing populations and reap the benefits of a world with healthy forests.

ANI DASGUPTA
President & CEO
World Resources Institute


Executive Summary

This report evaluates how and when forests – inside, near and far away from cities – contribute to health and well-being, water security, climate change mitigation, and biodiversity conservation benefits for cities and their residents. As city leaders face demands from growing urban populations, coupled with the impacts of a rapidly changing climate, they should consider the role that forests can play in addressing these challenges and meeting the needs of city residents.

HIGHLIGHTS

- A growing body of scientific evidence shows that conserving, restoring, and sustainably managing forests can provide robust, low-cost infrastructure solutions to help cities and their leaders meet the myriad demands of growing urban populations, such as increased clean and reliable fresh water, safe and healthy environments, and protection from natural disasters.
- Cities around the world are responding to this evidence, increasingly using forests inside, near, and far away from cities to address their challenges and meet the aspirations of residents.
- Forests are particularly effective at providing cities and their residents with four benefits: human health and well-being, a clean and reliable water supply, climate regulation, and biodiversity conservation.
- This report evaluates the evidence base to show how and where these benefits are delivered and what immediate actions cities can take to better conserve, restore, and sustainably manage forests for the desired benefits.
- It presents a review of hundreds of synthesis papers, original research papers, and key reports and collectively shows how different forest types at different levels can deliver a diverse suite of benefits to cities.

BETTER FORESTS MAKE FOR BETTER CITIES

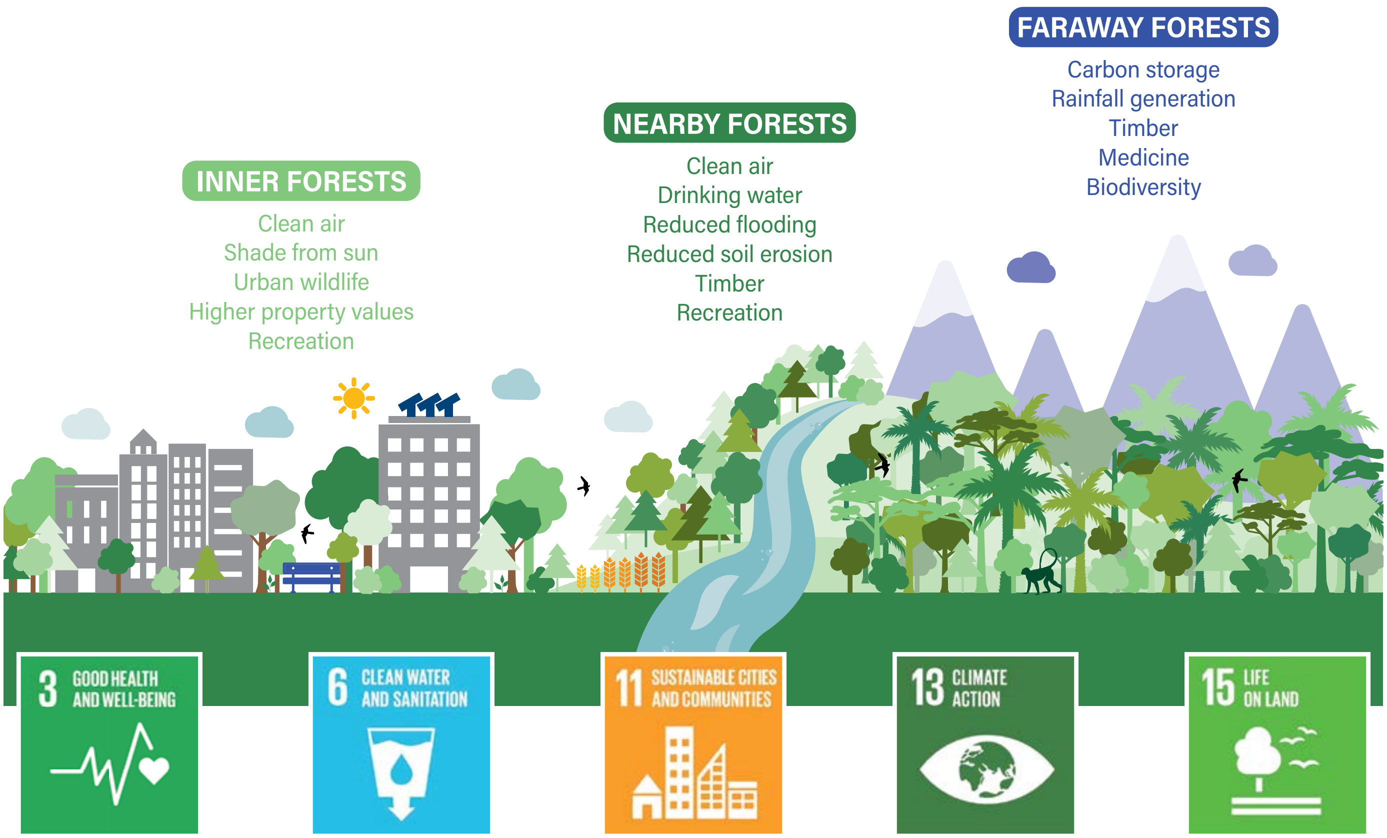
In the coming decade, city mayors and managers will face unprecedented demands from growing urban populations. Rapid urbanization and environmental changes are putting new pressures on burgeoning cities. City leaders are charged with providing urban residents with a safe place to live and work, environments that promote good health, clean and reliable freshwater, and protection from natural disasters. They will need to step up their climate action and meet other sustainability commitments—all of which are rising on political and media agendas. At the same time, city leaders will need to juggle these demands amidst dynamic conditions, often with tight financial resources.

Nature-based solutions[1] (NBS)—such as trees and forests—can help cities meet many of these needs. A growing body of scientific evidence shows that conserving, restoring, and sustainably managing forests can provide robust, low-cost infrastructure solutions to complement other traditionally built infrastructure. Cities around the world are responding to this evidence, increasingly using forests to address their challenges and meet the aspirations of residents.

Forests inside, near, and far away from cities (Figure ES-1) can help cities both meet their needs and contribute to commitments to act on global challenges:

- *Inner forests* include street trees, trees and forests on private property, patches of native woodland, forested ravines and corridors, and so forth, found within city boundaries. Inner forests can improve air quality, reduce the heat island effect (leading to lower energy use and energy bills), reduce stormwater runoff and urban flooding, provide access to nature and respite from the built environment, and support human health and wildlife.
- *Nearby forests* are trees, woodlands, and forests in the watersheds surrounding cities. They contribute to cleaner air in cities, support stable supplies of clean drinking water, reduce flooding, provide wildlife habitat, and offer space for recreation.
- *Faraway forests* are substantial, intact, and remote forests that are most often located far outside a city's boundary. These forests—particularly those in the tropics—sequester large amounts of carbon, generate reliable rains for

FIGURE ES-1 | Inner, Nearby, and Faraway Forest Benefits



Note: Forests at three levels provide benefits to cities and contribute to the achievement of the UN Sustainable Development Goals.
Source: Cities4Forests n.d.a.

cities and the world's agriculture belts, provide a wealth of products used by cities every day (including medicines, food, and building materials), and host the majority of the world's land-based biodiversity.

Forests are particularly effective at providing cities and their residents with four benefits: human health and well-being, a clean and reliable water supply, climate regulation, and biodiversity conservation. *Better Forests, Better Cities* evaluates the evidence base to show how and where these benefits are delivered by forests and, in unique circumstances, when and where they are not. This report presents a review of hundreds of synthesis papers, original research papers, and key reports. Collectively, this research shows how different forest types at different levels can deliver a diverse suite of benefits to cities.

FINDINGS FROM THE SCIENTIFIC LITERATURE

Health and Well-Being

Cities afford their inhabitants many benefits, but they also create conditions that can have negative impacts on health and well-being (Kuddus et al. 2020). Forests and trees, particularly in the inner forest, can improve the health and well-being of urban residents by these actions:

- *Reducing extreme heat.* The urban heat island effect—in which urban areas experience higher temperatures than their rural surroundings—presents a number of risks to human health. These include increased risk of heat-related deaths, increased concentrations of urban smog and ground-level ozone, spikes in energy and water demand, and power outages (Heaviside et al. 2017). Urban trees and forests can mitigate the urban heat island effect by providing shade and cooling the air via evapotranspiration. These processes reduce both the risk of heat-related illness or death and increase the livability of cities (Bowler et al. 2010a; Mohajerani et al. 2017; Wolf et al. 2020).

- *Enhancing urban air quality.* Ambient air pollution threatens the well-being of most urban residents. Nine out of 10 people breathe polluted air worldwide, leading to about 4.2 million deaths globally. Low- and middle-income countries are disproportionately affected (WHO 2016). Reducing emissions from the source is key, but carefully planned and managed inner forests can further improve air quality by removing and dispersing air pollutants (Nowak et al. 2014; Kumar et al. 2019; Hewitt et al. 2020).
- *Promoting mental and physical health.* Living in cities can take a toll on mental and physical health. Pollutants, being sedentary, and living close to other people can increase the prevalence of many kinds of diseases (Bai et al. 2012; Ventriglio et al. 2021). Forests and trees reduce noise, pollution, and other stressful conditions, and they provide opportunities for rest, relaxation, and recreation in nature (Hartig et al. 2014; Kuo 2015; Bratman et al. 2019; Wolf et al. 2020). Preventing deforestation and degradation of biodiverse forests outside cities may also reduce the spillover of infectious diseases, including novel viruses, from animal hosts to humans (Alimi et al. 2021).
- *Creating safe, walkable streets.* Cities around the world are working to increase biking and walking as ways to travel. Trees along streets and urban green spaces encourage active transport, providing shade, reducing localized air pollution, and making streets and pathways more beautiful and pleasurable (Wolf et al. 2020).
- *Supporting community connections.* Forests and other green spaces can build cohesion among urban residents by providing places for communities to gather, enhancing a "sense of place," and creating space for spirituality and reflection (Wolf et al. 2014; Jennings et al. 2016). Inner and nearby forests are desirable locations for social gatherings, recreation, tourism, and spiritual practice and contemplation (Kuo 2015; O'Brien et al. 2017; Irvine and Herrett 2018; Ngulani and Shackleton 2019).
- *Reducing inequity and empowering residents.* Social and economic inequality is a challenge facing most cities. Lower levels of urban tree canopy cover have been associated with relatively low-income and marginalized populations in some cities (Schwarz et al. 2015; Jennings et al. 2016; Gerrish and Watkins 2018; Watkins and Gerrish 2018). Unequal tree distribution can translate into unequal distribution of the important human health and well-being benefits trees provide (Jennings and Johnson Gaither 2015; Braubach et al. 2017). Engaging communities to plan and integrate more trees and natural areas into neighborhoods with marginalized and low-income residents can help to address systemic inequalities in urban areas (Wolch et al. 2014; Kondo et al. 2015; Jelks et al. 2021). Meaningful community engagement and leadership is essential to realize these benefits.

- *Providing food, medicine, and raw materials.* Although city residents rely heavily on imported goods sold in formal markets (e.g., stores), inner and nearby forests can help improve food access, especially for lower-income or marginalized groups in cities. These forests can provide food, medicines, and raw materials for subsistence or can provide income (Pramova et al. 2012; Shackleton et al. 2015).
- *Enhancing economic well-being.* Inner forests can provide multiple economic benefits to cities and city residents (Nesbitt et al. 2017). Trees can increase property values for residents and associated property tax revenues for municipal governments (Roy et al. 2012). They can serve as a form of "green infrastructure" that can lower the costs of stormwater management, reduce flooding risks, lower energy costs, and provide other cost-saving measures.

Water

Forests and trees at all three levels can be a cost-effective way to help improve and stabilize city water resources. Many cities struggle to provide ample clean water (water is "too dirty"), address flooding and erosion (there is "too much" water), plan for droughts (there is "too little" water), and deal with new levels of inconsistency in once-reliable rain patterns (water is "too erratic").

***Too dirty*: Many cities find it difficult to provide residents with a reliable supply of clean drinking water.** Contaminated drinking water causes severe health issues in many regions, and water treatment facilities can be costly to establish and maintain. Forests in watersheds can prevent soil erosion and filter sediment and pollutants (Kuehler et al. 2017), keeping surface waters and aquifers cleaner and reducing costs to cities. For example, recent analysis finds that upstream forest protection and restoration can reduce costs for water utilities in the world's 534 largest cities collectively by US$890 million per year (McDonald and Shemie 2014). Mature native forests provide these benefits more reliably than plantations.

***Too much*: By 2030, riverine flooding will impact around 130 million people and $535 billion in urban property, and coastal flooding will impact another 15 million people and $177 billion in urban property.**[2] Forests—especially nearby forests—can prevent or reduce the severity of flooding. Forests intercept and store rainwater, reducing stormwater runoff. They improve the ability of soil to hold water, increasing both infiltration (entry) and percolation (downward movement) of rainwater (Berland et al. 2017; Kuehler et al. 2017). They increase the amount of water returned to the atmosphere by evapotranspiration. And they can store excess runoff, holding and slowing the release of water much like a sponge. Forested watersheds (near cities) regulate water flows and help prevent flooding and landslides. Trees and other vegetation in bioretention areas, green roofs, and bioswales can also complement traditional, engineered water infrastructure solutions for stormwater management in urban areas.

***Too little*: Water scarcity can be caused by drought, groundwater depletion, or reduced river flows. Many cities around the world—especially in arid regions—face seasonal or year-round issues with water supply.** The "Day Zero" drought-induced water crisis in Cape Town of 2017–18 drew worldwide attention to the risks of too little water: thousands of people lost their jobs, food security decreased, and a political crisis ensued. Preventing deforestation and restoring forests can help sustain water availability (Brauman et al. 2007; Filoso et al. 2017; van Dijk and Keenan 2007; Zhang et al. 2017) by increasing the infiltration capacity of soils, which promotes groundwater recharge, although benefits may lag in reforested areas and water yields may decline initially in the years immediately following restoration or reforestation (Filoso et al. 2017). Forests also affect rainfall patterns at regional and even global levels. By capturing and recycling precipitation, evapotranspiration sends water into the atmosphere, creating "flying rivers" that transport water to fall as rain in downwind regions far from the forest.

***Too erratic*: Urban residents are vulnerable to increasingly erratic weather patterns, including longer and more intense droughts and heavy rainfall, linked to climate change.** Variability and unpredictability in precipitation and water supply create additional challenges for municipal leaders, such as providing a reliable water supply to residents or preparing for unpredictable water highs and lows. Because of their role in the global water cycle, forests can help reduce this variability. Forests, especially large tracts of intact forests and rain forests, recharge atmospheric water supplies and thereby influence rainfall patterns hundreds to thousands of miles away. Forests also can reduce local water variability by enabling a slow release of water over time. Conserving and restoring forests are important strategies for stabilizing precipitation levels and groundwater availability in a changing climate (Melo et al. 2021).

Climate

The effects of climate change—including heat waves, flooding, rising sea levels, and droughts—threaten both the well-being of urban residents and the costs of operating a city. Not surprisingly, urban residents' concerns about climate change are growing rapidly. Forests are good for both climate change adaptation and mitigation, and some of the adaptation benefits (for example, flooding reduction) have previously been mentioned. This section focuses on how forests can mitigate climate change. Cities around the world are committing to bold action to reduce their greenhouse gas (GHG) emissions and tackle climate change. C40 Cities Climate Leadership Group (an international network of megacities that have committed to take action on climate change), ICLEI—Local Governments for Sustainability, and the Carbon Neutral Cities Alliance are all examples of city networks committed to reducing GHG emissions. The first important step is to reduce GHG emissions from sources within cities and from city consumption, but forests can help cities go further.

Forests and trees in cities can reduce energy-related GHG emissions by modulating temperature. Inner forests reduce extreme heat in summer and shade buildings (Mullaney et al. 2015; Ko 2018). These trees can help residents and businesses adapt to rising temperatures while simultaneously reducing emissions generated by cooling and heating buildings with fossil fuels. In the United States alone, urban forests reduce electricity use by 38.8 million megawatt-hours at a savings of $4.7 billion annually, with reductions in heating use estimated at 246 million British thermal units at a savings of $3.1 billion annually, and avoided emissions valued at $3.9 billion annually (Nowak et al. 2017).

Inner forests provide modest opportunities to sequester and store carbon in wood and soils (Nowak et al. 2002; Roy et al. 2012; Nowak and Greenfield 2018b). However, total carbon storage is limited by the cost and availability of space in cities, and both total storage and sequestration rates in urban forests vary with climatic and other biophysical factors (Nowak et al. 2013; Dobbs et al. 2014; Chen 2015). Cities with favorable growing seasons, ample water supplies for vegetation, and robust urban forest management programs tend to store more carbon. Although inner forests do store carbon (and provide many cobenefits), planting trees and expanding the urban tree canopy will never be a sufficient way for cities to meaningfully compensate for their energy and transportation emissions. The number of trees that can fit within an urban area (and thus their stored carbon) is very small relative to a city's annual carbon emissions (Pataki et al. 2011). Urban forests can only sequester a tiny fraction—often less than 1 percent—of overall city emissions. Urban forests can also be carbon neutral or carbon positive in some cases, meaning that they may emit as much or more carbon as they sequester. Throughout China, for example, the annual carbon sequestration of urban vegetation in 35 of its largest cities could offset only 0.33 percent of these cities' total annual emissions (Chen 2015). Importantly and in all instances, urban forests will always sequester more carbon than they would if the forests were converted to other land uses.

Protecting and restoring faraway forests is critical to reduce emissions and mitigate global climate change. Often underappreciated by city climate action planners, faraway forests provide large-scale carbon sequestration for climate change mitigation. Forests, especially tropical forests, are large reservoirs of carbon that are released if the forest is cleared. But if forests are conserved, those stores are protected, and standing or restored forests continue to sequester even more carbon. Cities can play a big role in realizing this carbon opportunity and can help meet their own carbon reduction or neutrality commitments in the process. For instance, cities can lower their forest-carbon footprint by ensuring that the commodities they purchase for city infrastructure and operations—such as timber, paper, and food—come from deforestation-free supply chains or by reducing food loss and waste or shifting the diets of their residents towards more plant-based foods. Cities can partner with selected faraway forests that have a social or economic link to the city, offering programs that support the conservation and/or restoration of that faraway forest. Moreover, cities can financially support reductions in tropical forest-related emissions by participating in jurisdictional REDD+ (reducing emissions through deforestation and degradation, plus the sustainable management of forest and the conservation and enhancement of forest carbon stocks) programs verified by a credible standard.

Biodiversity

Biodiversity—global and local—provides many direct and indirect benefits to cities, and cities can play a key role in protecting biodiversity at regional and global levels. The biodiversity of plants, animals, fungi, and other life forms is declining rapidly because of human activities, both in and outside of cities (Tilman et al. 2017; Mazor et al. 2018). Maintaining—or even increasing—biodiversity in inner forests is increasingly appearing on municipal agendas (Brende and Duque 2021). Yet municipal policies and practices can support forest biodiversity in nearby and faraway forests too. Supporting forest-based biodiversity is important to cities for a number of reasons, including providing direct benefits and supporting many of the benefits in the other three sections of this report.

- *Biodiverse forests often provide more—and more reliable—goods and services* (Fischer et al. 2006; Flynn et al. 2011; Cardinale et al. 2012; Oliver et al. 2015). To provide the myriad benefits of trees to urban residents, forests must be able to persist and recover from changes in the environment, including storms, droughts, and a changing climate. High levels of biodiversity can serve as biological "insurance"—when an ecosystem has many species fulfilling similar roles, it can continue to function even if some of those organisms are lost or if a disease (e.g., Dutch elm disease; chestnut blight) wipes out an entire species from an area (Yachi and Loreau 1999; Brandon 2014).
- *Biodiverse forests store more carbon, more reliably.* Undisturbed native forests sequester more carbon and store it for longer than degraded forest or monoculture plantations (Holl and Brancalion 2020; Watson et al. 2020). Biodiverse forests have higher resilience to fluctuations in climate, pest outbreaks, and diseases than tree monocultures. This higher resilience makes them a more reliable carbon sink (Turner et al. 2009; Brandon 2014; Seddon et al. 2019).
- *Biodiverse forests protect watersheds.* Native, biodiverse forests in watersheds are more effective than planted monocultures at supplying water resources to downstream cities (Alvarez-Garreton et al. 2019; Bonnesoeur et al. 2019; Yu et al. 2019). This is due to the structure, impact on soils, and greater resilience of native forests creating better conditions for storing and filtering water.

- *Biodiversity provides blueprints for new medicines.* Biodiversity within forests has provided compounds and genetic material for making antibiotics, anticancer agents, anti-inflammatory compounds, and analgesics used around the world (Chivian and Bernstein 2010; Sen and Samanta 2014). In developing countries, 70–95 percent of the population, including those living in cities, rely on traditional remedies such as herbal medicines derived from forests for primary care (Robinson and Zhang 2011).
- *Biodiverse forests support urban food supplies* (Krishnan et al. 2020). Thirty-five percent of food produced globally comes from 800 plants that rely on pollination by insects and other animals (Klein et al. 2007). Forests provide critical habitat for many of these pollinators (Öckinger and Smith 2007; Nicholls and Altieri 2013; Bailey et al. 2014; Hipólito et al. 2019).
- *Protecting biodiverse forests can reduce risks of zoonotic and vector-borne diseases.* Deforestation, forest degradation, and the associated wildlife trade has been linked with the spread of diseases that jump from animals to humans—which cause immense health and economic damages (Wolfe et al. 2007; Karesh et al. 2012; Jones et al. 2013; Borremans et al. 2019). Examples include the Ebola virus, yellow fever, malaria, Zika virus, and coronaviruses (Guerra et al. 2006; Wilcox and Ellis 2006; Karjalainen et al. 2010; Monath and Vasconcelos 2015; Olivero et al. 2017). Evidence suggests that conserving tropical

forests and sustaining their high levels of biodiversity can decrease transmission of some infectious diseases (Evans et al. 2020; UNEP 2020).

- *Access to biodiverse nature in cities can provide more reliable and richer benefits to residents, including an important list of mental and restorative health benefits* (Fuller et al. 2007; Lai et al. 2018; Wood et al. 2018; Marselle et al. 2019; Ngheim et al. 2021). Urban trees and forests are one of the main ways urban residents experience nature (Pregitzer et al. 2019). Biodiversity in the urban forest also contributes to the distinctive character of cities around the world (Hausmann et al. 2016).
- *Inner forests can house high biodiversity.* Urban forests can be highly biodiverse and can serve as corridors for some species. But they also tend to have more invasive species, "generalist" species, and fewer endemics (species with very limited ranges) than rural forests in the same habitat type (Concepción et al. 2015; Ducatez et al. 2018; Borges et al. 2021). Managing urban forests for biodiversity can provide access to nature within cities and create more resilient urban forests, essential for delivering other forest benefits.
- *Tropical forests hold most—up to 90 percent—of the planet's terrestrial biodiversity and thus are essential to urban well-being* (Wilson 1988; Reid and Miller 1989; WRI et al. 1992). Tropical forests continue to be lost at alarming rates.

Cities around the world are responsible for the lion's share of deforestation via their consumption. This also puts them in a strong position to improve their own biodiversity impacts through local policies that reduce negative impacts on tropical forests.

Right Trees, Right Place

Forests can provide the many benefits described in this report. But sometimes, the wrong trees in the wrong places can result in unintended and negative consequences. For example, monocultures of trees along city streets are vulnerable to pest and disease outbreaks (such as Dutch elm disease and the emerald ash borer). Our research found that some tree species emit volatile organic compounds and bioparticles (such as pollen) that can worsen urban air quality. In some situations, trees planted in urban street "canyons" formed by tall buildings can trap polluted air near the ground, preventing air currents from dispersing the pollution. Invasive tree species planted in cities can reduce native biodiversity and can even damage neighboring forests if they spread beyond city limits. Some species of tree also fail to thrive in harsh urban environments where air pollution, wind, and harsh temperatures can damage trees. In nearby and faraway forests, monoculture tree plantations can decrease biodiversity and sometimes even reduce carbon stores, especially if they replace native forests. In certain circumstances, upstream tree planting or forest restoration will decrease downstream water availability. For example, in Quito, Ecuador, millions of eucalyptus trees planted throughout the city and in nearby watersheds now diminish urban biodiversity, create forest fire risks, and can lead to soil erosion (compared to native tree species). Thus, ensuring the "right trees" are in the "right place" is critical for receiving the full benefits of forests at all levels.

Recommendations for Policy and Action

What can city leaders do to realize the myriad benefits forests provide to their cities and residents? Our analysis has identified actions cities can take, and our synthesis of the literature and interviews categorized these under five thematic categories:

1. Measurement and monitoring
2. Planning
3. Partnerships
4. Finance
5. Markets

The following are a suite of "no regrets" measures that allow a city to take immediate action to capture the potential of inner, nearby, and faraway forests to help meet their goals (Figure ES-2). While not exhaustive, they provide directions towards tangible actions. Underpinning these measures are a set of guiding principles that apply to all recommendations (Box ES-1). Suggested policy actions are divided by level—inner, nearby, and faraway forests—and the thematic category that each action addresses.

FIGURE ES-2 | Forest-Positive Actions across Five City Action Categories and Three Forest Levels

	INNER FORESTS	NEARBY FORESTS	FARAWAY FORESTS
1. Measurement	1. Map, inventory, and monitor your city's urban forest 2. Quantify the benefits of urban trees 3. Align forest monitoring metrics with city goals 4. Articulate clear forest-related goals	1. Map peri-urban and watershed forests and identify where forests are being lost 2. Quantify the benefits of trees in areas around the city	1. Conduct an analysis of city-wide consumption linked to tropical deforestation 2. Identify and track local attitudes and initiatives towards promoting deforestation-free commodities 3. Articulate clear goals to guide action
2. Planning	5. Develop an urban forest management plan 6. Designate land specifically for natural areas 7. Create connectivity	3. Support the development of "nearby forest" management plans 4. Articulate clear forest-related goals	4. Calculate and develop an action plan to reduce the consumption of forest-risk commodities and city-driven carbon dioxide emissions associated with deforestation
3. Partnerships	8. Seek out organizations conducting innovative work on inner forests 9. Cultivate interagency and cross-jurisdictional collaboration	5. Articulate and amplify shared goals	5. Establish a "partner forest" 6. Establish relationships with organizations involved in forest conservation, restoration, and sustainable management to help implement faraway forest programs 7. Call on subnational and national governments as well as businesses and financiers to conserve, restore, and better manage tropical forests 8. Incentivize the use of responsibly sourced forest-risk products
4. Finance	10. Explore diverse, long-term financing mechanisms	6. Clarify that forest protection and management are eligible infrastructure expenses 7. Make the economic and business case for action on forests 8. Establish upstream-downstream partnerships to finance watershed management	9. Compensate for urban emissions by funding tropical forest conservation 10. Match conservation and restoration efforts in the city with conservation in faraway forests
5. Markets	11. Develop wood waste reuse programs	9. Implement a robust procurement policy for local, sustainably sourced wood 10. Explore the role of carbon markets to finance forest conservation or restoration	11. Establish ecotourism ventures to conserve and sustainably manage forests threatened by competing land-use pressures 12. Initiate tropical forest-positive procurement policies and campaigns

Source: Authors.

BOX ES-1 | Guiding Principles

- *Conserve first, restore second.* Conserving native forests is a more effective and cost-effective way of sequestering carbon, conserving biodiversity, and maintaining water resources than planting new forests.
- *Protect large, old trees.* Old trees support biodiversity and provide benefits that cannot be replaced by planting new trees.
- *Define forests as essential infrastructure.* Forests are often seen as a luxury or amenity, but given the benefits they provide, they should be viewed in policy and practice as essential infrastructure for cities alongside traditional built or "gray" infrastructure.
- *Create a clear vision for the role of forests.* Forests and trees can serve multiple city goals and also imply trade-offs. It is important to collaboratively develop a vision for the role that forests can play in reaching success.
- *Give voice to communities.* Empower and engage community members, including a diversity of voices to ensure benefits are equitably distributed and suit residents' needs.
- *Emphasize equity.* For low-income and marginalized populations, the benefits of forests and trees may hold disproportionate value.
- *Collaborate across jurisdictions and city agencies.* Collaboration across agencies, sectors, and jurisdictions (including both other municipalities and regional and national governments) is crucial for capturing synergies in data, expertise, and resources.
- *Use forests to complement measures to reduce greenhouse gas emissions.* As a climate change mitigation strategy, forest conservation and restoration should complement city efforts to reduce urban emissions from energy generation, industry, and transportation. Reducing emissions will help keep forests healthy—a double win for climate change mitigation.
- *Prioritize biodiverse, native forests.* Biodiverse forests and native tree species, as opposed to monoculture plantations or non-native species, are more resilient to stress and provide a broader suite of benefits.
- *Use the "right tree, right place" approach.* The species and placement of forest planting and regrowth should be aligned with the specific goals, adapted to local conditions, and resilient to a changing climate.

Recommendations for Inner Forests: Urban Trees, Parks, Green Infrastructure, and Natural Areas

The following options can help city leaders advance the quantity and quality of inner forests—and thus the benefits those forests provide to urban residents. Since most inner forests fall within a city's jurisdiction, cities often have full authority to pursue these recommendations.

Measurement and Monitoring: Inner Forests

- *Map, inventory, and monitor your city's urban forest.* Develop an urban tree cover baseline and land cover map as a first step towards planning and monitoring urban forests. Include an inventory of large, old, and culturally relevant trees. Evaluate key urban environmental challenges that could be improved through better forest management, such as heat islands, urban flooding, and inequities in access to green space (WRI Mexico 2016; Singapore-ETH Centre n.d.).
- *Quantify the benefits of urban trees, especially iconic and mature ones.* Such an analysis is critical for informing policies and investments in urban trees and can garner political and resident support. For example, following

its success in the United States, i-Tree Eco[3]—an online tool developed by the U.S. Forest Service to quantify and value ecosystem services provided by trees—was recently adapted, translated, and launched for Mexican cities, allowing cities across Mexico to quantify the extent and composition of urban forests and calculate ecosystem services and monetary values.

- *Align forest monitoring metrics with city goals.* Although canopy cover is often measured to assess urban forests, this single metric does not provide comprehensive information on all forest benefits. Use other metrics that improve forest function, such as forest types, species diversity, carbon density, proximity to residents, and distribution (Pregitzer et al. 2019).
- *Articulate clear goals.* These are a few examples:
  - *Increase forest canopy by* X *percent.* The appropriate canopy cover targets will depend on what is appropriate for local conditions (e.g., climate, natural tree canopy cover outside the city) and should be used with additional targets—such as species diversity or a mix of stand ages—to ensure forest diversity and health.
  - *Ensure every resident has green space within a half mile of home.* This addresses the increasing appetite of cities to achieve equitable access to green space for their residents.
  - *Reduce heat island or stormwater threats by* X *percent.* In the face of climate change, cities are increasingly looking to establish targets that address climate risks, such as flooding, drought, and heat

Planning: Inner Forests

- *Develop an urban forest management plan.* The plan should be scientifically informed, inclusively developed, and climate resilient. The plan should inform and be informed by other citywide plans, such as transportation, housing, land use, parks, and economic development.
- *Designate land specifically for natural areas.* These include parks, vacant lots, and along roadways. For example, the Miyawaki method—in which diverse plantings of native trees and shrubs are used to create "microforests"—has been used to improve local access to nature and increase urban biodiversity in many cities around the world (Nargi 2019). Be explicit about the use of these natural areas to promote community gathering and better access to nature for all residents.
- *Create connectivity.* Corridors of tree-covered green space can facilitate the spread of pollinators, support wildlife, alleviate stress, increase foot and bike commuting, and reduce exposure to pollution for residents. Successful examples of green corridor projects include the Medellín Green Corridors (UNEP 2019) and the Barcelona Green Corridor Network (O'Sullivan 2017).

Partnerships: Inner Forests

- *Seek out organizations conducting innovative work on inner forests.* For example, the Natural Areas Conservancy in New York City is a formalized partnership that focuses on maintaining and improving the city's vast natural areas network, integrating the city's needs with the conservation benefits these areas provide.[4]
- *Cultivate interagency and cross-jurisdictional collaboration.* Managing forests for multiple benefits spans different city agencies, including health, water, land use, transportation, economic development, climate, air pollution/quality, and parks/recreation. The Joint Benefits Authority[5], which is being pioneered in San Francisco, is an example of a new mechanism that allows multiple departments within a city to jointly plan, implement, and finance projects to increase the quantity and quality of inner forests.

Finance: Inner Forests

- *Explore diverse, long-term financing mechanisms to manage, protect, and expand urban forests.* Innovative financing tools include the following:
  - Green bonds and climate bonds, which fund projects that have positive environmental and/or climate impacts through the use of proceeds or asset-linked bonds
  - Pay for performance environmental impact bonds (also known as pay for success bonds and social benefit bonds), which allow private investors to fund specific interventions and earn a return based on performance (i.e., paying for results rather than services)
  - Community-based public-private partnerships between local governments and private entities, which align the interests of public, private, and community stakeholders around common goals
  - Tree-planting funds from taxes and stormwater fees
  - Tree banks, which collect funds when trees are removed and their replacement value cannot be achieved and support replacements in other places throughout the city
  - Mitigation fees, which require that development activities mitigate their impacts by planting trees on sites where disturbance occurs or pay the equivalent fees into the city's tree canopy conservation account
  - Integration of forests into compliance plans for environmental requirements
  - Incentives for city residents to support trees and forests through tax reductions

Markets: Inner Forests

- *Develop wood waste reuse programs.* Rather than disposing of wood from urban trees in landfills, municipalities can develop wood waste reuse programs. Dead trees can become timber for local industry and construction and a variety of other energy-saving products. These programs help defer costs, create employment, store carbon, and foster integrative thinking and charismatic sustainable policies centered on trees in cities.

Recommendations for Nearby Forests: Watershed and Recreation Areas around Cities

The following options can help city leaders advance the quantity and quality of their nearby forests—and thus the benefits those forests provide to urban residents. Since most nearby forests fall outside city agency jurisdiction, partnership, and collaboration with other government agencies (e.g., state, provincial, federal), landowners, and managers will be necessary for implementation.

Measurement and Monitoring: Nearby Forests

- *Map peri-urban and watershed forests and identify where forests are being lost around the city.* Understanding where forests are, where loss is occurring, where risk of loss from fire or land-use change are high, and where restoration opportunities exist is essential for planning engagement with nearby forests.
- *Quantify the benefits of trees in areas around the city.* This can help garner support from residents and partners to support watershed management for city water supply.

Planning: Nearby Forests

- *Support the development of "nearby forest" management plans with measurable goals and success metrics.* A city could provide resources, such as funding, administrative support, and staff participation, and promote collaborative planning between government jurisdictions.
- *Articulate clear goals.* These are a few examples:
  - Restore *X* hectares by 2030.
  - Remove invasive species from key watersheds.

Partnerships: Nearby Forests

- *Articulate and amplify shared goals.* Forming collaboratives between city agencies, other government agencies, and landowners can be an effective way to do this. For example, the city of Denver collaborates with the National Forest System and state agencies in the Forests to Faucets initiative[6], which has the shared aim of reducing wildfire risks and improving watershed services across Colorado's Front Range (CSU n.d.).

Finance: Nearby Forests

- *Clarify that forest protection and management are eligible infrastructure expenses.* Many existing funds for infrastructure have not clearly stated their ability or priority for funding NBS, such as forests. Explicitly making NBS eligible for funds can open new funding sources for forest protection and management.
- *Make the economic and business case.* A "Green-Gray Assessment"[7] (Gray et al. 2019) assesses the costs and benefits of using green infrastructure (i.e., forests and trees) or green and gray infrastructure versus relying solely on traditional gray infrastructure for securing stable and clean water supplies.
- *Establish upstream-downstream partnerships to finance watershed management.* Identifying the downstream beneficiaries (e.g., water utility, beverage company) of forest watershed services is a key first step to securing performance-based arrangements with the upstream land managers. Types of financing mechanisms being pioneered by cities include green bonds, forest resilience bonds, water funds, and water utility rate surcharges.

Markets: Nearby Forests

- *Implement a robust procurement policy for local, sustainably sourced wood.* Sourcing wood from sustainably certified managed forests within a city's "woodshed" can help keep forests from being converted to other land uses.
- *Explore the role of carbon markets to finance forest conservation or restoration.* King County in the U.S. state of Washington established the Forest Carbon Program[8]; it provides the opportunity for local companies to compensate a portion of their own carbon emissions and support healthy forests within the county (King County 2020).

Recommendations for Faraway Forests: Intact and Remote Forests, Especially in the Tropics

City leaders can advance the quantity and quality of faraway forests—and thus the benefits those forests provide to urban residents. Because faraway forests fall outside a city agency's jurisdiction, partnership and collaboration with other governments and stakeholders will be necessary for implementing the following actions. Given the critical role of tropical forests in mitigating climate change and the current threats they face, cities should allocate special attention to conserving and restoring tropical forests.

Measurement and Monitoring: Faraway Forests

- *Conduct an analysis of city consumption linked to tropical deforestation.* Tools such as the Forest Footprint[9] can estimate a city's impact on tropical deforestation driven by urban consumption of commodities (e.g., beef, soybeans, timber) associated with tropical deforestation (Cities4Forests n.d.b).

- *Identify and track local attitudes and initiatives towards promoting deforestation-free commodities.* This can help gauge levels of political support a city may have in taking steps to drive deforestation-free commodity procurement policies.
- *Articulate clear goals to guide action.* This is an example:
  - *X* percent of tropical wood and forest-risk commodities will be sustainably procured by *X* date.

Planning: Faraway Forests

- *Calculate and develop an action plan to reduce the consumption of forest-risk commodities and city-driven carbon dioxide emissions associated with deforestation.* The Forest Footprint tool can help cities to identify the size of their forest impact and the key commodities driving deforestation, which can help them plan their mitigative actions.

Partnerships: Faraway Forests

- *Establish a "partner forest."* A partner forest[10] is a faraway (usually tropical) forest connected to a city through a meaningful and mutually beneficial exchange. The city supports the partner forest by directing its purchasing power towards a product or service that the forest provides (e.g., shade-grown coffee, climate benefits, ecotourism). The goal of a partner forest program is to visibly support a tropical forest that provides direct benefits to the city and raise awareness of those benefits among city residents (Cities4Forests n.d.c).
- *Establish relationships with organizations involved in forest conservation, restoration, and sustainable management to help implement faraway forest programs.* Instead of trying to develop in-house expertise, cities can partner with one or more nonprofit organizations with on-the-ground experience in the forests of interest to help scope, design, and implement a faraway forest program.
- *Call on subnational and national governments as well as businesses and financiers to conserve, restore, and better manage tropical forests.* Being home to the majority of voters in many countries, cities can flex their political muscle by being vocal with state and national government leaders about the importance of faraway forests for city resident well-being. If faraway forests are to remain, the voice of cities needs to be heard.
- *Incentivize the use of responsibly sourced forest-risk products.* For example, the UK city of Chester, led by the Chester Zoo and the local member of Parliament, worked to encourage local businesses to use and sell products with palm oil certified by the Roundtable on Sustainable Palm Oil. Chester was recently certified as the first sustainable palm oil city worldwide (Chester Zoo 2019).

Finance: Faraway Forests

- *Compensate for urban emissions by funding tropical forest conservation.* Cities will have difficulty reaching carbon neutrality by cutting their direct emissions alone. Financing tropical forest conservation and restoration, certified by credible jurisdictional REDD+ programs, may offer ways to compensate for remaining urban emissions. A "climate co-op" could be created where cities purchase high-quality forest carbon credits via the voluntary carbon market to finance long-term forest conservation with associated carbon benefits.
- *Match conservation and restoration efforts in the city with conservation in faraway forests.* For example, for every tree planted within the city, a city could support parallel restoration efforts in a tropical forest. The London Enfield Council woodland restoration project is developing such a partnership on restoration with the city of Port Moresby (Papua New Guinea).

Markets: Faraway Forests

- *Establish ecotourism ventures to conserve and sustainably manage forests threatened by competing land-use pressures.* Cities can support the implementation of community owned and operated sustainable tourism programs by promoting these amongst their residents to develop a steady clientele pipeline, thereby bolstering the efforts of regional governments to boost local economies while also conserving faraway forests (Fitzgerald n.d.).
- *Initiate tropical forest-positive procurement policies and campaigns.* Cities can implement policies that discourage purchasing commodities implicated in deforestation and provide incentives for purchasing better-sourced commodities (or alternatives with lower tropical forest impacts). Tropical timber, coffee, chocolate, soy, and beef are commodities that are especially amenable to this approach.

For all of these measures—for inner, nearby, and faraway forests—healthy communications and engagement with city residents will be important (Box ES-2).

BOX ES-2 | The Importance of Communications and Resident Engagement

To achieve forest-related goals, city leaders will need to communicate with city residents to raise awareness, generate a shared vision, and mobilize political support and individual action. These are some of the key features of an effective communications program:

- Educate residents about the value of inner, nearby, and faraway forests.
- Engage youth through classroom education and field trips.
- Cultivate trusted messengers.
- Articulate clear city goals with respect to inner, nearby, and faraway forests.
- Use storytelling and highly visible demonstration projects to garner local support and make forest benefits "real," such as how the city of Glasgow is doing through the Every Tree Tells a Story program.

CONCLUDING THOUGHTS

Home to more than half of the world's population, cities are growing in their size, power, and impact on the natural environment. They face pressing challenges to provide their residents with essential services, including healthy, livable neighborhoods, clean and reliable water, action on climate change, and access to nature and biodiversity. Cities can use trees and forests to help meet these challenges.

Within cities, trees and forests—inner forests—can reduce extreme temperatures, reduce stormwater runoff, promote mental health, and provide shared spaces for recreation and relaxation. Forests around cities—nearby forests—can improve water resources, provide many forest goods, and offer access to nature. And faraway forests around the world are key to mitigating climate change, conserving biodiversity, and maintaining global rainfall patterns. Cities have many options available to support forests at all three levels and make the best use of the benefits they provide. Forests can also help cities reduce operating costs and pay long-term dividends that often increase over time. *The best time to plant a tree was fifty years ago. The second-best time is today.*


CHAPTER 1

Introduction

Forests around the world are under severe threat. Despite this, the evidence base that shows how and where forests provide benefits to cities and their residents is growing. As centers of untapped political, economic, financial and social power, cities can play a role in protecting, restoring and sustainably managing the world's forests, to ensure the long-term sustainability of the benefits they provide.

City leaders around the world are working hard to meet the needs of ever-growing urban populations. By 2050, an estimated 70 percent of the world's population will live in cities (UNSD n.d.). City leaders strive to provide their residents with a safe place to live and work and with access to resources and environments that promote good health. They seek to improve and sustain clean, reliable water supplies and provide protection from natural disasters. And cities are increasingly stepping up to take action on climate change mitigation and to meet other sustainability commitments. International agreements to combat climate change and conserve biodiversity, city-level commitments to reduce greenhouse gas (GHG) emissions, and the need for companies based in cities to reduce their carbon footprints all put pressure on cities to find cost-effective solutions to environmental challenges. At the same time, they juggle these demands in dynamic environments, often with tight financial resources.

At their disposal is a nature-based solution that can help cities meet many of these aspirations: forests and trees. Cities around the world are turning to nature-based solutions[11] (NBS) to address their challenges and meet their goals. Forests, in particular, are increasingly recognized as a cost-effective way to deliver multiple benefits. This report synthesizes the literature on how forests can deliver four key benefits[12] for cities and their residents:

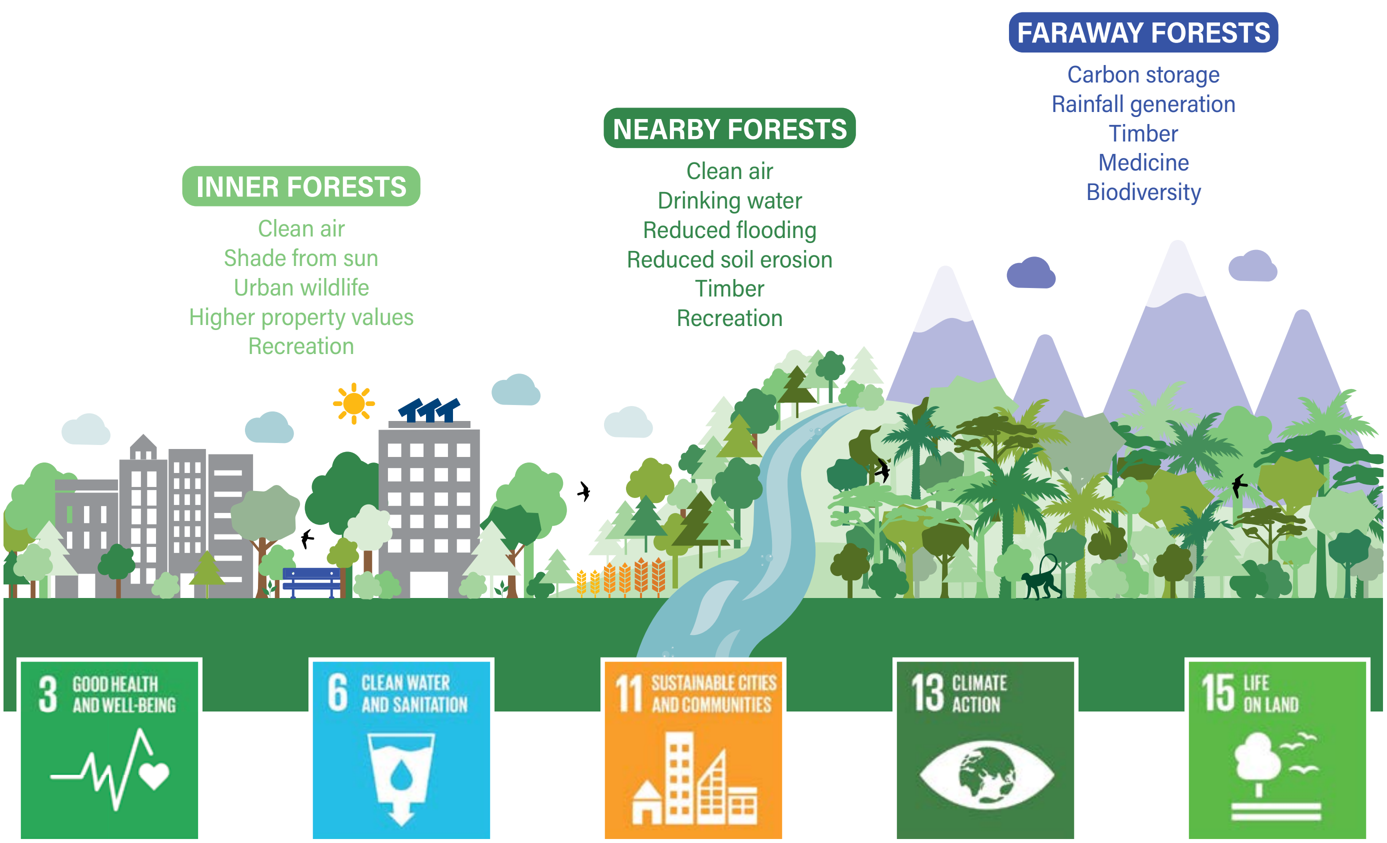
- *Health and well-being* by creating habitable, healthy, and favorable living conditions for city residents
- *Water* by securing access to clean and reliable water supplies, both within cities and in the key agricultural regions that feed them
- *Climate* by contributing to climate change mitigation and its effects on millions of urban residents
- *Biodiversity* by protecting essential global biodiversity, which supports many of the systems people rely upon, such as pollinating crops, providing medicines, regulating climate, and underpinning many spiritual values

BENEFITS OF FORESTS

Forests—both within and beyond city boundaries—provide benefits to cities and their residents. Our framework (Figure 1) divides forests into three levels—inner, nearby, and faraway—to show what the benefits are, how they differ depending on the location of the forest, and how cities can support forests to harness the greatest benefits. This framework was conceived by the founders of the Cities4Forests[13] initiative, based on multiple projects and engagements with both forest and city landscapes.

- *Inner forests* include trees and forests growing along streets, in city parks, on private property, as remnant patches of native forests or woodland, and in urban coastal areas within cities. These inner forests can improve air quality, offset heat islands (leading to lower energy use and bills), reduce stormwater runoff and urban flooding, and support human health and wildlife.
- *Nearby forests* include forests, woodlands, and trees found in watersheds surrounding cities. They enhance urban air quality, regulate temperature, provide stable supplies of clean drinking water, reduce flooding, and offer opportunities for relaxation and recreation.
- *Faraway forests* are intact forests located beyond a city's watershed. These forests, particularly those in the tropics, sequester large amounts of carbon, generate rain for cities and the world's farm belts, provide a wealth of useful products, and host the majority of the world's land-based biodiversity.

FIGURE 1 | Inner, Nearby, and Faraway Forest Benefits



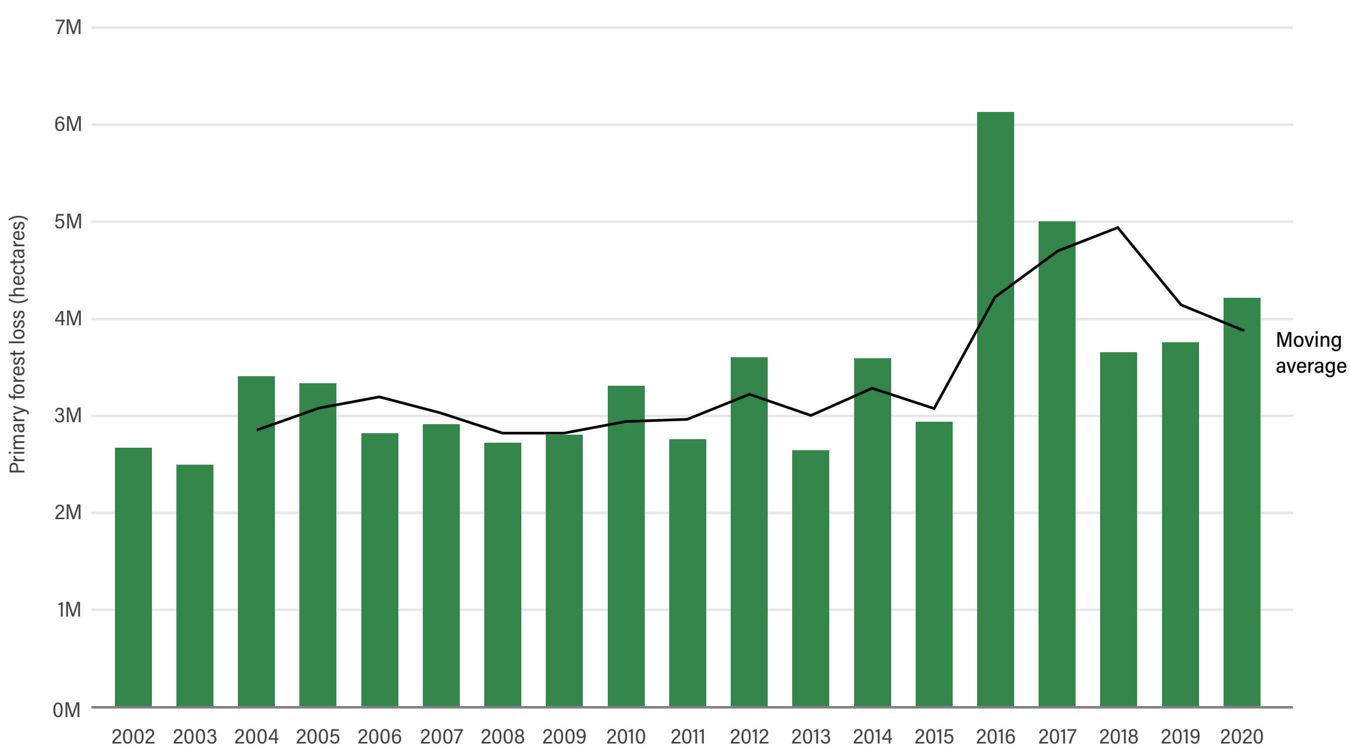
Note: Inner, nearby, and faraway forests provide multiple benefits to cities, many of which are aligned with the UN Sustainable Development Goals.
Source: Cities4Forests n.d.a.

THREATS TO FORESTS

Across the globe, forests are under threat. During the decade 2010–19, global forest cover declined by an average of 4.7 million hectares (ha; 11.8 million acres) per year (FAO 2020).[14] In 2019 alone, the world lost an area of tropical primary forest the size of a football pitch every six seconds (Weisse and Goldman 2020). In the world's largest intact forests, deforestation and forest degradation are driven largely by agriculture, fires, and logging (Figure 2). Inside cities, pollutants, high temperatures, compacted soils, pests, and diseases create challenging conditions for trees to grow and survive. Urban tree cover has been decreasing at an average rate of 0.04 percent per year (Nowak and Greenfield 2020). In the United States alone, this loss represents about 36 million trees per year, equating to an estimated financial loss of US$96 million per year in benefits (Nowak and Greenfield 2018a). Urbanization often encroaches on woodlands surrounding cities, and an estimated 9 in 10 cities have lost significant amounts of natural land cover in their source watersheds to agriculture and development (McDonald et al. 2016).

Global deforestation is not evenly distributed; tropical forests are being cleared at much higher rates than those in temperate and boreal regions. Commercial production of globally traded agricultural commodities—such as soy, beef, and palm oil—is the leading driver of tropical deforestation (Curtis et al. 2018). In response to consumer demand from people—including city residents—thousands of miles away, tropical deforestation rates continue to rise. For the past several decades deforestation rates have been much lower in temperate and boreal regions, although in temperate areas many of these forests were cleared in the past (Currie and

FIGURE 2 | Tropical Deforestation Rates over Time



Source: WRI n.d.a.

Bergen 2008). Forest loss in temperate and boreal regions is now mainly due to fire and harvesting for wood and paper products, and forests sometimes regrow after clearing (Figure 2; Curtis et al. 2018).

Cities suffer the costs. The impacts of deforestation and forest degradation always extend far beyond the cleared region. Cities experience poorer air quality, flooding, landslides, and more extreme weather events, to name a few, as a result of deforestation near and far. Deforestation decreases the benefits that cities receive from forests (Figure 1) with negative impacts on the physical, economic, and mental well-being of urban residents. In a world struggling to combat COVID-19, deforestation and forest degradation have been linked to increased incidence of vector-borne diseases such as malaria (Karjalainen et al. 2010) and the emergence of infectious zoonotic diseases such as coronaviruses (Afelt et al. 2018).

OPPORTUNITIES FOR CITIES

Cities play a major role in forest loss and degradation. Consumption in urban areas is directly responsible for about 75 percent of global carbon dioxide (CO_2) emissions and two-thirds of global energy use (Seto et al. 2014). And although cities cover only a small proportion of the earth's surface, their footprints are large: as major "net importers," cities depend heavily upon resource extraction and production beyond their boundaries (Weinzettel et al. 2013). A midsize city in North America, for example, is responsible for thousands of hectares of tropical deforestation per year via the goods it consumes.[15]

Cities—as places where people increasingly live and work—can make major contributions to addressing these issues. The public policies and procurement practices of cities—as well as the values, votes, and consumption patterns of residents—have enormous potential to support the conservation, restoration, and sustainable management of forests. Many cities already support forests, for example, through efforts to expand urban tree cover and parks. Some cities provide incentives to protect watersheds for their water supplies, and there is growing investment in forests as "green infrastructure." Some cities are implementing procurement guidelines to reduce tropical deforestation driven by city consumption. But the potential to do more is immense. The Intergovernmental Panel on Climate Change's (IPCC) *Special Report on Climate Change* (Jia et al. 2019) estimates that 11 percent

of global carbon emissions come from land-use change—especially tropical deforestation. If tropical deforestation were a country, it would rank third only behind China and the United States in GHG emissions (Gibbs et al. 2018). Conserving, sustainably managing, and restoring forests and other ecosystems could reduce global GHG emissions by up to 30 percent and provide 23 percent of the cost-effective mitigation measures needed to prevent global temperatures from rising 2°C (Griscom et al. 2017; Wolosin and Harris 2018). Much more can be done to promote forests as a climate change solution (Seymour and Busch 2016).

ABOUT THIS REPORT AND HOW TO USE IT

This report addresses two key questions: How and under what conditions do forests support cities? And what can cities do to support forests? To answer the first question, we rigorously research and explore four ways forests benefit cities[16] and describe each in its own section (Table 1).

TABLE 1 | The Four Sections of This Report

HEALTH AND WELL-BEING	WATER	CLIMATE	BIODIVERSITY
Thriving, vibrant cities provide their residents with ample opportunities for social interaction, with food and water security, with enhanced economic opportunities, and with comfortable, safe living conditions. Forests in and around cities can promote recreation, mental restoration, and spirituality. They also help to mitigate hazardous urban environmental conditions related to extreme temperatures and exposure to air pollutants. Finally, they can supplement food supplies and provide livelihoods for many–including vulnerable and marginalized populations. Faraway forests also play a critical role in providing the templates for new pharmaceuticals. And by protecting tropical forests and other biodiversity hotspots from degradation, we may be able to avoid novel infectious diseases.	Forests interact with climate and the hydrological cycle at local, regional, and global scales.[a] Inner forests can support cities as they strive to provide clean, readily available water to their residents and can also reduce burdens on urban infrastructure and prevent flooding. Nearby forests improve urban water quality by shielding rivers from high temperatures, pollutants, and erosion that can negatively affect the natural balance of the ecosystem. Faraway forests—especially tropical forests—influence precipitation patterns in cities and agricultural regions hundreds of miles away as they cycle water into the atmosphere.	Climate change poses a special threat to cities. Cities experience higher temperatures than rural areas, and many cities lie on coasts. As concentrated centers of people, culture, and economic activity, urban areas are extremely vulnerable to natural disasters. Forests can help to mitigate climate change and promote adaptation.[b] Photosynthesis—nature's own carbon capture and sequestration solution—makes forests a highly cost-effective climate change mitigation option. Investing in forests inside cities can lower city emissions via urban cooling. Conserving and restoring forests outside cities via deforestation-free consumption and sustainable forest management can protect some of the most important carbon sinks on the planet: large, contiguous forests—especially tropical forests.	Biodiversity, the variation of life on Earth, supports ecosystem function,[c] fosters connection to place, stimulates tourism,[d] and harbors potential blueprints for nutritional and medicinal products key to human health.[e] It also provides endless opportunities for discovery and wonder. Inner and nearby forests can serve as habitat, climate refugia, and corridors for key flora and fauna, including pollinators, edible plants, and iconic birds and mammals. Forests at all levels can play a key role in preserving biodiversity for future generations and promoting ecosystem functioning, but conserving and sustaining intact tropical forest is vital. Tropical forests contain most of the planet's biodiversity on land. Yet to date, only 18% of the world's forests and 27% of tropical forests are currently protected.[f]

Note: References for the summaries in this table are given in the relevant sections of the report.

Sources: a. van Noordwijk et al. 2014; b. Tye et al. 2022; c. Cardinale et al. 2012; d. Hausmann et al. 2016; e. Karjalainen et al. 2010; f. FAO and UNEP 2020b.

City representatives can use each section separately or all together, depending on their focus and objectives. For example, a city employee concerned with improving air quality could read Section 2 to learn more about how trees and forests can help. An official interested in making trees and green space a focus of the city agenda might read all four sections.

Sections 2–5 have a similar overall structure, with a "Background" section about the topic and its relevance for cities as well as a section that describes what forests do and—when data allows—quantifies their benefits. This latter section is formatted differently between sections to suit the specific subject. The "Caveats and Considerations" section highlights the nuances that are important for realizing the benefits, including when forests will not produce benefits, and what types of forests are most appropriate. This section helps urban decision-makers avoid unintended consequences and get the most from their investment in trees and forests. Collectively, this information can be used by city governments, city managers, other agencies, and groups such as nongovernmental organizations (NGOs) and community-based organizations that work with cities to rethink how they should engage with and use forests to achieve specific end goals.

The question "What can cities do to support forests in return?" is addressed in Section 6, which outlines what city leaders, managers, and other city stakeholders can do. The section includes recommendations on resident engagement and awareness, communications campaigns, public policies and procurement, finance, and more.

METHODS

This report synthesizes the latest research on how inner, nearby, and faraway forests benefit cities and urban residents. It summarizes research findings gathered through several literature reviews, including several "reviews of reviews" (surveys of published review papers; e.g., van den Bosch and Sang [2017]), supplemented by reviews of primary literature and expert-recommended texts. Reviews covered four main topics: health and well-being, water, climate, and biodiversity. There is a geographical bias of the "reviews of reviews" methodology, which was limited to published documents written in English. We partially correct for this by including findings from relevant empirical papers and by including case studies from under-represented areas identified through reference lists and expert recommendations. Sections of the report, such as Section 6, are also partly based on conversations with city representatives, interviews with topical experts, and experiences from years of projects that World Resources Institute (WRI), Pilot Projects, and Cities4Forests have worked on.

There is no universally accepted definition of *forest* (Chazdon, Brancalion, et al. 2016), and different fields of study use the term in different ways. We include research on both trees and forests as well as on natural and planted forests, and we make distinctions where appropriate. We also include work on urban nature, green infrastructure, and green spaces more broadly when forest-specific studies are lacking. A more detailed methodology can be found in Appendix A.

CHAPTER 2

Health and Well-Being

Integrating trees and forests into the urban landscape makes cities more vibrant and livable, and can generate a diverse suite of health benefits, from cooler temperatures to improved mental health to space for social interaction and community building. Outside cities, forests hold the blueprints to medicines, help provide cleaner water, and provide spaces to relax and recreate.

BACKGROUND

Living in cities provides numerous benefits, including access to economic and educational opportunities, shorter commutes, public services, and intercultural exchange. But urban living can have negative impacts on the mental and physical health of residents. Exposure to air pollution, chronic stressors such as noise pollution, sedentary lifestyles, increased risk of communicable disease in crowded conditions, and extreme temperatures in the built environment can erode overall health and quality of life—and can sometimes be deadly (Bai et al. 2012; Kuddus et al. 2020). Climate change threatens to amplify impacts through higher temperatures, aberrant rainfall, and, for coastal cities, rising sea levels (Revi et al. 2014).

As they strive to create healthier cities, city leaders can embrace sustainably managed inner or "urban" forests as an NBS. When trees are integrated into the urban landscape in socially and ecologically appropriate ways, cities can become more livable and vibrant spaces. Evidence suggests that, unlike many issue-specific municipal investments, the "urban forest" can generate a diverse suite of benefits at the same time—from cooler temperatures and air quality improvement to improved health and space for social interaction.

How forests relate to human well-being

In 1984, a pioneering study found that patients whose windows looked out upon a group of trees healed from surgery faster and needed fewer painkillers than those whose windows had no view of nature (Ulrich 1984). Since then, a rapidly expanding and compelling body of evidence—spanning disciplines as diverse as epidemiology, psychology, forestry, and geography—suggests that forests and nature play an important role in human health. Evidence also indicates that forests in and around cities may contribute to social and economic well-being because benefits accrue to individuals using forests to support their livelihoods, to property owners whose parcels increase in value, and to entire regions as forests support tourism or other industries.

Why context matters

Cities are immensely diverse in climate, culture, politics, language, and environmental contexts. As such, considering the local cultural, political, climatic, environmental, and socioeconomic contexts is important for successfully integrating trees and forests into city planning. The benefits that forests in cities provide will vary from city to city around the world.

Inner forests (and related green infrastructure) may not always provide the intended benefits, and they can sometimes present unintended risks (Hartig et al. 2014; Lõhmus and Balbus 2015). By understanding these risks and deliberately incorporating how to address them into the planning and decision-making processes, the potential for unintended negative outcomes can be minimized and the many positive benefits realized (Lõhmus and Balbus 2015; Wolf 2017). And by empowering communities to guide urban greening initiatives and stewardship of the inner forest, these living elements of urban infrastructure can help to diminish—rather than exacerbate—inequities among groups.

About This Section

Forests near and far support human health and well-being—socially, economically, and ecologically. In the following sections, we summarize the ways that inner and nearby forests affect the quality of life of city residents. Local forests provide many direct and indirect health benefits. This section thus focuses on inner forests that provide unique opportunities for leaders seeking to create healthy and habitable cities. Nearby and faraway forests also provide health benefits via water access and treatment, climate change mitigation, and biodiversity, which are addressed in the respective sections.

To explore these benefits, we synthesized statements and goals shared by many city leaders around the world into eight specific goals related to health and well-being:

1. Reducing extreme heat
2. Enhancing urban air quality
3. Promoting physical and mental health in city residents
4. Creating walkable, safe streets
5. Supporting community connections
6. Reducing urban environmental inequity
7. Ensuring provision of food, medicine, and raw materials
8. Enhancing economic well-being

GOAL 1: REDUCING EXTREME HEAT

Context

Cities suffer from the heat island effect. Most cities are dominated by buildings and pavement, with relatively little vegetation and green space, which contributes to "urban heat islands"—elevated temperatures in urban areas compared to their rural surroundings. Urban areas can be 2°C–4°C—and as much as 15°C—warmer than adjacent areas (Taha 1997; Heaviside et al. 2017; Mohajerani et al. 2017). The heat island effect presents a number of risks to human health and well-being, including the following:

- *Increased risk of heat-related mortality and morbidity,* especially during heat waves; high temperatures can cause heat stroke, dehydration, exacerbate existing diseases, and even cause death (Luber and McGeehin 2008); stifling heat may also interfere with worker productivity (Zander et al. 2015) and with learning and educational achievement (Park et al. 2020)
- *Potential for negative effects on mental health,* although more research is needed (Thompson et al. 2018)
- *Spikes in energy demand* (Li et al. 2019)
- *Power outages* due to high energy demand at midday, which can further affect resident safety, impair economic activity, and burden health and emergency services (WMO and WHO 2015)
- *Degradation of environmental quality,* such as increased concentrations of urban smog (Akbari et al. 2001), increased ground-level ozone (Luber and McGeehin 2008; Jacob and Winner 2009), and decreased water quality (Phelan et al. 2015; Heaviside et al. 2017)

Climate change will exacerbate these risks. Since the advent of the Industrial Revolution, the average temperature near Earth's surface has increased about 1°C (1.8°F; IPCC 2018). The urban heat island effect magnifies the effects of climate change for cities, leading to higher temperatures than rural areas and more extreme heat waves (Estrada et al. 2017). Already, extreme heat in cities has been responsible for thousands of excess mortalities in recent decades (Heaviside et al. 2017). The 2003 European heat wave, for example, killed more than 70,000 people (Robine et al. 2008). Thousands in India and hundreds in Pakistan died as temperatures surpassed 45°C in 2015 (Masood et al. 2015; Sarath Chandran et al. 2017). In 2021, a lingering heat wave shattered records in western North America, spiking heat-related illnesses and killing hundreds, an event the World Weather Attribution initiative described as "virtually impossible without human-caused climate change" (WWA 2021). Records suggest July 2021 was the hottest month on record (NOAA 2021).

Some urban residents are more susceptible to these risks than others. In general, lower-income and marginalized communities are disproportionately exposed to the deleterious effects of heat islands (UN DESA 2020). Children, people above the age of 50, and those with preexisting health conditions are particularly vulnerable to heat-related illnesses (Kovats and Hajat 2008). Densely settled and lower-income communities often lack access to places to cool down, such as shaded green spaces and open areas (Harlan et al. 2006; Luber and McGeehin 2008). In addition, many low-income households lack insulation, air conditioning, and access to resources necessary to cope with extreme temperatures (Harlan et al. 2006; Ko 2018).

What roles can trees and forests play?

Trees in urban areas can mitigate the urban heat island effect, especially locally, by the following actions (Figure 3):

- *Shading surfaces and people.* Tree canopies intercept and reflect up to 90 percent of incoming solar radiation. Shade makes heat more tolerable and can protect people from excessive sun exposure during travel, work, or leisure (Nowak and Dwyer 2007). Trees that shade buildings can reduce surface temperatures in a wide variety of contexts (Wang et al. 2014); for example, surface temperatures were reduced by 11°C–25°C in Sacramento, California (Akbari et al. 1997); by 5°C–7°C in Akure, Nigeria (Morakinyo et al. 2013); and by 9°C in Melbourne, Australia (Berry et al. 2013). In Bangalore, India, streets with trees had local ambient air temperatures that were 5.6°C lower than streets without trees, and their surface temperatures were 27.5°C lower (Vailshery et al. 2013).

- *Cooling the air via evapotranspiration.* During the day, trees may create lower air temperatures by releasing water into the air as they photosynthesize (Bowler et al. 2010a; Säumel et al. 2016). As water vapor is released, it takes with it some of the ambient heat. Large trees with ample access to water may evaporate more than 100 liters of water in a single day, which dissipates about 70 kilowatt-hours of solar energy that would otherwise remain stored in the urban environment (Fath 2018).

Effects of cooling are most pronounced locally. A 2010 global meta-analysis found that parks were, on average, 0.94°C cooler during the day than surrounding urban areas, with greater benefits in larger parks and in those containing trees (Bowler et al. 2010a). A more recent review suggests large urban parks and green spaces (more than 10 ha)—especially those with mature trees—can reduce air and surface temperatures by 1°C–2°C (Aram et al. 2019). Some evidence shows that areas adjacent to green spaces also are cooler (Mohajerani et al. 2017), from a few hundred meters (Tyrväinen et al. 2005; Aram et al. 2019) to perhaps as much as a kilometer (Bowler et al. 2010a).

The urban forest can both reduce the risk of heat-related illness or death and increase perceived comfort for residents (Taha 1997; Tyrväinen et al. 2005; Salmond et al. 2016; Gunawardena et al. 2017; Wolf et al. 2020):

- Researchers estimate that in 97 U.S. cities alone, urban tree cover helps to avoid 245–346 premature deaths and 50,000 hospitalizations annually (McDonald et al. 2020).
- In Toronto, residents in neighborhoods with the lowest tree canopy cover (less than 5 percent) made 5 times as many heat-related emergency calls as residents in neighborhoods with more than 5 percent canopy cover and nearly 15 times as many emergency calls as residents in neighborhoods with more than 70 percent canopy cover (Graham et al. 2016).

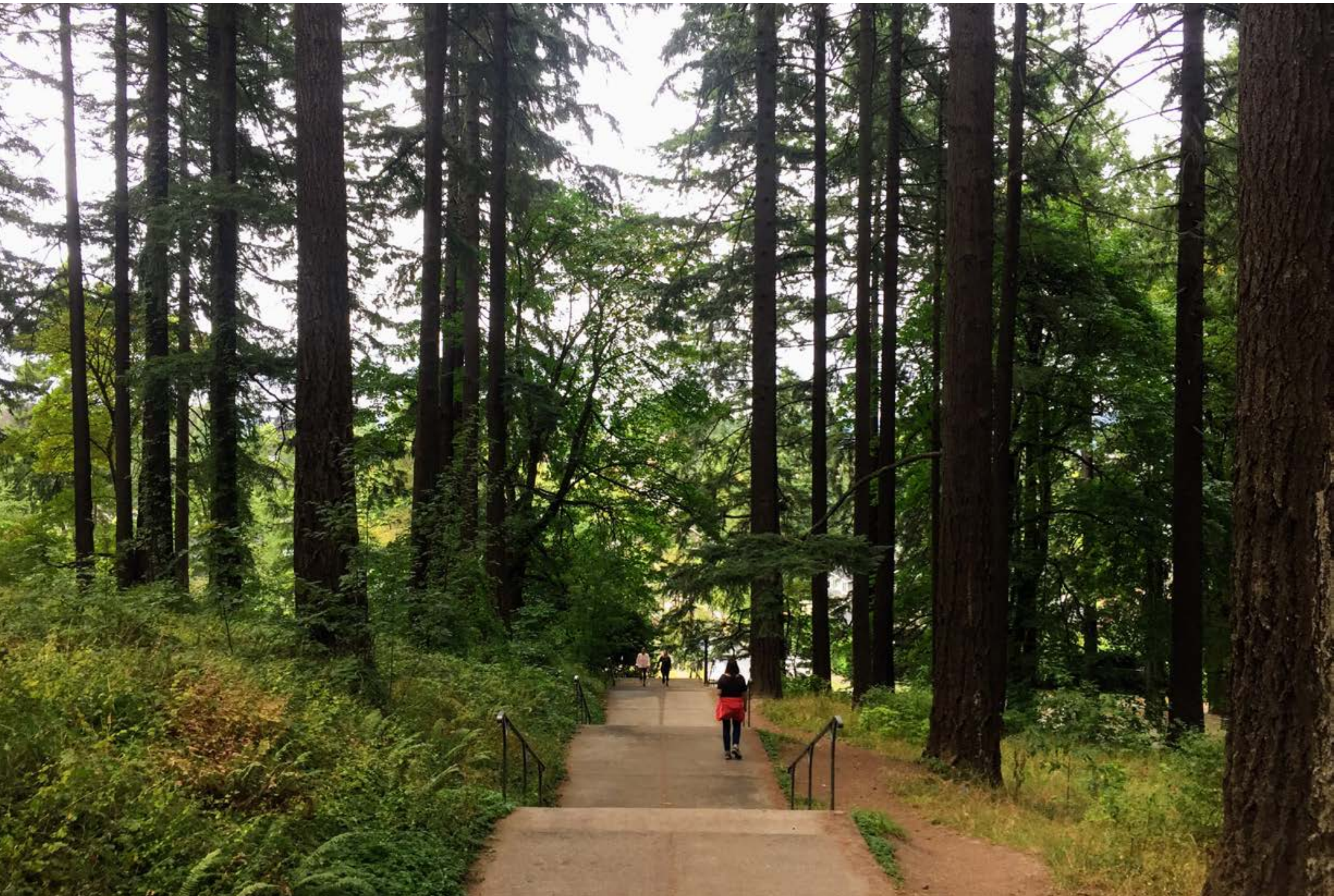
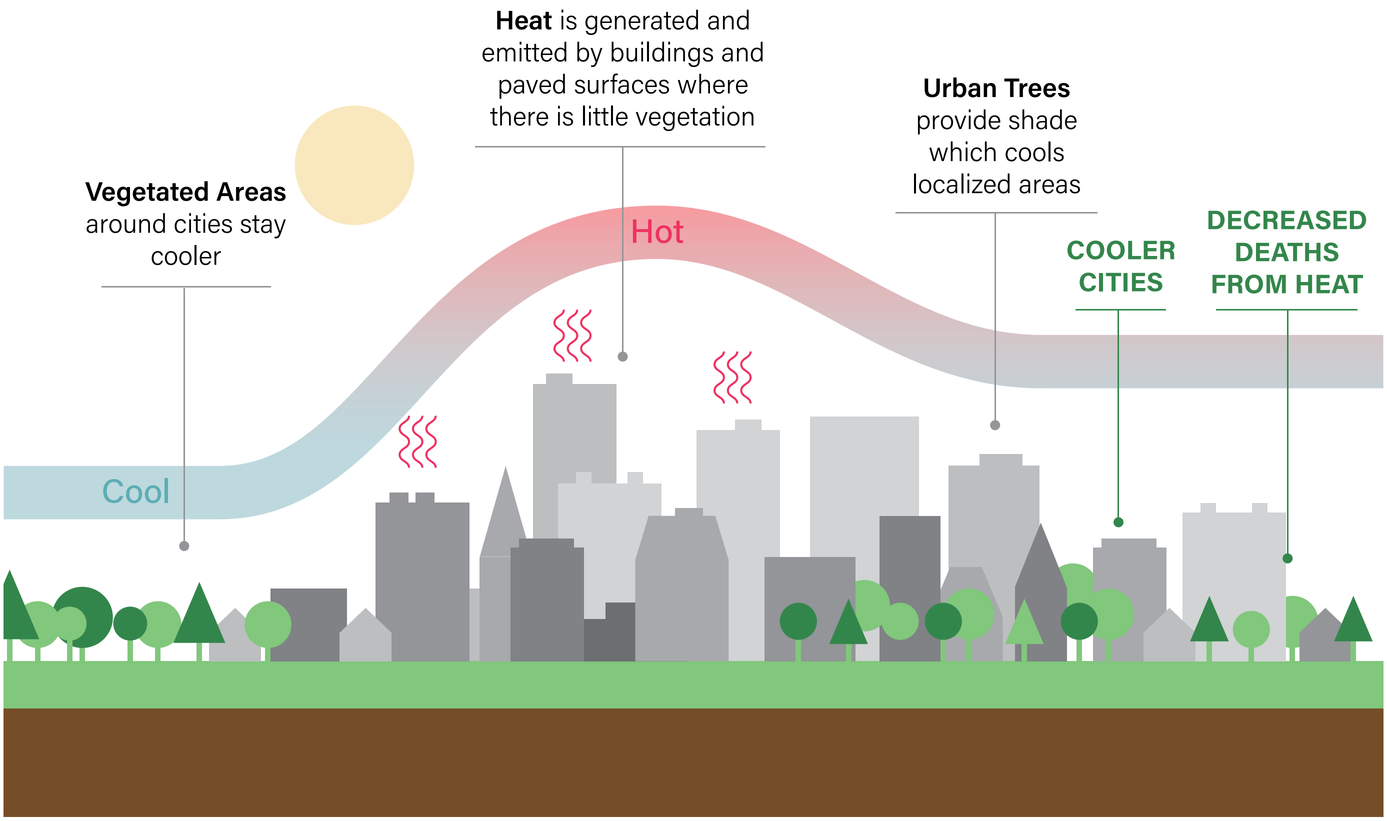


FIGURE 3 | Localized Cooling Benefits from Trees through Shading and Evapotranspiration



Notes: Pavement and concrete in cities absorb energy from the sun and then radiate that energy out, heating the air in cities more than in the surrounding countryside. Urban trees provide shade, preventing pavement and concrete from heating up, and also cool the air by transpiring water. Trees can cool neighborhoods by up to 4 degrees Fahrenheit (McDonald et al. 2016).

Source: Authors. Adapted from McDonald et al. (2016).

Caveats and considerations

Urban forests may complement or be incorporated into other interventions to reduce the urban heat island effect. These interventions include permeable pavements and green roofs (Mohajerani et al. 2017).

Cooling by urban trees will be greatest in local areas, and forests may not provide net benefits in some situations, such as these:

- Trees and shrubs very close to buildings may prevent nighttime radiative cooling of buildings (Bowler et al. 2010a; Wang et al. 2014; Ko 2018).
- Tall trees can reduce wind speeds (Mohajerani et al. 2017). This can be a benefit in cold climates but can be a disadvantage in warm or humid climates (Ko 2018). At night, tree canopies can also reduce airflow and thus retain heat (Bowler et al. 2010a; Salmond et al. 2016).
- The microclimate-altering effects of urban trees and other vegetation are more pronounced in cities in warm and dry climates (Taha 1997).
- Because evapotranspiration increases humidity (Salmond et al. 2016), high levels of evapotranspiration may reduce comfort for urban dwellers in hot, humid climates, even as evapotranspiration lowers near-ground temperatures. However, the increase in humidity may be small compared to the reductions in temperature (Vailshery et al. 2013).

Some species provide more cooling benefits than others. Leaf area index, evapotranspiration rate, crown diameter, and the albedo of different tree species affect the cooling benefits they provide (Jim and Chen 2009; Bowler et al. 2010a; Smithers et al. 2018). Fast-growing, long-lived, and drought-tolerant native species of trees with relatively reflective surfaces are most likely to deliver cooling benefits (Smithers et al. 2018).

GOAL 2: ENHANCING URBAN AIR QUALITY

Context

Air pollution threatens the well-being of most urban dwellers. An estimated 9 out of 10 people breathe polluted air worldwide (WHO 2016). Responsible for approximately 4.2 million deaths globally in 2016 (WHO 2016), exposure to ambient air pollution is considered one of the greatest risk factors for global public health (Burnett et al. 2018). Exposure to air pollution disproportionately affects residents of low- and middle-income countries. It disproportionately affects lower-income and racial or ethnic minority residents, as documented in North America (Landrigan et al. 2018; Tessum et al. 2019; Nicolaou and Checkley 2021).

Air pollution needs to be addressed at the source (Baldauf and Nowak 2014; EPA 2019) because more pollutants are emitted than can reasonably be contained with mitigation measures. But eliminating air pollution is an intractable challenge to even the most well-resourced governments—especially pollution from nonpoint sources such as vehicles and woodsmoke/biomass burning from residences. Trees and other green infrastructure can help to remove these pollutants locally and/or be used to create barriers between pollutant sources and the people or organisms exposed (Baldauf and Nowak 2014; Hewitt et al. 2020; Wernecke and Pool 2022).

What roles can forests play?

Typically, urban forests reduce air pollution by around 1 percent at the city scale (Litschke and Kuttler 2008; Baldauf and Nowak 2014; Salmond et al. 2016; Sicard et al. 2018; Xing and Brimblecombe 2020). But even a modest reduction in pollution can be very valuable to cities. For example, in 2010, forests in the continental United States (both inside and outside of cities) removed an estimated 17.4 million tons of air pollutants such as particulate matter (PM), contributing to health benefits—including 850 avoided premature mortalities—worth an estimated $6.8 billion (Nowak et al. 2014). However, reducing pollutants further may require a large expansion in tree canopy cover (Litschke and Kuttler 2008; Nieuwenhuijsen et al. 2017). Models of the effects of urban trees on local air quality (i.e., site scale) suggest larger reductions are possible with proper planning and species selection (Pugh et al. 2012; Janhäll 2015; Abhijith et al. 2017; Barwise and Kumar 2020).

Forests and other vegetation can have positive or negative effects because they interact with urban air pollutants in several different ways. Urban trees alter pollutant concentrations by trapping pollutants or by redirecting airflow:

- *Removing particles from the air (deposition)* by either taking in gaseous pollutants or having particles settle on their surfaces (Beckett et al. 1998). Trees remove pollutants at faster rates than other types of vegetation (Fowler et al. 2004). Dense but porous vegetation serves as an ideal surface for deposition, superior to the comparatively smooth surfaces of buildings and roads.
- *Dispersing pollutants (dilution)* in the urban environment by altering airflow patterns and slowing wind (Abhijith et al. 2017). Dilution of highly polluted air with clean air from surrounding areas enhances urban air quality. Trees can help or hinder dilution: they may act as an obstacle, slowing wind speeds and reducing the exchange between clean and polluted air, suppressing pollutant dispersion (Säumel et al. 2016; Abhijith et al. 2017; Xing and Brimblecombe 2020) or as a source of turbulence that increases the exchange, based on characteristics of the built environment and on meteorological conditions.

But trees can also emit two types of particles that affect air quality:

- *Biogenic volatile organic compounds (bVOCs)* can act as precursors to pollutants such as ozone and secondary organic aerosols and can worsen air quality (Laothawornkitkul et al. 2009; Leung et al. 2011; Calfapietra et al. 2013; Cariñanos et al. 2017). Even healthy plants produce bVOCs (Smith 1981), but exposure to drought, pollutants, heat, and excessive sunlight, as well as physical

- injury or attacks by pests, may all induce the release of additional bVOCs (Laothawornkitkul et al. 2009; Calfapietra et al. 2013). Increases in global temperature may increase bVOC emissions further (Laothawornkitkul et al. 2009; Wang et al. 2014).
- *Allergenic pollen* can undermine health (Smith 1981; Beckett et al. 1998; Cariñanos and Casares-Porcel 2011; Säumel et al. 2016; Eisenman et al. 2019; Hewitt et al. 2020). Climate change and air pollution have led to the increased production of pollen in some tree species (Cariñanos and Casares-Porcel 2011). Allergies due to pollen can decrease the quality of life of urban dwellers, and allergen exposure has been linked to ill health conditions such as cardiovascular disease, pneumonia, and asthma (Curtis et al. 2006). Air pollutant exposure can even worsen the health impacts of pollen. When pollen grains (as airborne PM) interact with other air pollutants, they can be modified, enhancing their allergic potential as well as their penetration potential into the respiratory tract (Eisenman et al. 2019). Exposure to air pollutants can also exacerbate allergy symptoms (Jianan et al. 2007; Cariñanos and Casares-Porcel 2011).

How do trees interact with the built environment?

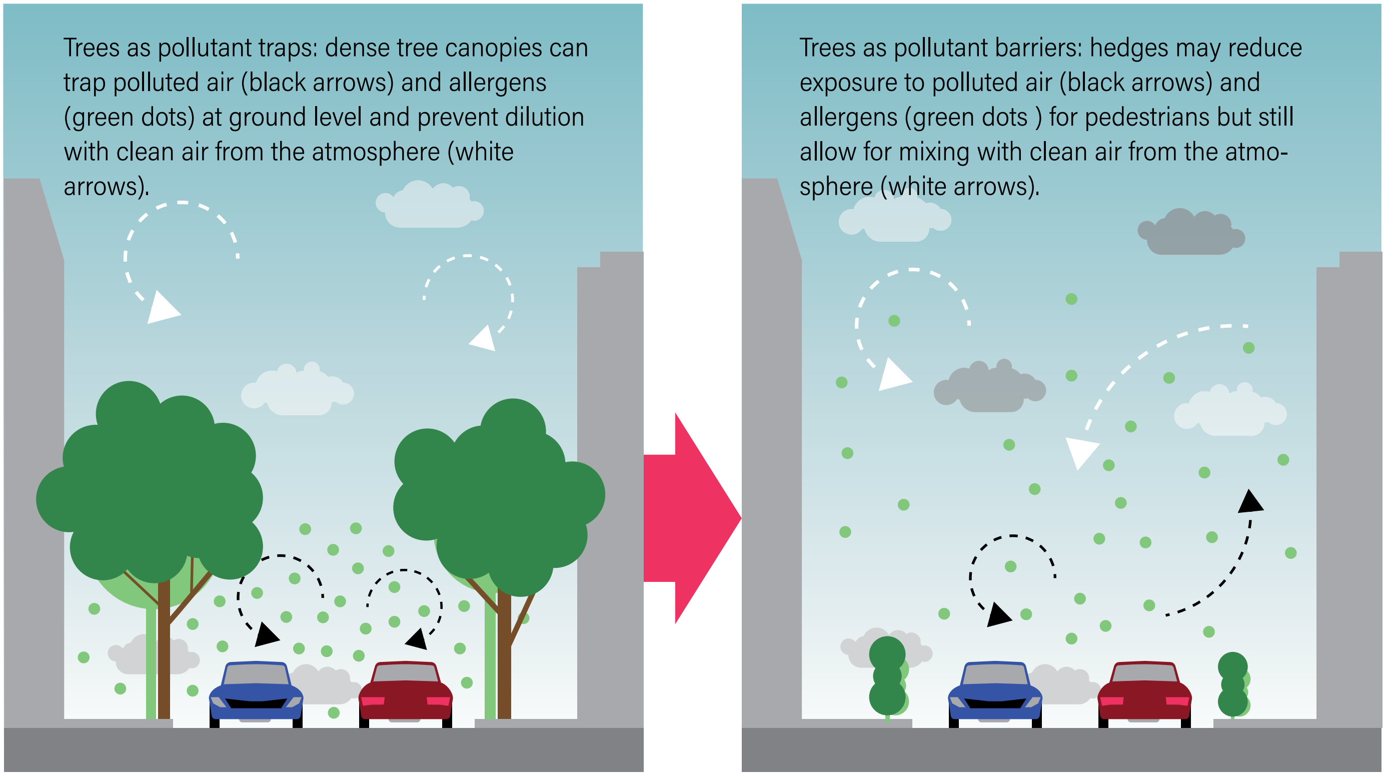
Trees in urban "street canyons" formed by tall buildings may trap polluted air near the ground level (Figure 4, top; Abhijith et al. 2017; Hewitt et al. 2020). In these street canyons, the movement of air is already restricted. Trees with canopies higher than 1–2 meters (m) may slow wind speeds and limit air pollutant dilution, increasing the concentration of various pollutants in urban canyons by as much as 20–96 percent (Abhijith et al. 2017). The aspect ratio (i.e., the height to width ratio of buildings to road) influences airflow in the canyon, as does vegetation density, tree spacing, and wind direction (Abhijith et al. 2017).

On the other hand, hedges and shrubs (around 1–2 m tall) in street canyons may provide an effective barrier between pedestrians and traffic emissions while permitting adequate dispersion of air (Figure 4; Janhäll 2015; Säumel et al. 2016; Abhijith et al. 2017). This is because low, permeable hedges create vortices that may carry air away from footpaths along roads and generally have positive effects on air quality at ground level (Abhijith et al. 2017).

Similarly, in open road conditions, trees and hedges can reduce the concentration of pollutants near highways by serving as barriers between pollution sources and human receptors (Figure 5; Abhijith et al. 2017; Xing and Brimblecombe 2020). Unlike vegetation in urban canyons, these barriers provide maximum benefits when the trees or hedges are tall (>0.5 m), thick (>10 m), and moderately porous (Baldauf 2017). Empirical studies have shown reductions in pollutant concentrations of 15–60 percent when trees and hedges are used as barriers along open roads (Abhijith et al. 2017).

Strategic plantings of trees along roadsides could shield sensitive populations from exposure to PM and other pollutants, especially in areas with insufficient green space. Because deposition of pollutants on plant surfaces decreases

FIGURE 4 | Air Pollution in Urban Street Canyons



Note: Urban trees can trap pollutants in urban street canyons (top) but can also serve as effective barriers between pollutants and people in some situations (bottom).
Source: Authors. Adapted from Trivedi et al. 2020.

with distance, trees should be planted as near as possible to the source of pollution (e.g., a road with automobile traffic) without blocking cleaner air from the atmosphere from entering the area (Litschke and Kuttler 2008; Leung et al. 2011; Janhäll 2015).

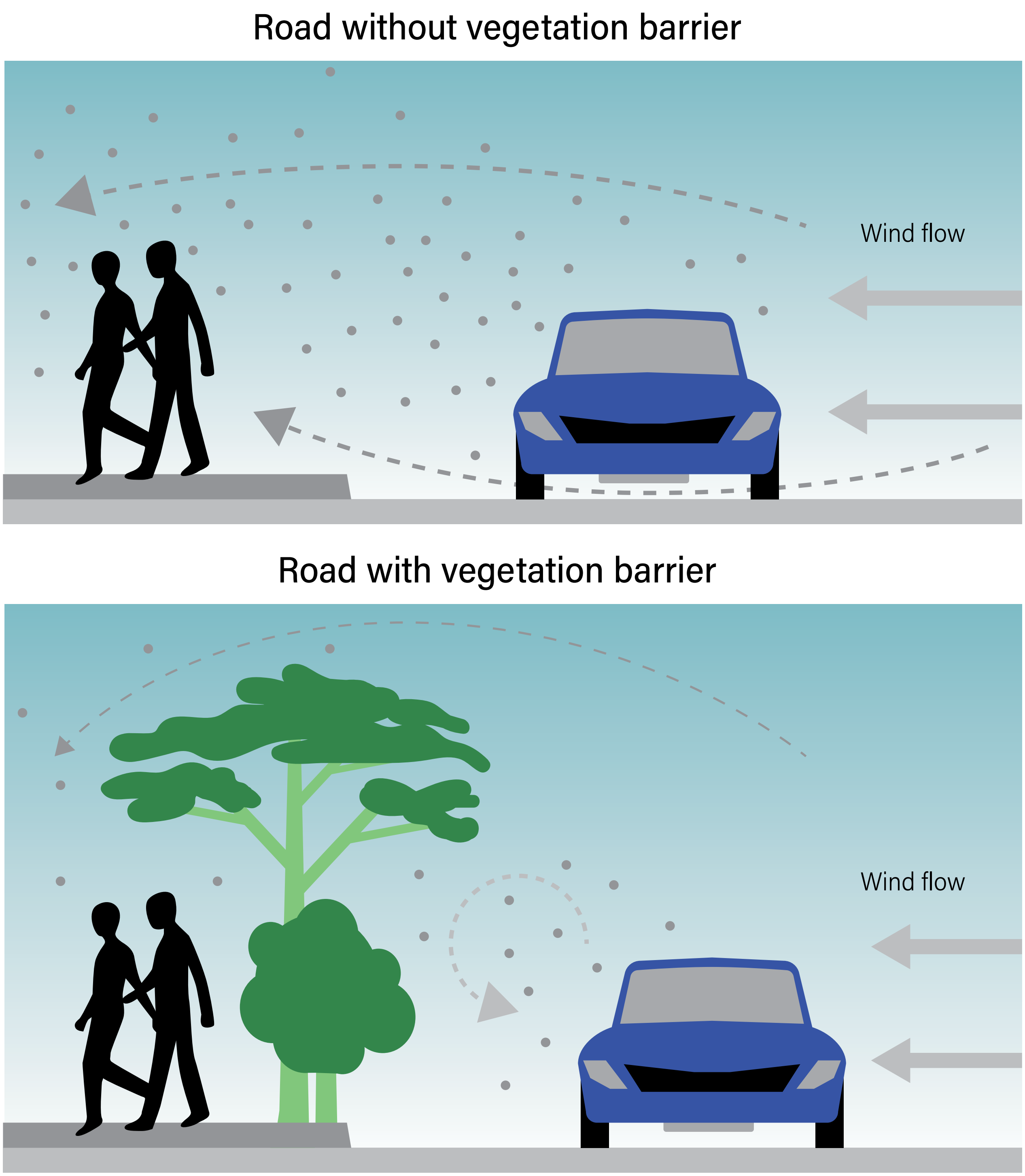
Caveats and considerations

As a result of the interactions, without adequate planning, the net effect of the inner forest on air quality in any given local area may be neutral or negative (Litschke and Kuttler 2008; Leung et al. 2011; Baldauf and Nowak 2014; Salmond et al. 2016; Sicard et al. 2018; Eisenman et al. 2019; Xing and Brimblecombe 2020).

When it comes to enhancing air quality, tree characteristics matter. Different trees remove different amounts of pollutant particles, depending on the following:

- *Leaf texture (e.g., waxy, hairy) and surface area* (Janhäll 2015). For example, leaves with many tiny hairs may capture more pollutants.
- *Growth form.* Shrubs (i.e., woody plants with many stems) remove more PM than trees, but both remove more PM than other types of plants, such as grasses (Cai et al. 2017). However, if the vegetation is too dense, it can become a barrier forcing air to move over instead of filtering through.
- *Growth strategy.* Evergreen coniferous species (e.g., pine) typically remove more pollutants and dust than deciduous species (e.g., sycamore or maple) because the tiny needle-like leaves of many coniferous species create an effective filter (Janhäll 2015). Evergreen species also bear leaves throughout the entire year and can thus intercept pollutants year-round (Cavanagh and Clemons 2006; Litschke and Kuttler 2008).

FIGURE 5 | Trees as Effective Barriers between Pollutants and Pedestrians



Source: Authors. Adapted from Abhijith et al. (2017).

Adapting strategies to site characteristics and local context are important for good outcomes (Hewitt et al. 2020). A slew of factors in the built and natural environment affects whether trees will have a positive, negative, or neutral effect on air quality, including airflow patterns, wind speed, building height and density, local humidity, temperature, and proximity to and type of pollutant source, among other factors (Cavanagh and Clemons 2006; Litschke and Kuttler 2008; Elmqvist et al. 2015; Salmond et al. 2016; Cai et al. 2017; Kumar et al. 2019; Xing and Brimblecombe 2020).

Using low-emitting species can support air quality goals in urban areas by reducing bVOCs and pollen (Cariñanos and Casares-Porcel 2011; Calfapietra et al. 2013). Municipalities frequently overlook species selection during large-scale tree-planting projects (Churkina et al. 2015). One study estimated that selecting the low-bVOC-emitting tree species over high-emitting species in a large-scale tree-planting initiative in Denver would be equivalent to avoiding emissions from nearly 500,000 cars from inner-city traffic (Curtis et al. 2014).

More research is needed on how best to use trees to reduce air pollution in cities (Janhäll 2015; Abhijith et al. 2017; Eisenman et al. 2019; Kumar et al. 2019; Hewitt et al. 2020). In particular, research that explores the effects on dilution, empirically validates models, and reports on effects at multiple spatial scales is needed (Beckett et al. 1998; Janhäll 2015; Salmond et al. 2016; Xing and Brimblecombe 2020). Urban vegetation cannot substitute for source emissions reductions but can improve local conditions and lead to better health outcomes for residents.

GOAL 3: PROMOTING PHYSICAL AND MENTAL HEALTH IN CITY RESIDENTS

Context

Living in cities presents health risks (Bai et al. 2012; Kuddus et al. 2020). As a result of heightened exposure to air, light, and noise pollution and decreased exposure to sunlight and key microorganisms, urban dwellers may be more vulnerable to noncommunicable, immune, and respiratory diseases and infections (Flies et al. 2019). Urban lifestyles often permit fewer opportunities for physical activity, time in nature, and spaces for social connection with neighbors (Frumkin 2002).

Mental health can also be affected by the social, economic, and environmental conditions of the city landscape. Urban living can increase the risk of developing some mental illnesses and disorders (Peen et al. 2010; Lecic-Tosevski 2019; Ventriglio et al. 2019). Abundant sensory stimuli and high population densities in cities can create stress, with few opportunities for coping. Stress manifests in both the brain and the body (McEwen 2008) and is a factor in illnesses ranging from depression to cardiovascular disease (Cohen et al. 2007).

Many of the environmental hazards of cities—such as exposure to air pollution, unsafe drinking water, or extreme temperatures—disproportionately affect lower-income communities and marginalized residents (Frumkin 2002; Kondo et al. 2015). Creating healthier cities will require

interventions to reduce disparities in access to health care, increase availability of safe housing, and further improve sanitation (Dye 2008). But the urban forest also serves as a dispersed and relatively low-cost element of public health infrastructure.

What roles can forests and green spaces play?

Natural environments can reduce stress (Case Study 1; Hartig et al. 2014; McCormick 2017; Nesbitt et al. 2017; Kondo et al. 2018; Summers and Vivian 2018; Bratman et al. 2019). Exposure to urban forests and other elements of nature may reduce risks related to chronic stress by the following actions:

- *Providing opportunities for restoration (i.e., recovery) of a person's adaptive capacity* to cope with stressful life events or exposure to environmental stressors (Hartig et al. 2014; Bowler et al. 2010b).
- *Dampening the effect of urban stressors.* Noise, for instance, is both a nuisance and an environmental stressor that can interfere with communication, alter behavior, and impair work performance (Stansfeld and Matheson 2003). The foliage of urban forests can create a physical barrier that absorbs the energy of sound waves and reduces noise overall (Nowak and Dwyer 2007; Dzhambov and Dimitrova 2014; Wang et al. 2014; Säumel et al. 2016).

Exposure to nature—including forests and urban green spaces—is associated with better mental health and psychological well-being, including

- improved mood, perceived well-being, sleep, and ability to focus (Bratman et al. 2019); and
- reduced risk of some psychological disorders (Bratman et al. 2019) and better mental health outcomes (Wolf et al. 2020). For example, the presence of urban green spaces or residential greenness have been linked to lower anxiety and depression (see Braubach et al. [2017] or Vanaken and Danckaerts [2018]).

Exposure to forests and nature may benefit children's mental development. A growing body of research shows that regular access to nature helps children thrive and is important for their mental health. Access to forests and nature has been found to improve cognitive functioning (Hartig et al. 2014;

CASE STUDY 1 | Shinrin-yoku, or Forest Bathing (Japan and East Asia)

Leisurely visits to forests for relaxation, known as "forest bathing," "forest therapy," or *shinrin-yoku* in Japanese, can offer a suite of health benefits.[a] *Shinrin-yoku* combines both physical activity and stress-reducing behavior, such as mindfulness and is a cultural practice employed by many in eastern Asia and elsewhere.[b]

Walks in forest settings may increase immune system activity compared with walks in urban settings, including the activity of anti-tumorigenic natural killer cells.[c] The benefits from forest bathing may arise from the inhalation of phytoncides, or antimicrobial biological volatile organic compounds emitted by plants, such as alpha-pinene or limonene.[d] Research has examined the effects of *shinrin-yoku* on the cardiovascular system, the respiratory system, and mental health conditions including depression, anxiety, and mood disorders.[e] One review of studies on forest therapy found significant improvements in depression in 21 out of 28 studies identified,[f] and forest bathing has been successfully incorporated into other evidence-based therapy programs.[g]

Forest bathing may significantly reduce stress, including lowering salivary cortisol levels[h] and both diastolic and systolic blood pressure.[i] Some evidence also suggests it can reduce insomnia and psychological distress associated with chronic illness and pain.[j] A review of randomized controlled trials found a consistent positive trend in a variety of psychological and physiological health outcomes after forest bathing.[k] Research on forest bathing is nascent but rapidly growing, and thus far it supports the benefits of forest bathing and provides yet another reason to conserve and allow access to intact inner and nearby forests.

Sources: a. Li 2010; Song et al. 2016; b. Hartig et al. 2014; c. see Li et al. 2008; Kuo 2015; d. Li 2010; Kuo 2015; e. Hansen et al. 2017; Oh et al. 2017; f. Lee et al. 2017; g. Hansen et al. 2017; h. Antonelli et al. 2019; i. Ideno et al. 2017; j. Hansen et al. 2017; k. Oh et al. 2017.

Jennings et al. 2016; McCormick 2017; Kondo et al. 2018) and reduce behavioral difficulties (Summers and Vivian 2018; Vanaken and Danckaerts 2018). Increased exposure to natural settings and outdoor activities in green spaces also may reduce attention-deficit/hyperactivity disorder (Braubach et al. 2017; Nesbitt et al. 2017; Summers and Vivian 2018; Vanaken and Danckaerts 2018), improve attention capacity (Tzoulas et al. 2007), enhance creative development (Bratman et al. 2019), and improve academic performance (Jennings et al. 2016; Bratman et al. 2019). For example, a study of more than 3,500 school-age children in London found that exposure to woodland was associated with higher cognitive development scores and lower risks of behavioral and emotional problems, even after controlling for other variables (Maes et al. 2021).

Exposure to green space, tree canopies, and urban nature is associated with better physical health (Case Study 1). Examples include the following:

- *Reduced risk of noncommunicable diseases,* including cardiovascular disease (Nieuwenhuijsen 2018; Wolf et al. 2020) and type II diabetes mellitus (den Braver et al. 2018; Twohig-Bennett and Jones 2018)
- *Reduced indicators for stress and disease,* such as salivary stress hormones, heart rate, and blood pressure (Meyer and Bürger-Arnd 2014; Hansen et al. 2017; Twohig-Bennett and Jones 2018; Wolf et al. 2020); forest bathing, in particular, seems to have positive effects on physiological states and immune activity (Case Study 1)
- *Lower body mass index* (Lachowycz and Jones 2011; Wolf et al. 2020), a predictor of other health outcomes
- *Improved pregnancy and birth outcomes (*Dzhambov et al. 2014; Braubach et al. 2017; Nesbitt et al. 2017; Twohig-Bennett and Jones 2018; Kloog 2019)
- *Reduced risk of premature death;* most evidence supports a significant inverse relationship between premature mortality and residential greenness (Gascon et al. 2016; Twohig-Bennett and Jones 2018; Rojas-Rueda et al. 2019)

Exposure to forests and nature can improve people's immune systems (Kuo 2015; Shanahan et al. 2015; Braubach et al. 2017). Being exposed to a diverse array of microorganisms—to which humans were exposed for much of our evolutionary history—may stimulate the immune system and enhance its ability to distinguish between beneficial and harmful bacteria, which can improve health outcomes, including autoimmune disorders, allergies, depression, or cancer (Rook 2013; Kuo 2015; Sandifer et al. 2015; von Hertzen et al. 2015; Lai et al. 2019). These microorganisms are accessed in forests and nature.

Preventing deforestation and degradation of intact forest ecosystems outside of cities may help control the spread of infectious diseases. Deforestation and land-use changes have been linked to the emergence and spread of pathogens (Karjalainen et al. 2010; Alimi et al. 2021; Austin 2021). For example, forest fragmentation and deforestation in North America is implicated in the increasing incidence of Lyme disease, while climbing rates of deforestation in Asia, Africa, and Latin America have been linked to increases in malaria and malaria vector populations (Karjalainen et al. 2010). Protecting highly biodiverse tropical forests may also prevent spillover of new zoonotic diseases, such as coronaviruses, from animal hosts to humans (Afelt et al. 2018; Sokolow et al. 2019).

Caveats and considerations

Urban trees can also sometimes pose health risks to urban residents, including the following:

- *Injury.* Branches and tree roots can pose a risk of injury, for example, when roots displace sidewalk paving or when tree limbs (or entire trees) fall on roads or property (Escobedo et al. 2011).
- *Zoonotic diseases.* Wooded areas may house unwanted animals, such as feral dogs, and pests that carry disease, such as ticks (Lyytimäki et al. 2008; Coutts and Hahn 2015; Lõhmus and Balbus 2015; von Döhren and Haase 2015; Stone et al. 2017).

To reduce these risks, cities may need to pursue targeted interventions. Examples include periodic tree trimming or removing hazardous trees, public education, and population control of animal hosts and vectors (Lyytimäki et al. 2008; Lõhmus and Balbus 2015). City leaders should include funding for tree pruning and removal in city budgets.

GOAL 4: CREATING WALKABLE, SAFE STREETS

Context

Cities around the world are striving to increase opportunities for public transport and active transit (i.e., by foot or by bicycle) as part of their decarbonization strategies. But greener cities are not the only benefit of such efforts. Physical inactivity is a leading global health concern (Kohl et al. 2012), with many harmful effects on the body (Tremblay et al. 2010). Creating more inviting spaces for active transport, physical exercise, and recreation could be a health-environment win-win.

What roles can forests and green spaces play?

Physical activity may explain part of the connection between health and nature exposure (Hartig et al. 2014). But evidence connecting green space directly to increased physical activity remains mixed (Lee and Maheswaran 2011; Nieuwenhuijsen 2018). Evidence suggests green spaces may either have a positive (e.g., Lachowycz and Jones 2011; Calogiuri and Chroni 2014) or neutral (e.g., Hartig et al. 2014; Hankey and Marshall 2017; Kondo et al. 2018) effect on physical activity. In one recent review, however, 18 out of 19 studies suggested a positive effect of urban trees on levels of physical activity (Wolf et al. 2020).

By providing shade, reducing exposure to air pollution, and enhancing aesthetic appeal, street trees might encourage active transport (Figure 6; Kumar et al. 2019; Wolf et al. 2020). Perceived safety, distance to destination, and presence of infrastructure (e.g., sidewalks, bike lanes) also drive decisions related to active transit (Hartig et al. 2014).

Urban green spaces and large, mature trees have been associated with reduced levels of crime, aggressive behavior, and other antisocial activities (Kondo et al. 2015; Wolf and Robbins 2015; Jennings et al. 2016; Wolf et al. 2020). Although evidence remains mixed, researchers have found lower crime rates related to characteristics such as street tree density, when controlling for other confounding variables. For example, increased canopy cover has been associated with reduced rates of homicide in Bogotá (Escobedo et al. 2018), and reduced rates of gunshot assaults in Philadelphia

(Kondo et al. 2017). In Baltimore, a 10 percent increase in canopy was associated with a 12 percent decrease in crime (Troy et al. 2012).

Well-placed and well-maintained urban trees also hold the potential to enhance transportation safety. The presence of trees may reduce the number of vehicle collisions (Lyytimäki et al. 2008; Wolf 2010; Van Treese et al. 2017). Trees may also help to demarcate the edge of the road or create a barrier between vehicles and pedestrians (Mullaney et al. 2015).

In addition, urban and nearby forests create spaces for recreation and play (Tyrväinen et al. 2005; O'Brien et al. 2017). Forested areas in and around cities can host hikers, campers, trail runners, birdwatchers, and provide space for children to engage in free play. The cooling and shading provided by trees moderates microclimates, which can encourage use. If accessing areas of urban nature is challenging or expensive, these benefits will not be equitably distributed among populations.

FIGURE 6 | Trees can be incorporated into urban streets to create favorable microclimates for active transit and play for children

Source: WRI Mexico.

Caveats and considerations

Aspects of urban trees can threaten residents' safety when commuting or exercising.

- *As mentioned above, tree roots can damage sidewalks and some pavements* (Randrup et al. 2001; Escobedo et al. 2011; Roy et al. 2012). Careful species and site selection for and maintenance of trees can reduce these risks and ensures accessibility for all users of public infrastructure.
- *Poorly placed trees can also be a hazard along roads.* Trees and other vegetation may block lines of sight for drivers, bikers, and other commuters (Wolf 2006; Lyytimäki et al. 2008). Species selection, placement, and proper maintenance can reduce this risk.

Urban forests may also affect residents' *perceived* safety (Figure 7, top; Kondo et al. 2015; Mancus and Campbell 2018). This is also mediated by the following factors:

- *Personal identity.* Obstructed views or shaded spaces may increase fear of crime or danger, particularly in women, ethnic minorities, and the elderly—and in those who have experienced crime directly or indirectly in the past (Jansson et al. 2013; Maruthaveeran and Konijnendijk van den Bosch 2014). This depends on the city context.
- *Local context and characteristics of the forested area.* Poorly maintained, poorly lit, or littered green spaces may be perceived as places for illicit activity or antisocial behavior (Tzoulas et al. 2007; Jansson et al. 2013; Maruthaveeran and Konijnendijk van den Bosch 2014; Kondo et al. 2015; von Döhren and Haase 2015; Wolf 2017).

FIGURE 7 | Inner Forests and Perceived Safety

Note: Areas with urban trees could make some residents feel unsafe (left), but these spaces can also be intentionally designed or maintained to increase perception of safety and resident comfort for all users (right).

Source: Authors. Adapted from Trivedi et al. 2020.

The quality and accessibility of green spaces affects how people use them for recreation and physical activity (Lee and Maheswaran 2011; Calogiuri and Chroni 2014). As described above, fear of crime may prevent certain groups from being physically active or commuting near these spaces, especially in the dark (Lyytimäki and Sipilä 2009; Jansson et al. 2013). In some contexts, maintaining vegetation and installing infrastructure (lights, etc.) may be necessary to create safe and accessible areas for all residents (Green City Partnerships 2019). Moreover, safeguards may need to be put in place to ensure that green spaces are used in a safe way that allows use by all residents (for example, regulating mountain biking on single-track pedestrian trails).

GOAL 5: SUPPORTING COMMUNITY CONNECTIONS

Context

Strong social networks in communities form the foundation for thriving cities. Robust social networks may increase community resilience against disturbances such as natural disasters (e.g., Islam and Walkerden 2014; Townshend et al. 2015). In individuals, social relationships and shared trust support health and well-being (Hartig et al. 2014; Braubach et al. 2017) and buffer against stress (Jennings et al. 2016). Such social cohesion can also reduce feelings of loneliness and isolation (Wolf 2017), which have been linked to higher rates of illness and mortality (Kondo et al. 2015; Braubach et al. 2017).

What roles can forests and green spaces play?

Urban forests and other green spaces can enhance social well-being by providing cultural ecosystem services, including benefits such as aesthetic appeal, recreation, and spiritual connection (Millennium Ecosystem Assessment 2005). For centuries, trees have been planted in and around cities to beautify public spaces, gardens, streets, and yards to provide aesthetic benefits as they improve scenic quality or visual appeal (Roy et al. 2012; Säumel et al. 2016) and even produce pleasant smells and sounds (Zhou and Parves Rana 2011).

Furthermore, inner and nearby forests can promote a "sense of place"—the idea of identity and emotional connection to the local environment (Wolf et al. 2014; Jennings et al. 2016; O'Brien et al. 2017). When green spaces increase residents' connections to their communities, they may be more likely to engage in health-promoting social or physical activities (Jennings et al. 2016). Sense of place may even stimulate economic activity—for example, it can drive the preferences of tourists and their intention to revisit certain locations (Hausmann et al. 2016).

By reinforcing a sense of place and stimulating feelings of attachment and belonging, well-kept green infrastructure may also foster community identity (Jennings and Gaither 2015; Jennings and Bamkole 2019):

- Forests, woodlands, parks, and urban green spaces may also be places for recreating, for gathering culturally relevant foods, or for expressing oneself through photography or art (O'Brien et al. 2017).
- Green spaces, especially those with temperature regulation by trees, can be desirable locations for social interaction (Lee and Maheswaran 2011; Zhou and Parves Rana 2011; Shanahan et al. 2015; Braubach et al. 2017; Nesbitt et al. 2017; Bratman et al. 2019).
- Direct participation in tree-planting programs or other green space stewardship activities may stimulate a sense of community identity and ownership (Higgs 2003; Nowak and Dwyer 2007; Jennings et al. 2016).

Around the world, forests serve as settings for spiritual practice, sacred symbols, and spaces for contemplation for both individuals and groups (Daniel et al. 2012; O'Brien et al. 2017). For some people, forest environments trigger feelings of "awe" or transcendence (Dwyer et al. 1991; Williams and Harvey 2001; Kuo 2015; Irvine and Herrett 2018). Spirituality may mediate the relationship between human well-being and nature (Kamitsis and Francis 2013; Hansen et al. 2017). In addition to specific institutional spaces such as churches, mosques, or other formal structures of worship, forests and green spaces provide space for spiritual practice (Okyerefo and Fiaveh 2017; Ngulani and Shackleton 2019). For example, in Accra, Ghana, the Achimota Forest is considered a sacred place of gathering, where urban dwellers seek serenity (Okyerefo and Fiaveh 2017). In Japan and India, sacred shrine or temple forests have been protected as the areas around them are urbanized—sometimes for centuries (Ishii et al. 2010; Daniel et al. 2012).

Caveats and considerations

As with most benefits, the ways forests can provide cultural benefits should be considered with local context and perspectives in mind:

- *The aesthetic preferences of some groups may conflict with others.* For example, non-native species are preferred by some, whereas others prefer native natural areas (Lõhmus and Balbus 2015; von Döhren and Haase 2015).
- *Spiritual services are not easily generalized or valued in economic terms.* Their value may vary widely across urban subpopulations (Daniel et al. 2012).

GOAL 6: REDUCING URBAN ENVIRONMENTAL INEQUITY

Context

The livable and sustainable cities of the future are equitable cities. But technological innovation, urbanization, and migration exacerbate existing income inequality in many nations—and climate change threatens to erase progress in reducing income inequality among nations (UN DESA 2020). Within cities, lower-income and marginalized communities disproportionately inhabit "riskscapes," which are geographic areas with limited access to resources and high risk of exposure to environmental stressors and hazards such as pollution and natural disasters (Jennings et al. 2012; Kondo et al. 2015).

Inequality in the distribution, funding, and maintenance of urban tree canopies is an environmental justice issue (Jennings and Gaither 2015; Schwarz et al. 2015). Lower levels of urban tree canopy cover have been associated with lower-income populations (Schwarz et al. 2015; Jennings et al. 2016; Gerrish and Watkins 2018) and with racial or ethnic minority populations (Watkins and Gerrish 2018; Locke et al. 2021) in some cities (Jennings et al. 2016). Developments in monitoring technology are making it easier to identify and correct these trends. In 2021, for example, American Forests released its Tree Equity Score tool—which reflects levels of tree canopy cover and demographic income such as race or age in around 150,000 neighborhoods in 486 municipalities in the United States—providing valuable data to residents and community leaders alike.[17]

What roles can forests and green spaces play?

Forests in and around cities, as well as other types of green infrastructure, may be managed, protected, or expanded in ways that can help reduce inequities between groups of people. Addressing inequities in tree distribution helps to distribute the important health benefits provided by forests across all residents. Evidence suggests that lower-income and marginalized groups may benefit from the expansions in urban canopy cover (or other urban greening efforts) more than other groups (Braubach et al. 2017). For instance, access to and engagement with urban green spaces by lower-income and marginalized groups may reduce disparities in rates of cardiovascular disease, obesity, heat stress, or psychological illness (Jennings and Gaither 2015). Urban forest planting, management, and stewardship also present opportunities for employment as well.

Caveats and considerations

Careful planning is required to ensure that inner forest expansion does not exacerbate existing disparities in health and well-being in cities (Kondo et al. 2015; Jennings et al. 2016). Expanding urban forests (or other green infrastructure) may inflate property and housing costs in a way that burdens or contributes to the displacement of low-income residents in these areas—a phenomenon coined as *eco-gentrification* (Wolch et al. 2014; Wolf 2017). A scoping review of 15 empirical studies found that longtime residents who are negatively impacted by green gentrification can experience a lower sense of community and belonging, which may result in lower green space use when compared with newcomers (Jelks et al. 2021). Additionally, residents inhabiting rental properties may either lack the authority or incentive to plant trees on the property (Heynen et al. 2006).

To avoid unintended negative outcomes for residents and to provide benefits to those most in need, city leaders should work with community leaders and local grassroots organizations at every stage of forest planning, management, and development. When communities are not adequately engaged and consulted, well-meaning initiatives may fail to meet their objectives; for example, in Detroit nearly 24 percent of residents approached by a nonprofit declined to have trees planted in their yards, citing insufficient engagement and concerns about a lack of tree maintenance by the city

in the past (Carmichael and McDonough 2018). Although inclusive governance and authentic community engagement can require greater investment of time and resources, it can help to prevent unintended negative outcomes and ensure that residents' needs are met. This will ensure that trees and other green infrastructure are installed where they are most needed and in ways that reflect community preferences.

GOAL 7: ENSURING PROVISION OF FOOD, MEDICINE, AND RAW MATERIALS

Context

As urban populations climb, cities grapple with issues of food security and nutrition (Crush and Frayne 2011). Many city residents lack access to fresh, nutritious food, leading to inequities in health among residents (Dixon et al. 2007). Still others lack adequate access to health care, cooking fuel, or raw materials for trades or crafts.

What roles can forests and green spaces play?

Forests—including those within cities—play an important role in supplying cultivated and foraged foods and medicines as well as other raw materials. Although cities rely heavily on imported goods and materials, opportunities to meet residents' needs using urban and peri-urban ecosystems may help to address disparities in access among low-income or marginalized groups while reducing pressure on natural rural ecosystems near cities. Examples include the following:

- *In urban areas, forests can provide foods, fuel, and medicine,* particularly to low-income or marginalized groups, particularly in developing countries (Karjalainen et al. 2010; Pramova et al. 2012; Lwasa et al. 2015; Wolf and Robbins 2015; Lindley et al. 2018). Such products may serve as invaluable safety nets—especially for low-income communities most at risk (Pramova et al. 2012).
- *Trees on the urban fringe provide fuelwood, medicine, food, and even products that can be sold for income, particularly in developing countries.* This is especially the case for low-income residents and those who live in informal settlements (Shackleton et al. 2015). For example, wood gathered from urban and peri-urban eucalyptus plantations makes

up the livelihoods of marginalized groups—primarily women—in Addis Ababa, Ethiopia (Fetene and Worku 2013). Urban foraging for foods and medicines can connect individuals to their cultural heritage or increase food security (Poe et al. 2013).

- *Trees—especially nitrogen-fixing species—may also complement agriculture in and around cities* (Pramova et al. 2012). Integrating trees into farmland to improve or diversify agriculture (agroforestry) can ameliorate microclimate for crops, improve soil fertility, and reduce water stress, depending on the crop type and region (Pramova et al. 2012).
- *Trees in and around cities can diversify incomes* by supplementing crop production, supporting animal husbandry, or providing raw materials (Salbitano et al. 2016). In the Pacific Islands, agroforestry in home gardens has historically enhanced diet diversity and provided raw materials for construction and craft making (Thaman et al. 2006).
- *Forest plants, fungi, and microbes represent an enormous reserve of compounds with potential pharmaceutical or nutritional value* (Karjalainen et al. 2010). Even the urban forest can provide medicines that may be of particular importance to certain ethnic or cultural groups or to marginalized individuals. The medicinal value of the urban forest has been recognized in North America (Poe et al. 2013), Latin America and the Caribbean (Dobbs et al. 2019), and other regions.
- *By providing wood for fuel or timber, urban forests may also help shield some natural forests from overexploitation* (Salbitano et al. 2017).

Caveats and considerations

To maximize these benefits, urban decision-makers should consider the following:

- Some municipal policies and regulations specifically prohibit foraging and gathering from urban trees or woodlands (Shackleton et al. 2017).
- Urban foraging and gathering may shield intact rural forests from overexploitation, but plants and fungi of the urban forest are also vulnerable to overharvesting (Shackleton et al. 2017). Investing in management and harvesting strategies is essential to prevent overuse.
- When urban food cultivation takes place near road corridors or rights-of-way, it may be necessary to create barriers between the roadside and urban agriculture to reduce the risk of pollutant uptake by crops (Säumel et al. 2016).

GOAL 8: ENHANCING ECONOMIC WELL-BEING

Context

Healthy cities are also economically secure cities. To be resilient, communities need to provide economic opportunities to residents and bolster small businesses. They also need to harness the power of nature to reduce municipal costs and address multiple problems simultaneously.

What roles can forests and green spaces play?

In some contexts, installing or managing urban trees can pay for itself through benefits accrued by the municipality and property owners (Nowak and Dwyer 2007). Estimates of benefit-cost ratios of urban trees vary widely, depending on species and location, from around 5:1 to 24:1 in a global review of studies (Roy et al. 2012). And because larger, more mature trees can provide more benefits, such as shade or air filtration, healthy and properly maintained urban forests represent a municipal capital investment that may actually appreciate in value over time (Stagoll et al. 2012; Salbitano et al. 2016).

Urban forests provide multiple economic benefits to municipalities and their residents:

- *Iconic forests and urban vegetation can stimulate tourism* (Nesbitt et al. 2017; Salbitano et al. 2017) and green infrastructure in general (Wolf and Robbins 2015; Nesbitt et al. 2017; O'Brien et al. 2017). Research from North America also suggests that consumers may prefer shopping districts with greater numbers of trees, a preference reflected in the duration of time and their willingness to pay for various products (Wolf et al. 2005).
- *The presence of trees can increase property values* (Nowak and Dwyer 2007; Roy et al. 2012; Mullaney et al. 2015; Nesbitt et al. 2017) in residential, rental, and commercial contexts. Adjacency or proximity to woodlands, urban parks, and other green infrastructure may also increase property values (Wolf and Robbins 2015; Jennings et al. 2017; Nesbitt et al. 2017; O'Brien et al. 2017). But green spaces and urban trees do not influence property values in all global contexts, due in part to perceived issues of safety or security (Cilliers et al. 2013).
- *The presence of trees can increase municipal revenue* related to increased property taxes (Nowak and Dwyer 2007) or fees associated with tree removal during development.
- *Managing urban forests and green infrastructure can provide "green jobs"* in nurseries, tree-care services, forest management, and other related areas (Case Study 2; Kondo et al. 2015).
- *In some cases, urban tree maintenance costs can be recouped when urban wood waste is repurposed.* In the United States alone, waste from urban trees, yard waste, and even demolition could be worth an estimated \$89—\$786 million when repurposed into wood chips, lumber, and fertilizer (Nowak et al. 2019).
- *Forests can reduce energy costs in both residential and commercial settings and can reduce costs related to water management* (see Sections 3 and 4 for more details).
- *As described above, the presence of trees and other green infrastructure could reduce public health costs, including those related to exposure to extreme heat and air pollution or improved mental health status.* For example, findings from a recent analysis of the heat-related benefits of existing urban forests in the United States suggest that urban trees can provide between \$17 and \$42 per capita (for the entire United States) per year in benefits related to avoided death, illness, and electricity use alone, compared to the typical \$5 per capita in expenditures necessary for urban forest maintenance (McDonald et al. 2020).

Caveats and considerations

Although they provide numerous benefits to economic well-being, urban trees are often costly. Like other urban assets and infrastructure, urban forest maintenance and management requires capital related to pruning, planting, emergency tree removal, and damage to pipes or roads by roots. Potential disservices may include damage to infrastructure, such as sidewalks (Randrup et al. 2001) or private property (Escobedo et al. 2011; Cilliers et al. 2013). Recognizing these costs creates realistic expectations for municipalities and encourages proactive, informed planning and management.

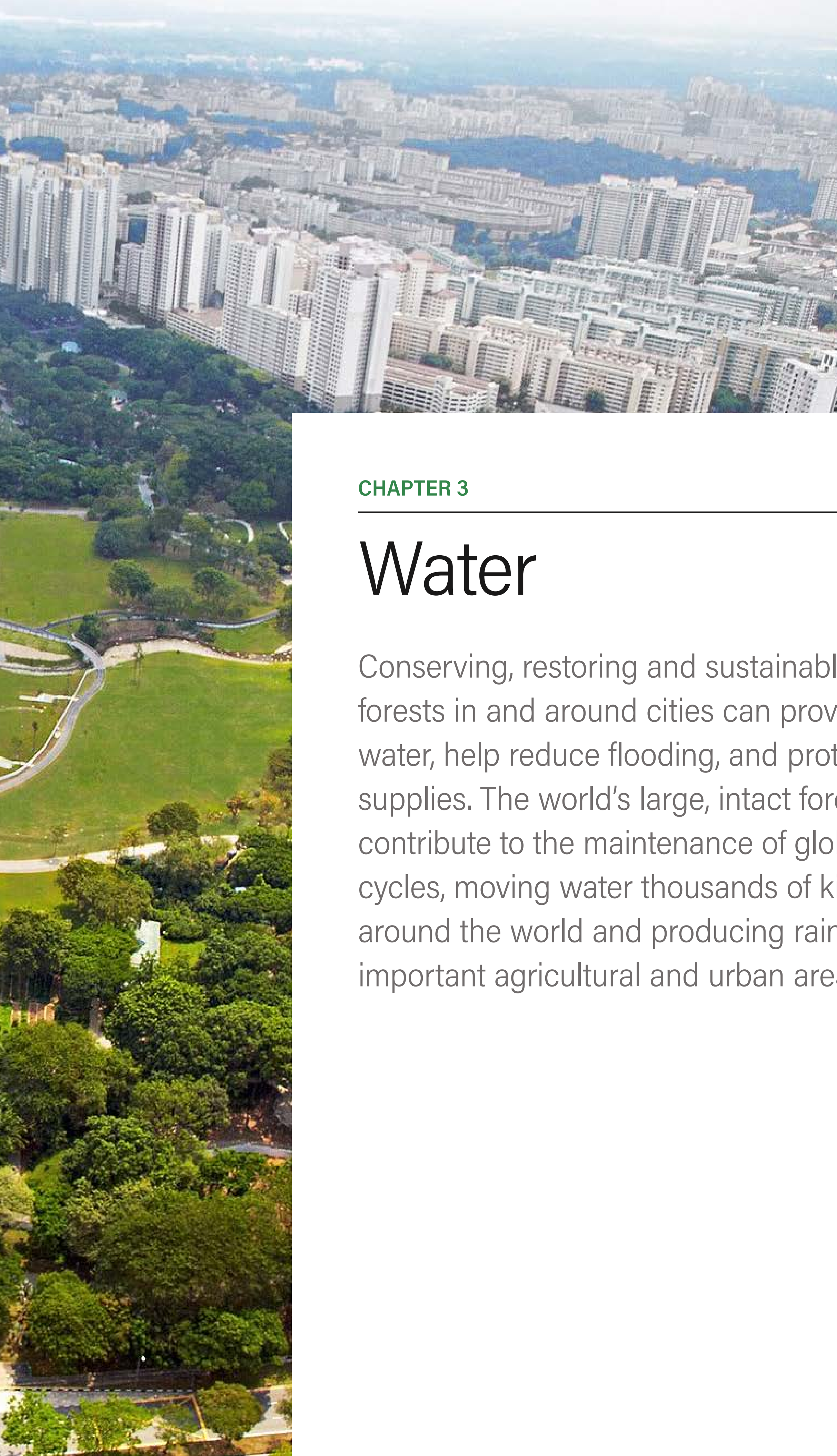
It is also important to consider the distribution of these benefits. By increasing land value and rental prices, proactive management or expansion of the urban forest may generate direct revenue for local governments—a win for tight-strapped municipalities. At the same time, increases in property value and subsequent increases in property taxes may place a financial burden on some property owners (Nowak and Dwyer 2007) or even contribute to their displacement (Wolch et al. 2014). To ensure that urban forest expansion and urban greening do not burden low-income residents, these projects should be tailored to suit local contexts and should incorporate extensive community input.

CONCLUDING THOUGHTS

Forests and nature are important to human health and well-being in cities. Well-planned, well-protected, and well-managed forests in and around cities can ensure that residents have access to a suite of ecosystem services, including ameliorated microclimate and air quality, recreation, mental restoration, and much more. Forests and other green infrastructure can help to reduce poverty, increase social cohesion, and bring communities together, but these outcomes are more likely when community perspectives and needs are incorporated at all stages of forest planning and management.

Integrating trees and forests into city plans to support health and well-being is not always easy. For example, although the value of urban forests for recreation, heritage, and aesthetic value has been recognized in low- and middle-income nations, such as in Latin America and Africa, local governments often do not act to implement forest-based solutions—in part because of the need to prioritize pressing issues, such as access to housing and sanitation (Cilliers et al. 2013; Dobbs et al. 2019). And it may take years or even decades to reap some of the benefits created by trees and other green infrastructure. Yet few interventions offer as many potential cobenefits as urban forests.

For urban health and well-being, forests can offer diverse and dispersed benefits that cities need now more than ever. Many city residents have limited access to interact with forests and nature, and in many places these environments are increasing in use and declining in quality (Bratman et al. 2019). Urban leaders envisioning the vibrant, habitable cities of the future should integrate forests as NBS and essential aspects of urban infrastructure.



CHAPTER 3

Water

Conserving, restoring and sustainably managing forests in and around cities can provide cleaner water, help reduce flooding, and protect water supplies. The world's large, intact forests also contribute to the maintenance of global hydrological cycles, moving water thousands of kilometers around the world and producing rainfall in important agricultural and urban areas.

BACKGROUND

Cities around the world face multiple challenges in providing residents with adequate, clean water (Juno and Pool 2020). Extensive urbanization and population growth, land conversion, and water diversion have put pressure on local and regional water supplies in and around cities. Ongoing climate change threatens to disrupt water cycles even further, increasing the incidences of both drought and flooding. Water-related challenges have an impact on the economy, human health, and overall city resident well-being. These are the main water-related challenges for cities:

- *Too dirty.* Many cities are unable to provide their residents with an essential and basic service: a reliable supply of clean drinking water. Contaminated or unclean drinking water causes severe health issues in many regions. Water treatment facilities and infrastructure are costly to establish and maintain.
- *Too much.* Flooding threatens the lives and safety of 15 million people as a result of coastal flooding and 132 million people as a result of riverine flooding, putting at risk $177 billion and $535 billion in urban property, respectively (Ward et al. 2020). Safeguarding water and preventing flooding are essential services to urban residents and a key agenda item for many city leaders.
- *Too little.* Water scarcity can be caused by extreme drought, depletion of groundwater, or reduced river flows. Many cities around the world—especially in arid regions—face seasonal or year-round issues with water supply, which are likely to increase as populations grow.
- *Too erratic.* City residents—like much of the world—are also vulnerable to the increasingly erratic weather patterns, including longer and more intense droughts and heavy rainfall (Seneviratne et al. 2012). Variability and unpredictability in precipitation and water supply create additional challenges for urban leaders. Shifting precipitation patterns at the global scale—driven by climate change and land-use change—may exacerbate existing issues related to flooding or water scarcity.

To face these water challenges, leaders—from China to the United States to Brazil—are embracing NBS such as forests to complement traditional "gray" city water infrastructure solutions. Increasing areas of forest and green space in strategic locations in cities can reduce burdens on aging or overburdened water infrastructure while delivering key cobenefits. And in contrast to gray infrastructure, green infrastructure can appreciate in value over time.

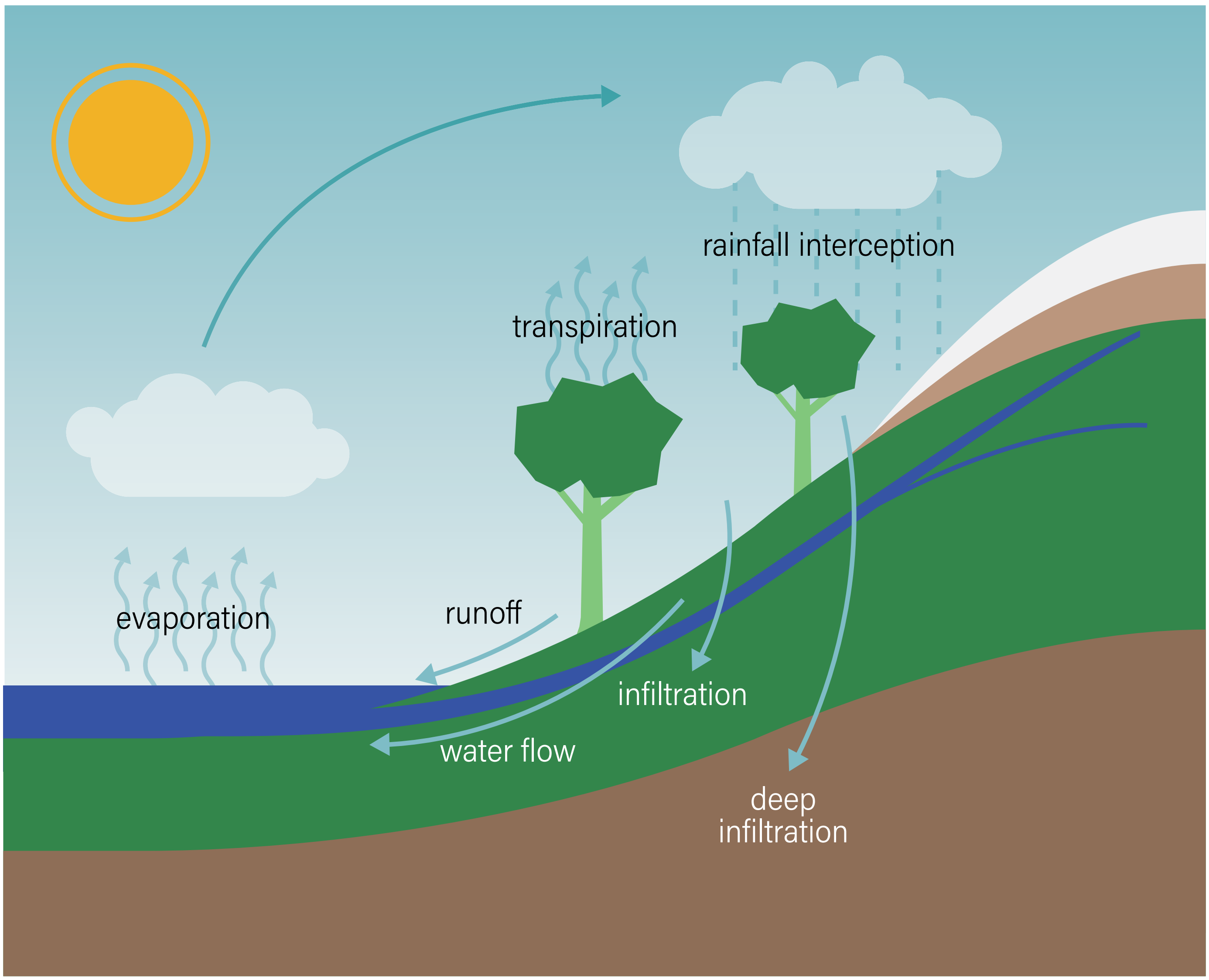
Scientific evidence suggests that forests and trees can help address all four of these challenges. In this section, we outline the forest benefits:

- *Provide cleaner water.* Forests help to filter sediments and pollutants from the water upon which cities rely. Forested watersheds, in particular, provide higher-quality water than other land uses because forests filter pollutants and prevent erosion and sedimentation of streams and rivers (Brauman et al. 2007; Calder 2007).
- *Help reduce flooding.* Within cities, forests intercept rainwater and reduce the burden of stormwater on built water infrastructure, reducing the risk of combined sewer overflows and flooding (Figure 8). Trees and other vegetation in bioretention areas, green roofs, and bioswales can complement traditional "gray" water infrastructure (i.e., engineered systems using materials such as concrete and steel) solutions for stormwater management in urban areas (Berland et al. 2017). Forested watersheds regulate flows and help prevent flooding and landslides.
- *Protect water supply.* Forests in and around cities can replenish groundwater supplies and help sustain rainfall patterns and regulate quantity across seasons (Neary et al. 2009; Ellison et al. 2017).
- *Support healthy hydrological cycles.* Forests play a vital role in global regulation of water cycling, which supports sufficient precipitation in cities and in agricultural regions key to supplying cities with food. Forests (especially large, intact rain forests) can affect hydrological cycles and rainfall patterns hundreds to thousands of miles away by "recharging" atmospheric moisture supplies (Ellison et al. 2017). This linkage between faraway forests and climate hundreds or thousands of miles away has substantial implications for urban residents and global food security (see Box 1 in Section 4). And because of the key role forests play in the global carbon cycle, climate change mitigation by forests may also help to prevent further shifts towards extremes.

Why context matters

Forest benefits related to water will vary with the local context. The effects of watershed deforestation on water quantity, including seasonal flow regulation, depend on the local geographical context, climate, and the type of forest. The impacts of reforestation on water also depend on the context, such as species used and other elements of planting design. Reforestation may even negatively affect water availability in the near term (Filoso et al. 2019). Additionally, the effects of climate change may alter forest-water interactions (Jones et al. 2020).

FIGURE 8 | The Role of Trees and Forests in the Water Cycle



Notes: Simplified hydrological cycle, showing (1) the role of forests and other vegetation in intercepting and recycling precipitation, which is then transported across landscapes, and (2) the role that forests play in promoting infiltration and deep infiltration into groundwater sources.

Source: Authors. Adapted from Ellison et al. (2017) and Bonnesoeur et al. (2019).

WATER CHALLENGE 1: TOO DIRTY

Context

Most cities draw water from local watersheds. Development, industrialization, land-use change, and deforestation in catchment areas above cities can lead to problems related to sedimentation, eutrophication, and contamination by pollutants—including sewage, microplastics, hormones, and other pharmaceutical products and chemicals from mining processes—which all translate to reductions in water quality (McGriff 1972). Combined, these issues may increase burdens on water filtration and treatment facilities, passing on a slew of added considerations and unexpected costs to cities and water utilities.

What roles can forests play?

The protection of water quality—a measure of the pollutants, nutrients, microbes, and sediment present—is an important benefit of both inner and nearby forests (Brauman et al. 2007). Watersheds covered by forests tend to have superior water quality and less sedimentation than degraded watersheds and can also reduce water treatment costs. In fact, 33 of the world's 105 largest cities currently rely on forested protected areas to supply their water (Dudley and Stolton 2003). City source watershed degradation is widespread globally, with 9 in 10 watersheds having lost significant amounts of natural land to agriculture and urbanization, resulting in increased water treatment costs for 1 in 3 large cities globally (McDonald et al. 2016). This close interconnection means that clearing and degrading forests in watersheds can affect municipal water supply.

Forests support water quality in urban areas and watersheds by the following actions:

- *Increasing infiltration and reducing rates of erosion*, thereby preventing sedimentation of streams and rivers (Neary et al. 2009; Carvalho-Santos et al. 2014; Tellman et al. 2018), reducing treatment costs
- *Absorbing or transforming contaminants from both soil and water* (e.g., heavy metals, hydrocarbons, pesticides; Brauman et al. 2007; Luqman et al. 2013)
- *Tightly cycling nutrients* (Neary et al. 2009), reducing the likelihood of eutrophication (i.e., excessive concentrations of nutrients in a body of water) that can contribute to algal blooms and "dead zones" in water bodies
- *Stabilizing riverbanks and steep slopes* (Brauman et al. 2007), which also reduces soil erosion and sedimentation of waterways
- *Shading streams and rivers*, which maintains conditions for aquatic biodiversity (Richardson and Béraud 2014)

Forest loss, however, can impair water quality. Compared with forests, industrial or agricultural land uses generate pollution and reduce the landscape's capacity to intercept pollution and sediment (Postel and Thompson 2005). Grazing, logging, and the construction of roads may all further degrade forest ecosystems and can dramatically increase runoff (Brauman et al. 2007; Bonnesour et al. 2019).

Inner forests

Trees can be incorporated into various "green infrastructure" or hybrid "green-gray" systems designed to capture and filter stormwater. In doing so, they can reduce sedimentation and pollution carried in surface runoff (Browder et al. 2019). For example, in Portland, Oregon, urban green infrastructure reduced flooding in the city by up to 94 percent and filtered 90 percent of pollutants, leading to $224 million in water infrastructure savings (City Parks Alliance n.d.). Trees also played an important role in Philadelphia's Green City, Clean Waters initiative (Case Study 2).

Targeted tree plantings may offer benefits in highly contaminated urban areas. In a process called phytoremediation, targeted plantings on contaminated urban lands may offer a low-cost method to reduce soil and water contamination while providing other cobenefits, such as increased aesthetic appeal (Song et al. 2019).

CASE STUDY 2 | Philadelphia's Green City, Clean Waters Action Plan

Philadelphia is one of the largest cities in the United States. After significant population decline during the 20th century, the city is once again growing. To accommodate a larger population and reduce burdens on water infrastructure, Philadelphia is leveraging its urban forest.

Philadelphia's contracting budget and aging infrastructure—including one of the oldest sewer systems in the nation—posed a particularly formidable challenge to the Philadelphia Water Department (PWD).[a] With increasing impervious surface cover, the city especially struggles with combined sewer overflows.

The Green City, Clean Waters Action Plan

Rather than invest in a tunnel below the Delaware River at a cost of up to US$10 billion to manage its stormwater,[b] the city chose to focus its efforts on restoring its waterways and on large-scale implementation of green infrastructure to reduce pressure on its stormwater systems and reduce risks related to its combined sewer overflows, reaching an agreement with the U.S. Environmental Protection Agency to do so in 2011. Green City, Clean Waters is a 25-year implementation plan to realize its sustainable water management vision. PWD plans to invest $2.4 billion—an avoided cost of up to $6.5 billion—in these efforts to reduce stormwater pollution by 85 percent.[c] After 45 years, the value of benefits to residents will exceed the cost of investment, for example, by increasing property values of homes near restored parks and green spaces by up to $390 million and by sequestering CO_2 emissions equivalent to removing 3,400 vehicles from the road every year.[d]

To ensure adequate buy-in, PWD has partnered with community members and a suite of different municipal organizations, including its parks and recreation department, school district, and planning commission. It also has invested extensively in educational outreach programs and offered technical assistance to private property owners.[e] More than eight years into this program, PWD has already exceeded the targets it set by installing more than 1,000 "green acres," which capture runoff from impervious surfaces.

What Roles Do Trees Play in Green City, Clean Waters?

Tree planting and green space restoration play an important role in the program, including being used to

- improve appearance and manage stormwater around city streets;
- restore habitat around streams and rivers; and
- preserve and revitalize open spaces.

Unified Efforts to Expand the Urban Forest

Philadelphia also operates an innovative urban forestry program called TreePhilly,[f] which aims to achieve a canopy cover of 30 percent in all neighborhoods, a target set by the city in 2009. An interdisciplinary team of researchers found that if this 30 percent canopy cover was achieved, the city could avoid 403 deaths annually, including 244 avoided deaths per year in low-income areas.[g] With benefits for water quality, property values, jobs for marginalized populations, and human health, Philadelphia's urban forest management is helping to transition one of the United States' oldest cities to a green and sustainable future.

Note: For more information about TreePhilly, see https://treephilly.org/about/.

Sources: a. PWD 2011; b. Luntz 2009; c, d. PWD 2011; e. APA 2015; f. TreePhilly n.d.; g. Kondo et al. 2020.

Nearby forests

Water from forested watersheds is typically higher quality than water from watersheds with other land uses, such as agriculture or industry (Brauman et al. 2007; Calder 2007). Protection of forested watersheds can lower the costs of a clean water supply for cities downstream:

- *Forests can act as buffers for bodies of water*. The protection or planting of trees between agricultural fields and streams or rivers can reduce surface runoff of contaminants and nutrients into these water supplies (Brauman et al. 2007; Luqman et al. 2013). To provide and conserve habitat for biodiversity and maintain temperatures, riparian buffers of at least 30 m or more are recommended (Sweeney and Newbold 2014).

- *Ecologically sensitive forest management can reduce unwanted inputs into waterways.* In forest plantations on former agricultural lands, the adoption of management practices to conserve soil and reduce erosion can reduce sedimentation and nutrient loading into local rivers and streams (van Dijk and Keenan 2007). In Colorado, following two catastrophic wildfires in 1996 and 2002, it was estimated that the inflow of debris and sediment into Denver Water's main reservoir resulted in $26 million of city expenses to repair damaged water infrastructure and even more investment to restore its source watersheds in an effort to reduce future water treatment costs (Gartner et al. 2013).
- *Upstream forest protection and restoration can reduce costs for water utilities.* A cross-city analysis found that upstream forest protection and restoration can reduce costs for water utilities in the world's 534 largest cities by $890 million per year collectively (McDonald and Shemie 2014). Analysis from Rio de Janeiro suggests that restoring nearby forests could save the city up to $79 million in water treatment costs alone over 30 years (Feltran-Barbieri et al. 2018) and that restoring 4,000 ha of forest in São Paulo's Cantareira watershed could reduce sediment pollution by 36 percent in 30 years and reduce water turbidity by almost half, resulting in a 28 percent return on investment for the region's water utility, Sabesp (Ozment et al. 2018). And yet, globally, these cost-saving nearby forests are being rapidly lost. In the world's major city watersheds, tree cover has fallen from a historical average of 68 percent to 29 percent, according to data from Global Forest Watch Water (Springgay et al. 2019).

Caveats and considerations

Water quality benefits differ with context, and each individual effort to improve water quality that uses forests needs to consider site-based conditions and be designed based on observed, empirical data:

- *Trees can contribute organic matter such as leaves and branches to waterways*, which may contribute to excessive nutrient levels in local waterways, possibly decreasing the safety of drinking water (Pataki et al. 2011; Decina et al. 2020).
- *In arid and semiarid regions where ecosystems have been degraded, reforestation of watersheds can slow or reverse salinization*, increasing the quality of water resources and potentially making nonpotable water potable (Brauman et al. 2007).
- *Sedimentation of surface waters may increase in poorly managed plantation forests,* where erosion is significant due to the lack of forest understory and the presence of roads and heavy machinery (Calder 2007).
- *Benefits can change over time and differ with the age of the forest*; for example, younger forests do not provide the same water quality benefits as older, more mature ones (van Dijk and Keenan 2007).
- *Seasonal considerations affect benefits,* where the water purification services from trees that go dormant during the dry or winter seasons are not as high as those from evergreen forests or where there is no seasonal change (van Dijk and Keenan 2007).

WATER CHALLENGE 2: TOO MUCH

Context

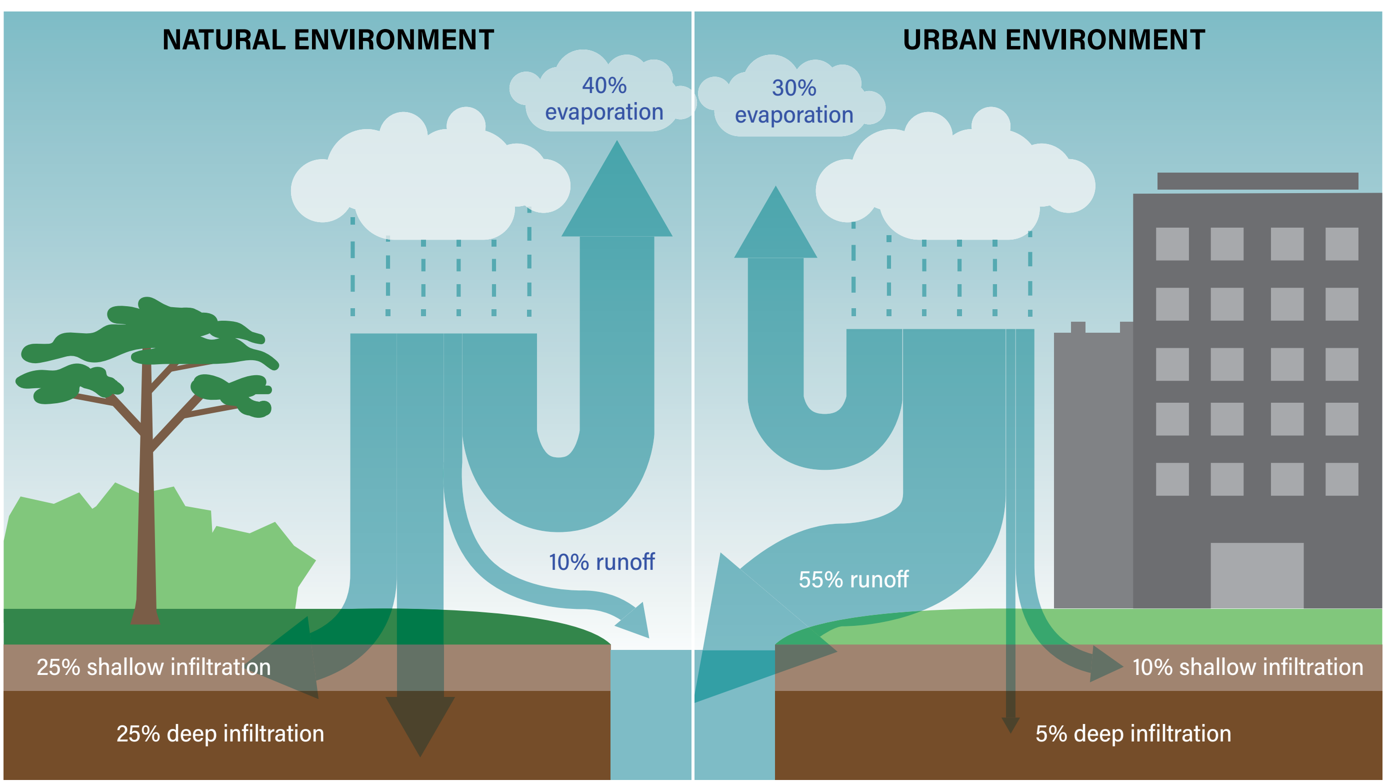
In and around urban areas, flooding—including pluvial, fluvial, and coastal—presents enormous risks to economic security and human safety. Poorly planned urbanization can compound these risks (Jha et al. 2012). Inhabitants of informal settlements are particularly vulnerable to the effects of flooding, both directly and in terms of structural damage (Jha et al. 2012; De Risi et al. 2013). Flooding can also lead to death, injury, water- and animal-borne diseases, and psychological trauma (Ahern et al. 2005). From 1995 to 2015, floods affected more than 2.3 billion people, mostly in Asia (CRED 2015).

The dangers posed by flooding continue to grow. The number of people impacted by river flooding over the next decade is expected to double to 132 million people annually (Ward et al. 2020). It is estimated that flood losses may total $1 trillion annually by 2050 under business-as-usual scenarios and approach $60 billion annually by 2050, even with significant adaptation measures. The most devastating impacts are projected to be in low-lying cities such as Guangzhou, China; and New Orleans (Hallegatte et al. 2013).

The urban environment is prone to problems with flooding:

- *Urban areas contain high amounts of impervious (sealed) surfaces*, which means rain events create runoff more quickly and peak runoff (flood) levels are higher (Figure 9; Douglas 2008). These sealed surfaces also decrease groundwater recharge, which in turn reduces regular flow of water in streams (McGriff 1972). Even soils and lawns in urban areas can become so compact that they act as impervious surfaces (Douglas 2008). These sealed surfaces also increase the likelihood of flooding: a 1 percent increase in impervious surfaces can increase the annual flood magnitude by 3.3 percent (Blum et al. 2020). Surface or street ponding and overflow (pluvial flooding) driven by rainfall may contribute to combined sewage overflows or residential flooding (Rosenzweig et al. 2018).
- *Urban areas tend to rely on extensive built infrastructure with a finite capacity.* Old or deteriorated infrastructure may be insufficient to manage the increasing variability in precipitation associated with climate change.
- *Urbanization transforms the characteristics of rivers and streams* as floodplains in urban areas are typically cleared of vegetation and streams may be channelized, redirected, or buried (Douglas 2008). These highly modified streams surrounded by impervious surfaces often flood quickly.

FIGURE 9 | Water Infiltration in Natural Areas versus Urban Areas



Source: Authors. Adapted from PWD (n.d.).

What roles can forests play?

Inner forests

The urban forest can reduce stormwater runoff and associated flooding (Figure 10) by

- intercepting and delaying water during rain events, reducing the amount of stormwater runoff (Berland et al. 2017; Kuehler et al. 2017), potentially reestablishing a hydrological cycle more closely resembling local historical conditions;
- altering soil water-holding capacities to promote infiltration (entry) and percolation (downward movement) of rainwater in the soil (Berland et al. 2017; Kuehler et al. 2017; Zhang and Chui 2019); and
- increasing the amount of water returned to the atmosphere by evapotranspiration (Berland et al. 2017; Kuehler et al. 2017; Jones et al. 2020). In doing so, trees free up space in soil, making room for stormwater storage in the future (Berland et al. 2017; Kuehler et al. 2017; Berland et al. 2017). Evapotranspiration also has a cooling effect and helps to mitigate the urban heat island effect (Berland et al. 2017).

As a result, cities with healthy urban forests often enjoy a number of benefits, including the following:

- *Reduced burden on sewer systems.* In combined stormwater and sewage systems, heavy rainfall can lead to a combined sewage overflow of thousands or millions of gallons of untreated sewage into nearby lakes and streams, potentially compromising the safety of drinking water supplies and the quality of aquatic habitats. By reducing the total amount of surface runoff during a storm event, the urban forest can help to reduce the likelihood of combined sewage overflows (Berland et al. 2017).
- *Reduced stormwater volume on surfaces.* By increasing infiltration, trees and other elements of green infrastructure provide space for rainwater storage, reduce surface runoff and pollutant inputs to local waters, and promote groundwater recharge and increased baseflow (Case Study 3; Zhang and Chui 2019).

CASE STUDY 3 | Integrating Trees and Forests into Infrastructure in Singapore to Catch Rainfall and Reduce Flooding

Singapore has one of the highest population densities in the world.[a] The city-state lacks the natural water resources to meet the demand of its residents. Since 1961, Singapore has imported up to 250 million gallons of water per day from the Johor River in Malaysia to meet about half of its 430 million gallons per day water demand.[b] Singapore also has two monsoon seasons per year that pose flood risks but also provide opportunities to harvest and collect rainwater.[c]

Singapore's national water agency, Public Utilities Board, has addressed these issues by managing water resources using blue-green infrastructure—which combines vegetation and natural waterflows—to reduce pollutant runoff into waterways, improve sanitation, and create new city green space, transforming the island into an urban water catchment area (Figure CS3.1). This has also helped reduce flood risk and increase water supply.[d]

Using blue-green infrastructure provides many socioeconomic benefits to Singapore, including the following:

- Operational and maintenance costs of the naturalized river were 75 percent lower than the concrete canal as stormwater infrastructure.[e]
- The naturalized river has a stronger ability to withstand extreme weather events.
- The surrounding vegetation absorbs rainfall and reduces runoff by about one-third compared to concrete alone, decreasing the flood risk of surrounding residential areas.[f]

CASE STUDY 3 | Integrating Trees and Forests into Infrastructure in Singapore to Catch Rainfall and Reduce Flooding (Cont.)

- The total value of ecosystem services provided by the park and value of recreational space to residents is estimated at US$73 million per year, which is over twice as much as the value of the park estimated without blue-green infrastructure at only $34.5 million per year.[g]

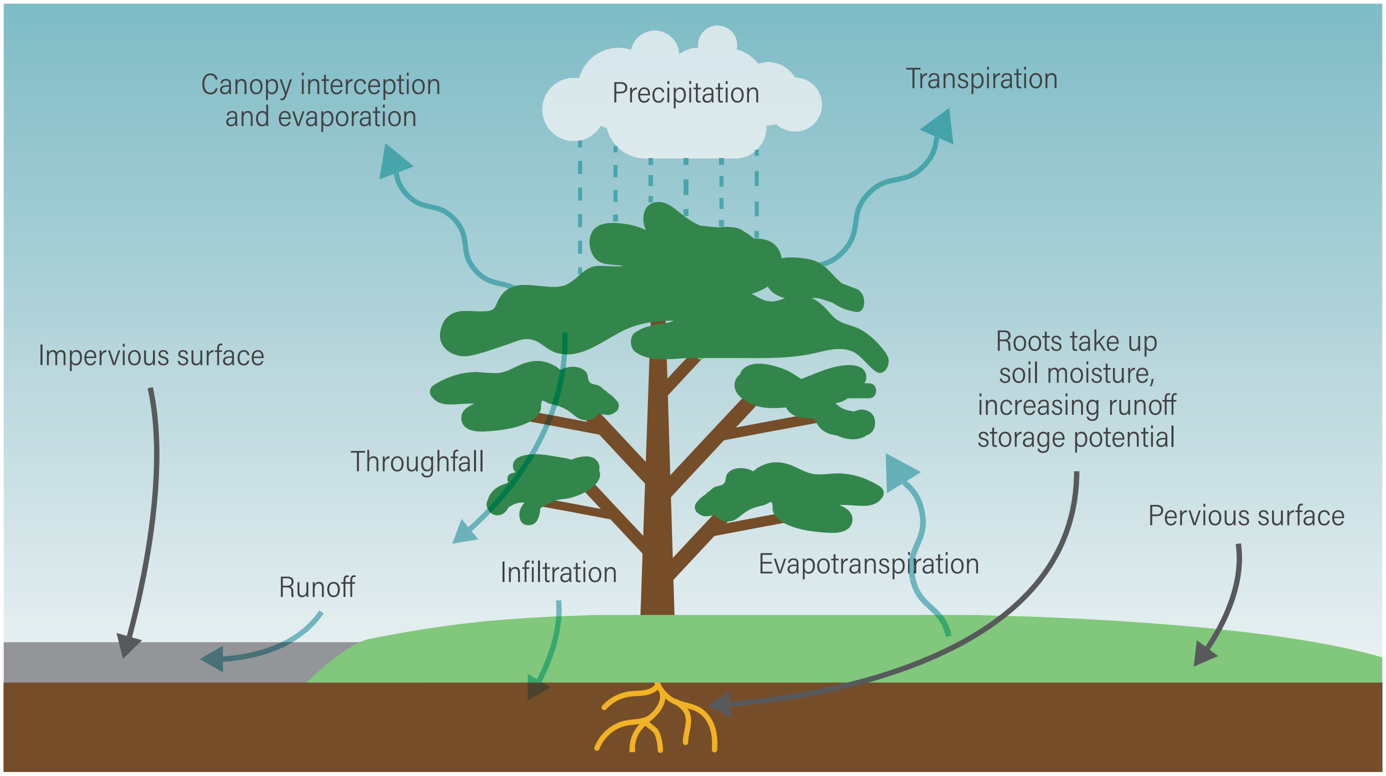
To date, 28 blue-green infrastructure projects have been implemented around the city. Collectively, they save Singapore $390 million per year in water costs by reducing the need to import water, reducing flood and water treatment costs, and increasing water supply.[h]

FIGURE CS3.1 | Before and After Blue-Green Infrastructure Pilot in Bishan-Ang Mo Kio Park, Singapore

Source: ASLA 2016.

Sources: a. Urban Green-Blue Grids for Resilient Cities n.d.; b. PUB 2022; c. Goh et al. 2017; d. Urban Green-Blue Grids for Resilient Cities n.d.; e. Dreiseitl et al. 2015; f. Yau et al. 2017; g. Dreiseitl et al. 2015; h. Kapos et al. 2019.

FIGURE 10 | Urban Trees and Rainfall



Source: Authors. Adapted from Marritz (2013).

Nearby forests

Outside city boundaries, natural forests can offer protection from small- and medium-sized floods, moderating the severity of impacts on both people and property (Lele 2009; Carvalho-Santos et al. 2014). This is true particularly along rivers and coasts (Lele 2009; Bhattacharjee and Behera 2018). Protection and restoration of forests in upstream areas can help to reduce peak streamflow and thus reduce the risk of river flooding. Trees lower flood risk by increasing infiltration in the soil, storing excess runoff, and slowing the release of water (Gunnell et al. 2019). In this sense, healthy forest ecosystems often act as "sponges" (Laurance 2007). Conversely, some research has linked forest loss to increased flooding frequency (Bradshaw et al. 2007), but more research is needed to better substantiate the link. Forested riparian zones (the areas immediately adjacent to rivers) and floodplain forests can also help to stabilize banks and restore natural river flow, further reducing the chance of flooding (González et al. 2017). Mangroves play an especially important role near coastal cities (Case Study 4).

Caveats and considerations

Urban leaders seeking to maximize the stormwater benefits of their urban forests should consider the following:

- *Built environment modifications.* To address urban flooding, it may also be necessary to increase the area of permeable surfaces and to promote connectivity between stormwater retention areas (Phillips et al. 2019).
- *Synergies with other NBS.* Strategically incorporating trees into other green infrastructure can make these interventions more effective. For example, trees planted in bioswales, green roofs, and bioretention basins may help to address pluvial flooding and restore predevelopment hydrological function (McDonald and Shemie 2014).
- *Limitations on capacity.* Although green infrastructure and urban forests can relieve some of the pressure on traditional infrastructure, cities will still need to consider multiple options to handle excess water—especially related to coastal and river flooding from climate change.

Flood prevention benefits of nearby forests are limited. Although existing forests can attenuate some flood-related risks, forest restoration is unlikely to have a significant impact on large-scale floods or extreme weather events, which can quickly overwhelm a forest's absorption capacity (Calder 2007; Ellison et al. 2017).

In some contexts, afforestation (planting trees where forests historically did not occur) with plantation forests can also reduce peak flows and the risk of flash floods following medium- to large-scale rain events in small catchments (van Dijk and Keenan 2007). However, the effect of plantation forests on large landslides is probably negligible and is currently poorly understood (van Dijk and Keenan 2007). Overall, the outcomes of afforestation on water may be unpredictable, and other interventions are generally better suited to address larger floods, including discouraging human settlement in floodplains (FAO and CIFOR 2005; van Dijk and Keenan 2007).

CASE STUDY 4 | The Value of Mangroves

On the heavily populated coasts—and major urban areas—of more than 100 nations in the subtropics and tropics, mangrove forests serve an especially integral role.[a] For cities, mangroves shield coastal developments from the force of waves and wind.[b] They can reduce global flooding losses by US$65 billion and protect 15 million people from exposure annually, including people and property in major cities such as Lagos, Mumbai, Karachi, Wenzhou (China), and Miami.[c] Indonesia is home to most of the world's mangroves (nearly 25 percent of remaining mangrove forests), followed by Brazil, Malaysia, and Papua New Guinea.[d] Mangroves can play a particularly important role in densely populated, socially vulnerable communities—including those in cities—where other stormwater infrastructure investment may be inadequate or absent.[e]

In the past fifty years, these underappreciated but immensely valuable forest ecosystems have been rapidly cleared and degraded.[f] Today, mangrove deforestation rates (0.16–0.39 percent annually) are decreasing after peaking in the 1980s and 1990s, but some regions are experiencing significantly higher rates (e.g., in Southeast Asia, where deforestation rates are estimated to be still around 3.5–8.0 percent).[g] Despite their importance to coastal resilience and economic activity, mangroves are being lost at a rate three to five times the average rate of forest loss globally.[h] Production of goods consumed in cities is a major driver of mangrove loss. For example, mangroves are cleared to make way for shrimp aquaculture ponds.[i]

Beyond attenuating flooding, mangroves provide other benefits:

- *Climate*. Mangroves trap sediment in their roots, locking away massive amounts of carbon[j]—approximately 907 metric tons per hectare. In comparison, intact tropical montane forests in Africa are estimated to store around 150 metric tons of carbon per hectare.[k] Mangrove clearing is responsible for a fifth of all carbon emissions from deforestation.[l]
- *Biodiversity and livelihoods*. Along coasts and in estuaries, mangrove forests provide habitat and serve as nurseries for juvenile fish.[m] The loss or degradation of coastal forests causes local decline and loss of species.[n] Local fishermen in Mexico, the Philippines, Kenya, and many other locations demonstrate extensive traditional ecological knowledge of these forests.[o]
- *Coastal protection*. Mangroves mitigate annual flood damages due to tropical cyclones and flooding under regular conditions by an estimated $65 billion and protect 15 million people around the world annually.[p]
- *Economy.* When harvested sustainably, mangroves provide fuel, charcoal, medicines, and other raw materials and products that supplement people's incomes.[q] In total, the ecosystem services mangrove forests provide are valued at an estimated $33,000–$57,000 per hectare annually to the economies of developing countries.[r]

Sources: a. Hamilton and Casey 2016; b, c. Menéndez et al. 2020; d. Hamilton and Casey 2016; e. Menéndez et al. 2020; f. Walters et al. 2008; Valiela et al. 2001; g. Hamilton and Casey 2016; h. UNEP 2014; i. Valiela et al. 2001; j. Walters et al. 2008; k. Cuni-Sanchez et al. 2021; l. UNEP 2014; m. Whitfield 2017; n, o. Walters et al. 2008; p. Menéndez et al. 2020; q. Walters et al. 2008; r. UNEP 2014.

WATER CHALLENGE 3: TOO LITTLE

Context

About 25 percent of the world's population faces extreme water stress (Hofste et al. 2019). Climate change and a growing population are projected to ramp up pressure on finite water supplies. Flörke et al. (2018) find that one in six large cities will face water deficits in the future. With more than 50 percent of the world's population concentrated in cities, urban water scarcity can have dire economic and health impacts. For example, the "Day Zero" drought-induced water crisis in Cape Town of 2017–18 resulted in the loss of thousands of jobs, dramatically reduced regional agricultural production, and put many more people at risk for diseases due to inadequate sanitation (Parks et al. 2019).

What roles can forests play?

Forests around cities play a vital role in protecting and sustaining water supplies (Figure 11). Maintaining forests in watersheds is generally positive for regulating water supply across the year. Deforestation and forest degradation in watersheds jeopardize water availability by altering local hydrology and reducing interseasonal stability in water supplies.

Nearby forests

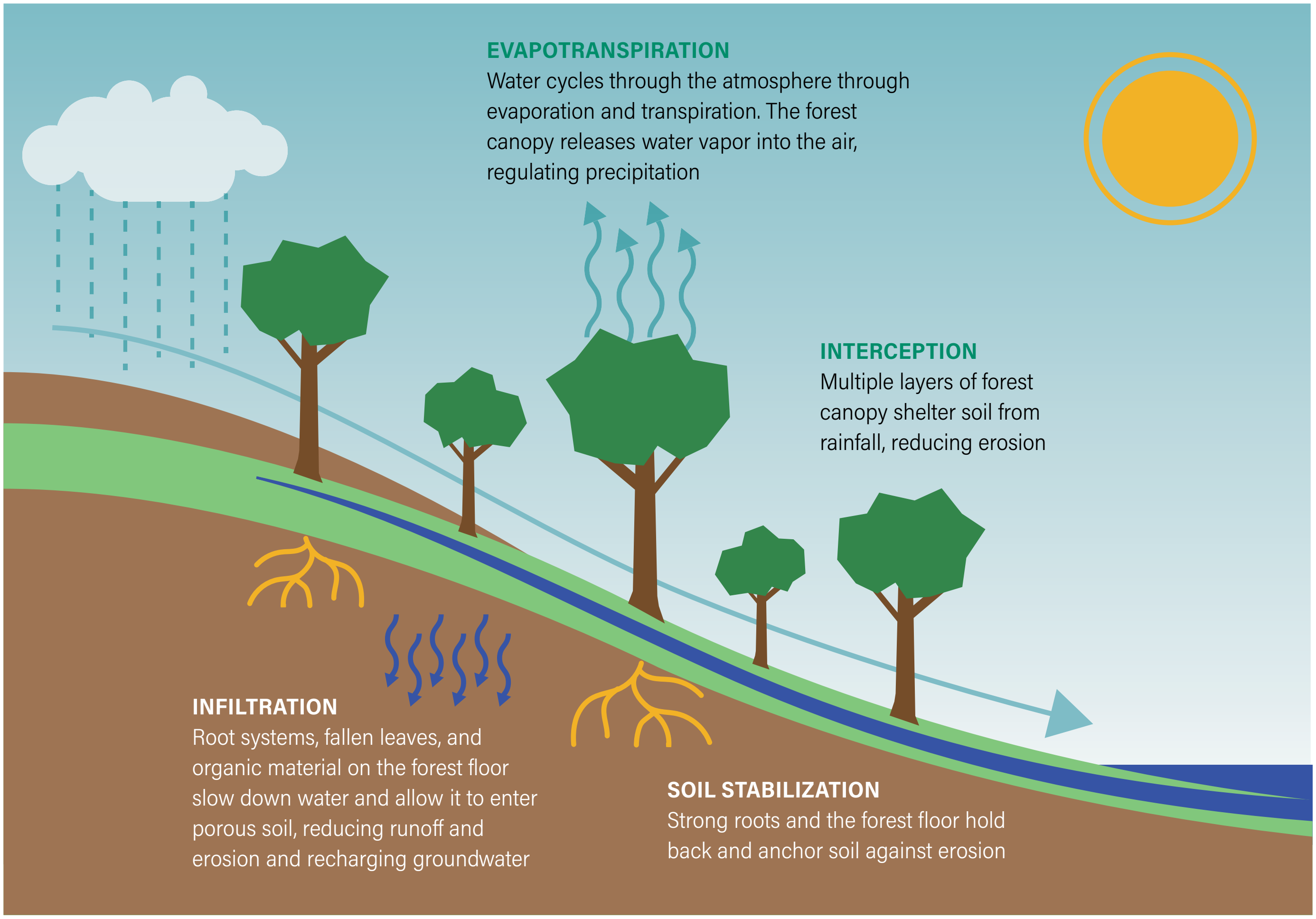
Forests drive downwind and interior precipitation. Forested areas often "use" more water than other ecosystems on a local scale because they have high evapotranspiration rates (Brauman et al. 2007). But from recent theoretical research, scientists have begun to posit that this water, rather than being "lost," serves as an important source for precipitation in downwind regions (Ellison et al. 2012; Ellison 2018). By capturing and recycling precipitation, evapotranspiration sends water into the atmosphere, where it can fall as rain in downwind regions (Ellison et al. 2017). For example, coastal forests can capture and transpire fog and humidity from oceanic winds, carrying it deeper into continental interiors than it might otherwise travel (Ellison et al. 2017). Thus, even forests beyond watershed boundaries can influence water availability and provide key water regulation services to agricultural and urban areas (Melo et al. 2021).

Intact forests in watersheds can reduce seasonal fluctuations in water availability. Forests generally use more water than other land uses (with the exception of irrigated crops), which means that forestation can reduce flows in catchments, and forested watersheds may have similar or slightly lower streamflow than nonforested catchments (Calder 2007; Carvalho-Santos et al. 2014). But forests play a key role in water *regulation* throughout the year: they reduce the impact of floods in wet periods and help to mitigate the impacts of droughts in dry periods (Neary et al. 2009). Consequently, forest conversion and degradation may lead to increased water flows in the wet season but reduced dry season flows in many contexts (Lele 2009). Forests increase the infiltration capacity of the soil, which promotes groundwater recharge (and reduces flood peaks), helping to stabilize flows throughout the year and benefiting areas far downstream. Soil penetration by tree roots improves the capacity of soil to store water, as does the presence of organic material from decaying plants and chemicals released by plants and other forest organisms in the soil (Brauman et al. 2007; Neary et al. 2009).

Montane cloud forests, for example, can be vital sources for water contribution during the dry season. Foliage in cloud forests in mountainous regions captures the water vapor of clouds, which run down the stems and leaves of plants and thereafter into soils and streams. Cloud forests have especially pronounced effects in drier regions (Postel and Thompson 2005). Fog capture can provide as much water as rain in many of these regions, which can be especially important for maintaining stream flow in the dry season (Ellison et al. 2017).

Avoiding deforestation is key for regulating water quantity in ecosystems. Deforestation can increase local water availability (Brauman et al. 2007; van Dijk and Keenan 2007; Ellison et al. 2012; Ellison et al. 2017; Filoso et al. 2017; Zhang et al. 2017), which, in water-scarce regions, may seem like a benefit. But deforestation often also increases runoff and short-term streamflow and can thus increase soil degradation and flood frequency (Brauman et al. 2007). The increase in surface water is only part of the picture: deforestation often

FIGURE 11 | How Forested Watersheds Protect Water Supplies



Source: Authors. Adapted from Qin and Gartner 2016.

decreases infiltration rates, leading to higher peak flows but reduced groundwater recharge and reduced dry season flows—two factors extremely relevant to land-reliant livelihoods in the tropics (Ellison et al. 2017). Short-term gains in water availability following deforestation do not make up for other important lost services, such as the regulation of water availability throughout the year between seasons, prevention of sedimentation, and reduced water treatment costs. For example, in Malawi, analysis of satellite data and household surveys showed that a 1 percent increase in local deforestation decreased household access to clean drinking water by 0.93 percent, suggesting that the deforestation Malawi has experienced in the last decade may have effectively had the same impact on water access as a 9 percent reduction in rainfall in the region (Mapulanga and Naito 2019).

Caveats and considerations

In contrast with the benefits of forests conservation or avoided deforestation, however, reforestation or restoration of degraded forests may reduce year-round water availability, at least in the short run, and particularly in arid or semiarid regions (Filoso et al. 2017). This is because forests generally increase water infiltration into soils and evapotranspiration, reducing the availability of water for other uses (Ilstedt et al. 2007; Filoso et al. 2017; Lozano-Baez et al. 2019). Trees planted in former shrublands or grasslands may reduce both flood peaks and low flows (Brauman et al. 2007). In some cases, infiltration rates can exceed evapotranspiration rates, with net positive effects on groundwater recharge. But in general, evidence suggests planting new forests typically has negative or neutral effects on annual catchment (surface water) flows (Calder 2007).

Furthermore, not all forest types provide equal benefits. Compared to native forests, plantation forests reduce water runoff, with negative effects on water supply (Case Study 5; Lele 2009; Alvarez-Garreton et al. 2019; Yu et al. 2019). Unlike native forests, plantations can put pressure on surface water quality and supply.[18] In particular, planting native grasslands or other native ecosystems with non-native trees, or planting non-native trees that use water inefficiently, can reduce dry season water availability (Postel and Thompson 2005). Fast-growing plantation species can reduce flows in catchments, especially while the trees are young (Brauman et al. 2007; Calder 2007; van Dijk and Keenan 2007; Bonnesoeur et al. 2019; Jones et al. 2020). For example, plantations of water-intensive eucalyptus have been shown to dramatically reduce surface runoff and streamflow in multiple climates, with effects persisting for decades (Case Study 5; Farley et al. 2005). Although these reductions may be desirable in certain watersheds (e.g., those struggling with salinization issues or highly degraded former agricultural lands), they could further endanger water supplies in many areas (Farley et al. 2005; Brauman et al. 2007; van Dijk and Keenan 2007).

WATER CHALLENGE 4: TOO ERRATIC

Context

Erratic and unpredictable weather—including extreme drought, torrential rainfall, and violent storms—continues to make global headlines and affects millions of people annually. Although some variability and extremes of climate are natural, evidence suggests that anthropogenic climate change has increased the frequency, intensity, and duration of many of these events (Seneviratne et al. 2012). Precipitation and drought are both expected to increase during the 21st century (Seneviratne et al. 2012). In addition to the effects of changing atmospheric GHG levels, large-scale changes

CASE STUDY 5 | Monoculture Eucalyptus Plantations and Decreased Water Availability

Eucalyptus trees are native to Australia and Southeast Asia but have been planted around the world because of their adaptability to different climates and fast growth rates.[a] The wood from eucalyptus trees can be used for paper, charcoal, firewood, construction lumber, and biofuel. However, eucalyptus requires more water to grow than most other types of trees because of its extensive root system, rapid growth, and high rate of evapotranspiration. The high water requirement of these trees has led to water shortages in some countries that have increased eucalyptus plantations. [b]

South Africa and Uruguay are two countries that experience more droughts because of extensive non-native eucalyptus plantations. South Africa has established over 515,000 hectares (ha) of eucalyptus plantations to meet high demand for timber. Replacing the native vegetation with eucalyptus has reduced streamflow in affected watersheds by 90–100 percent.[c] Similarly, in Uruguay, eucalyptus plantations cover over 1 million ha established in the 1970s.[d] In watershed regions, hydrologic yield was reduced by 50 percent when native vegetation was replaced with eucalyptus, and 13 percent of streams near eucalyptus plantations have dried up.[e]

In both countries, afforestation with eucalyptus resulted in less available drinking water and more severe droughts. Also, monoculture tree plantations tend to use more water than diverse, natural vegetation.[f] In South Africa, policymakers addressed this challenge with legislation that requires timber plantations to apply for permits to plant non-native trees in order to preserve water.[g] Policymakers should consider the impact of the type of tree on water supply and prioritize planting native trees. Legislation and economic incentives can be used to require monoculture plantations to pay for the amount of water they use and to prevent drought.

Sources: a. Albaugh et al. 2013; b. Cespedes-Payret et al. 2009; c. Albaugh et al. 2013; d. Pozo and Säumel 2018; e. Cespedes-Payret et al. 2009; f. Albaugh et al. 2013; Hubbard et al. 2010; g. Albaugh et al. 2013.

in land cover affect climate locally, regionally, and globally by altering surface temperature, humidity, evaporation, cloud formation, precipitation, and more (Mahmood et al. 2014).

Cities are vulnerable to these types of changes. Increases in flooding, drought, or heavy rainfall within the immediate vicinity of cities presents obvious challenges to urban leaders. Additionally, as net importers of water, food, and materials, cities rely on the functioning of productive ecosystems outside their boundaries. The vast majority of urban demand is met by goods imported from far beyond city boundaries—from rice to milk to timber. This means that cities both rely on food produced in the world's major agricultural areas and have significant effects on the world's forests via city consumption patterns. Thus, disturbances in supply chains due to increasingly erratic weather patterns around the world may have indirect impacts on cities too.

What roles do forests play in global precipitation patterns?

The world's large and intact forests play an important role in cycling and transporting water, thereby shaping global and regional weather patterns. Forests—especially intact tropical forests—affect large-scale weather patterns. Forests regulate regional and global precipitation patterns, which impact both city water supply and the production of food to city residents in key agricultural regions (Lawrence and Vandecar 2015).

Because land cover change is associated with changes in precipitation and climate (Mahmood et al. 2014), the persistence of forests can be a stabilizing factor.

Evapotranspiration by forests cycles large amounts of precipitation into the atmosphere, creating "flying rivers" (atmospheric currents laden with moisture capable of driving weather patterns in distant locales). Forests effectively recycle rain by returning moisture to the atmosphere, which contributes to future rain events (Ellison et al. 2012). This recycled "green water" released during evapotranspiration affects local areas, as described in the previous section, and also composes a large portion of the world's rainfall in locations far away. The emerging scientific literature on tropical forests and their impact on global air circulation, also known as teleconnections, highlights how these processes change when tropical forests are cleared, and how this affects global precipitation patterns.

Forests move water from the earth's surface to the atmosphere at large scales. Tropical forests contain air that is warmer and more humid than in surrounding areas, creating a low-pressure zone that drives wind patterns (Makarieva and Gorshkov 2010). It is estimated that the moisture moving over the Amazon rain forest is recycled five to six times as it moves westward across the continent (Lovejoy and Nobre 2018). Deforestation drastically reduces evapotranspiration rates and, with them, the movement of water.

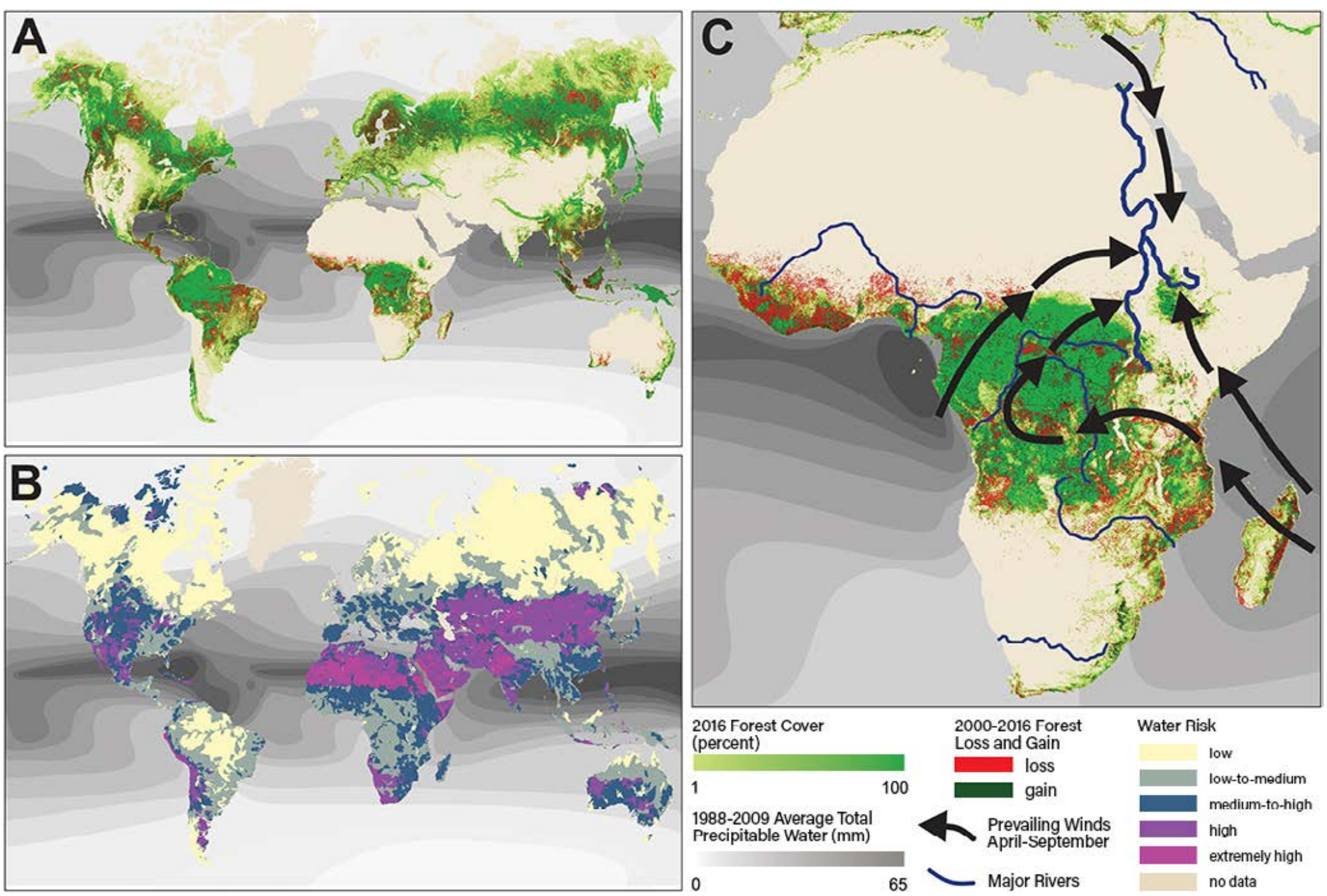
Current forest practices and risks for the hydrological cycle

Three major tropical forests disproportionately affect global water cycles:

- *Amazon rain forest.* The largest tropical forest in the world exerts great influence over regional (Davidson et al. 2012) and global precipitation and air circulation (Lawrence and Vandecar 2015).
- *Congo Basin* (Figure 12). This forest region in Central Africa drives precipitation patterns around Africa (Gebrehiwot 2019) and beyond (Lawrence and Vandecar 2015).
- *Southeast Asian rain forest.* The smallest of all three tropical forest basins—but the most humid and with the highest rainfall—the Southeast Asian rain forest influences the climate within and beyond the region through impacts to the Asian monsoon circulation, potentially resulting in higher rainfall in some areas and lower rainfall in others (Lawrence and Vandecar 2015).

Deforestation of tropical forest could impact wind patterns and circulation of precipitation regionally and around the globe, with potential for impacts on water availability for

FIGURE 12 | Forest Cover, Water Risk, and Water Movement



Notes: Because forests require more water than ecosystems such as grasslands, it is no surprise that forest cover (Box A) often coincides with areas of lower water risk (Box B). But as Box C shows, water also moves throughout the atmosphere, directed by winds. The loss of forests in Central Africa could have cascading impacts on those who depend upon the Nile River, for example, which is fed by precipitation from both areas to the south.

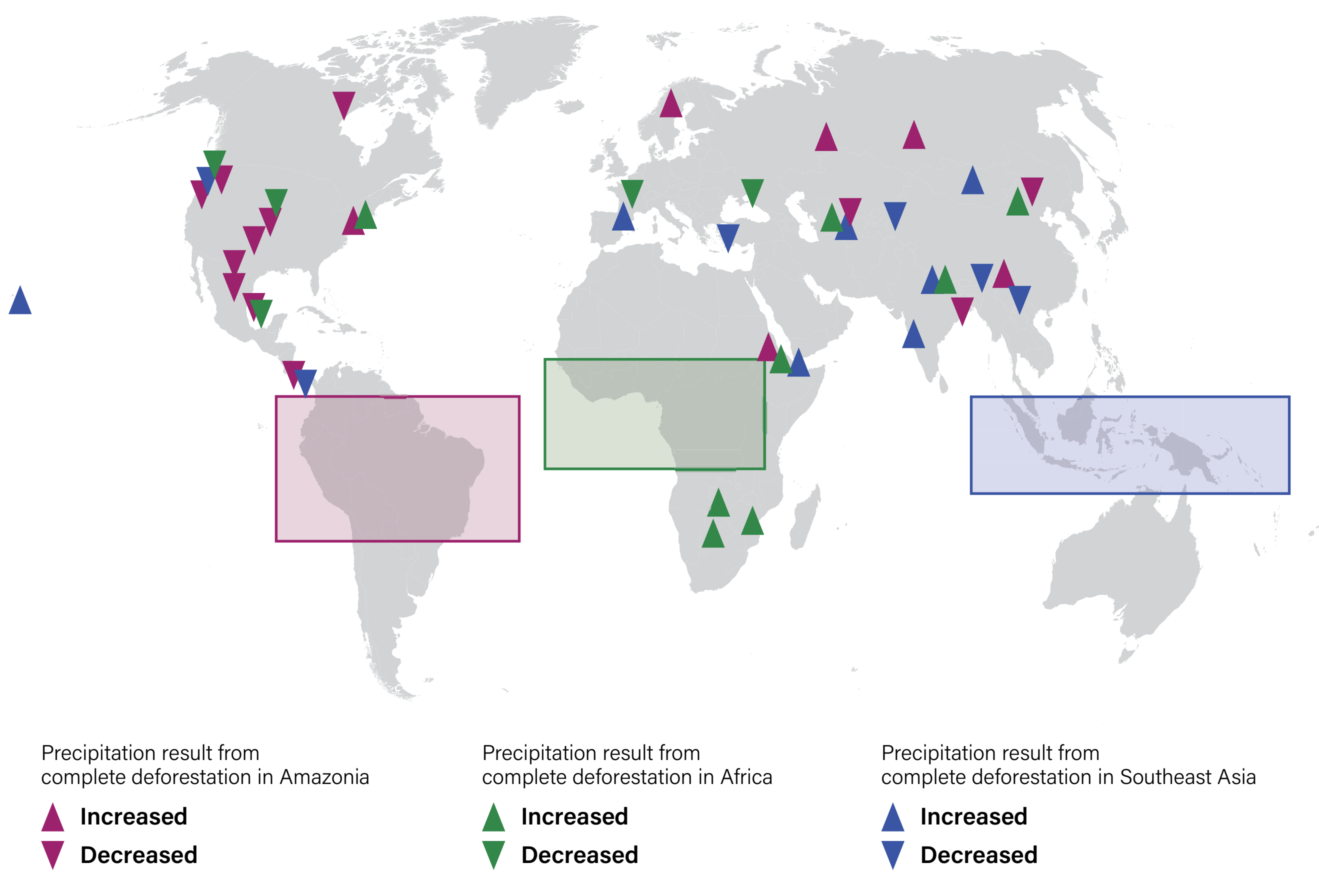
Source: Creed et al. (2019).

agriculture (Figure 13) (Lawrence and Vandecar 2015; Avissar and Werth 2005; Werth and Avissar 2005; Medvigy et al. 2013; Lawrence and Vandecar 2015). Continental interiors hold some of the world's most important agricultural areas. Without contributions to rainfall from forests, research suggests these downwind interiors may experience far less rain (Ellison et al. 2017). Likewise, deforestation also could affect precipitation in some of the world's continental interior cities, which could present significant challenges for their water supply. Water-scarce regions, such as the dry regions of northeastern Africa where the Nile River is the main water source, are likely to be most affected by deforestation (Ellison 2018).

In particular, changing weather patterns due to deforestation of tropical forests could have a large impact on water availability for agriculture (Lawrence and Vandecar 2015). Fluctuations in climate can have a huge impact on agricultural productivity (Liang et al. 2016). Figure 13 describes the impacts of deforestation of tropical forests in different regions. Evidence also suggests that climate and precipitation are already more variable because of deforestation. Research typically models impacts using simulations:

- Within the Amazon Basin, forest loss is associated with reductions in rainfall (an average of 8 percent by 2050) in model simulations, according to a 2015 meta-analysis (Spracklen and Garcia-Carreras 2015).

FIGURE 13 | Simulated Total Deforestation of Major Forest Regions and the Effects on Global Precipitation Patterns



Note: Despite global rates of deforestation, total deforestation of the world's major forest regions as simulated in this scenario is highly unlikely in reality.

Source: Authors. Adapted from Lawrence and Vandecar (2015).

- Modeling suggests that forest loss in the Amazon (Medvigy et al. 2013) and Central Africa (Akkermans et al. 2014) could reduce precipitation in the U.S. Midwest (Werth and Avissar 2005), with potential negative consequences on food production.
- Modeled changes resulting from deforestation in Southeast Asia appear to be smaller in magnitude but could reduce local precipitation in Southeast Asia as well as in Hawaii and the U.S. Pacific Northwest and even southern Europe (Avissar and Werth 2005).

These forests are in jeopardy. Since 2001, tree cover in the Congo Basin has decreased by more than 20 percent, mainly due to clearing for agriculture (Tyukavina et al. 2018). Southeast Asia is a global deforestation hotspot, with particularly high rates of habitat and biodiversity loss (Estoque et al. 2019). And, alarmingly, climate feedbacks between the Amazon Basin and Brazil's nearby Cerrado forest and grassland ecosystems—currently subject to high rates of deforestation and agricultural conversion—may further threaten the precipitation patterns of both of these valuable regions (Spera et al. 2016).

Forest loss may accelerate the unpredictability of changes related to global warming. It is unlikely that forest protection or restoration can prevent or undo the changes to climate seen in recent decades, but it is worth stating that forest restoration is a good way to sequester more carbon in the landscape and offset other emissions. Yet because of their essential contributions to global climate as well as climate change mitigation efforts, the persistence of large forests may prevent further acceleration of global changes in climate and weather patterns. Conversely, increasing land cover change—including forest loss—may create greater uncertainty (Mahmood et al. 2014).

Caveats and considerations

Tropical forests may soon approach a tipping point where deforestation is occurring at such a high rate that the forests lose their capacity to recycle water effectively (Nobre and Borma 2009; Mahmood et al. 2014; Lovejoy and Nobre 2018). For example, if deforestation continues at present rates in the Amazon, 8 percent mean annual reductions in rainfall are expected by 2050 (Spracklen and Garcia-Carreras 2015). Consequently, its capacity to maintain continental and global water flows may erode.

Conserving forest is important for global water regulation, but it is less certain what the effects of large-scale reforestation or afforestation would be on regional evapotranspiration, precipitation patterns, and teleconnections (Mahmood et al. 2014). Large-scale afforestation of midlatitude regions, in particular, could have unintended consequences related to regional water availability and temperatures, resulting from changes in albedo (Swann et al. 2012). Protection of existing forests and restoration of previously forested lands should thus be prioritized over forest expansion.

To better understand the effects of forest changes to water availability and movement, more research is needed. Although the field of research relating to forests and water continues to grow rapidly, little research has been conducted on the effects of forest loss and degradation on hydrology in many parts of the world, including many low- and middle-income countries (Jones et al. 2020).

CONCLUDING THOUGHTS

Although growing urban populations and shifting global climate patterns complicate efforts to provide clean and affordable drinking water, harnessing the power of forests in and around cities can help. Urban forests can reduce the burden of stormwater management on built infrastructure and insulate urban watersheds from the effects of pollution. In the watersheds surrounding cities, forests can protect water quality, buffer the risk of flooding, and ensure water availability from season to season. Vast tracts of intact forests—especially tropical rain forests—play an integral role in regional and global water movement and weather patterns. Yet global discourse and decision-making on protecting tropical forests does not yet sufficiently address their role in local, regional, and global hydrologic cycles (Ellison et al. 2017).

Cross-boundary water management is key to manage the interdependency of catchments and watersheds at multiple scales (Melo et al. 2021). Global cooperation is warranted to protect tropical forests because deforestation impacts agriculture, flood risk, and water availability around the world. To ensure that key agricultural regions—vital for urban sustenance—have adequate water supplies, cities will need to act to protect forests far beyond their boundaries.


CHAPTER 4

Climate

Forests inside, near and far away from cities can all help to mitigate climate change. Carefully managed inner forests only sequester modest amounts carbon but help to lower energy demands via cooling. Forests outside cities absorb and store massive amounts of atmospheric CO_2, which is released when forests are cleared. Protecting these forests from clearing is essential to mitigate global climate change.

BACKGROUND

Around the world, cities are committing to bold action on climate change. Representing more than 700 million residents and one-fourth of the global economy, the dozens of members of the C40 Cities Climate Leadership Group (C40) have pledged to reduce GHG emissions in accordance with the goals of the Paris Agreement. Likewise, the ICLEI—Local Governments for Sustainability, which unites more than 1,700 cities, seeks to dramatically reduce its membership's carbon emissions. Numerous similar initiatives—including the Climate Neutral Cities Alliance—exist to reduce carbon emissions in urban areas.

Cities are vulnerable to climate change. The effects of climate change—including heat waves, flooding, rising sea levels, and droughts—threaten the well-being of urban residents. Cities are hubs of innovation and economic activity and have a disproportionate concentration of both wealth and poverty residing in low-lying, coastal, and drought-prone areas (Rozenweig et al. 2010). Displacement due to sea level rise threatens to drive residents from some cities while causing influxes of rural climate refugees into other cities (Oppenheimer et al. 2019). Lower-income and marginalized residents are particularly vulnerable to the impacts of climate change, especially those in informal or unplanned settlements typical of rapidly growing cities. These threats are projected to continue to increase (Revi et al. 2014; Seto et al. 2014).

Urban residents' concern about climate change is growing rapidly. City residents are demanding action from governments to take stronger, more decisive action on climate change. In September 2019, millions of city residents around the world took to the streets in protest, demanding action on climate change (Sengupta 2019; Taylor et al. 2019). Many urban-based climate action groups have started in recent years, and the demand for action from governments—including cities, by their residents—is growing and is likely to continue to grow as the impacts of climate change increase. While government action at all levels is important, more and more city governments are demonstrating their autonomy and sense of responsibility by taking action.

Reducing emissions within cities is the first important step, but forests can help cities go further. Cities consume more than 60 percent of the world's natural resources (UN n.d.) and are responsible for approximately 75 percent of the world's GHG emissions, when factoring in the goods consumed in cities but produced elsewhere (Seto et al. 2014). Decisions made in cities can have a large impact on climate change mitigation efforts. Unabated deforestation, especially in the tropics, may negate even the boldest reductions in emissions from fossil fuels (Griscom et al. 2017). To maintain a habitable climate, cities—the world's largest pool of consumers—should examine how their consumption and actions affect the world's forests at all levels and work to conserve and restore them.

Forests at all proximities to cities have a role. Increasing inner forests can have a mitigating impact on climate change in two key ways: sequestering carbon by urban trees and forests and lowering energy demands (and thereby energy-generated emissions) due to the temperature-moderating effects of the urban forests. Forests outside cities can help to mitigate climate change by absorbing and storing atmospheric CO_2. The IPCC's 2019 *Special Report on Climate Change* underscores the urgency: without actions in the land sector, efforts to mitigate climate change are unlikely to succeed. To limit global warming to well below the 2°C target of the 2015 Paris Agreement, action on many fronts is needed (Griscom et al. 2017; Olsson et al. 2019).

About This Section

There are many ways that forests can help cities meet their climate change mitigation targets (Box 1). Forests can directly and indirectly alter atmospheric GHG concentrations, and they also influence other important biophysical processes that affect climate stability across scales.

The following section summarizes some of the most important ways that cities can mitigate global climate change through actions related to forests:

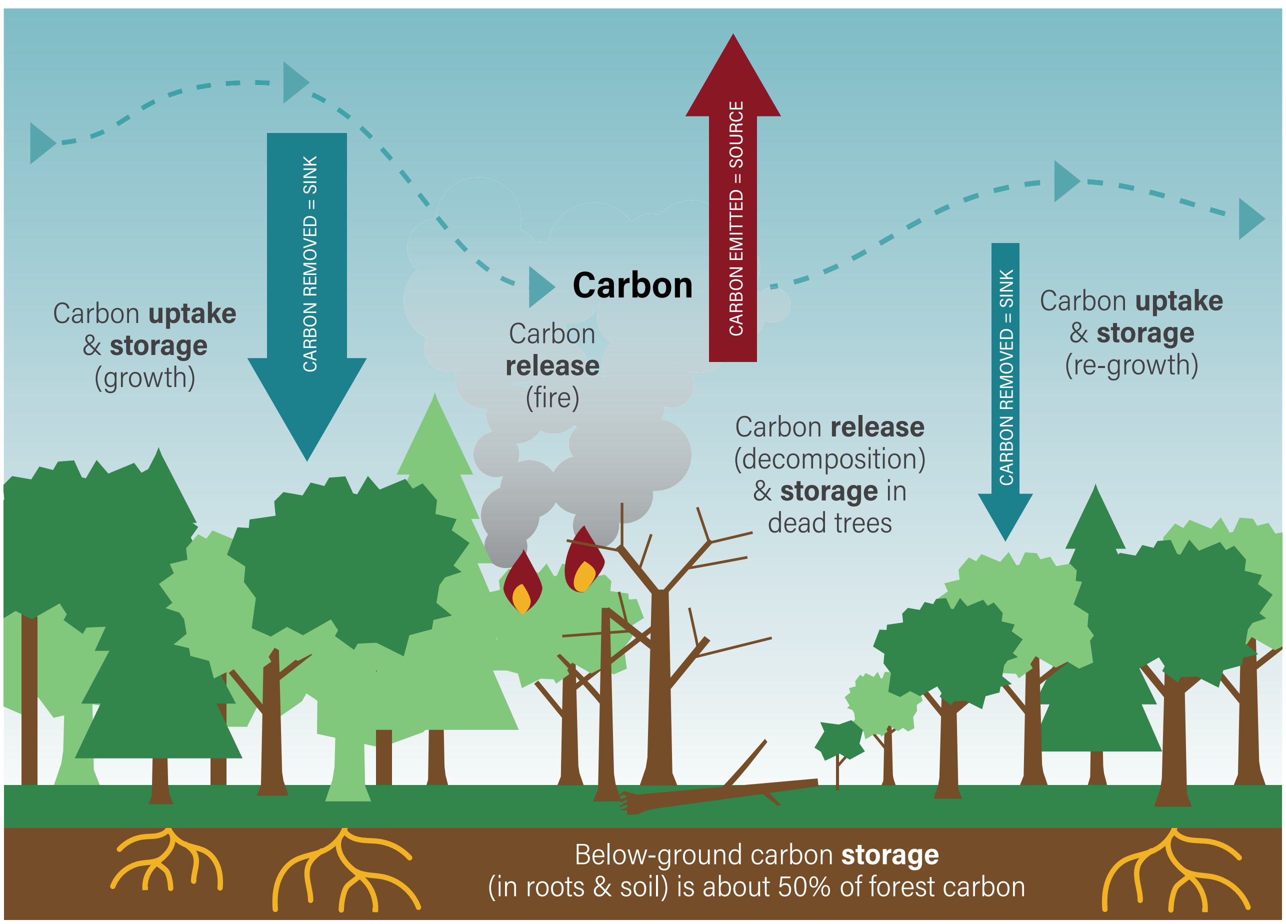
- *Inner forests:* Reduced energy emissions due to the temperature-moderating effects of the urban forests
- *Inner forests:* Carbon sequestration and storage by urban trees and forests
- *Forests outside cities (near and far away):* Global climate regulation and large-scale carbon sequestration and storage by forests, especially tropical forests

BOX 1 | The Important Role of Forests in Mitigating Global Climate Change

Globally, forests store and sequester enormous amounts of carbon. It is estimated that forests and forest soils around the world hold between about 660 and 860 metric gigatons (Gt) of carbon (C).[a] This represents more carbon than the total atmospheric emissions from fossil fuel use and industry since 1870 (about 600 GtC)[b] and potentially more than is contained in fossil fuel reserves (estimated at about 800 Gt).[c] Maintaining forests as carbon stores is critical for mitigating climate change.[d] Globally, the world's forests serve as a valuable carbon sink,[e] with more than half of gross sequestration occurring in tropical and subtropical forests.[f]

When cleared or degraded, however, forests can become carbon sources (Figure B1.1). Deforestation and forest degradation drastically reduce the ability of forests to store and sequester carbon. When forests are cleared, most of the carbon stored in aboveground biomass is released to the atmosphere through burning or decay, as is carbon stored in the soil, which is often drastically.[g] Emissions related to tropical deforestation make up about 8 percent of net global emissions annually.[h] Over the last twenty years, however, the absorption of carbon from the atmosphere by tropical forests has been approximately double their contributions to atmospheric carbon dioxide (CO_2; Figure B1.1).[i]

FIGURE B1.1 | The Forest Carbon Cycle



Note: Forests are carbon sinks; when cleared, they become sources of carbon emissions from the burning and decay of vegetation and soils.

Source: Adapted from USDA Forest Service n.d.

BOX 1 | The Important Role of Forests in Mitigating Global Climate Change (Cont.)

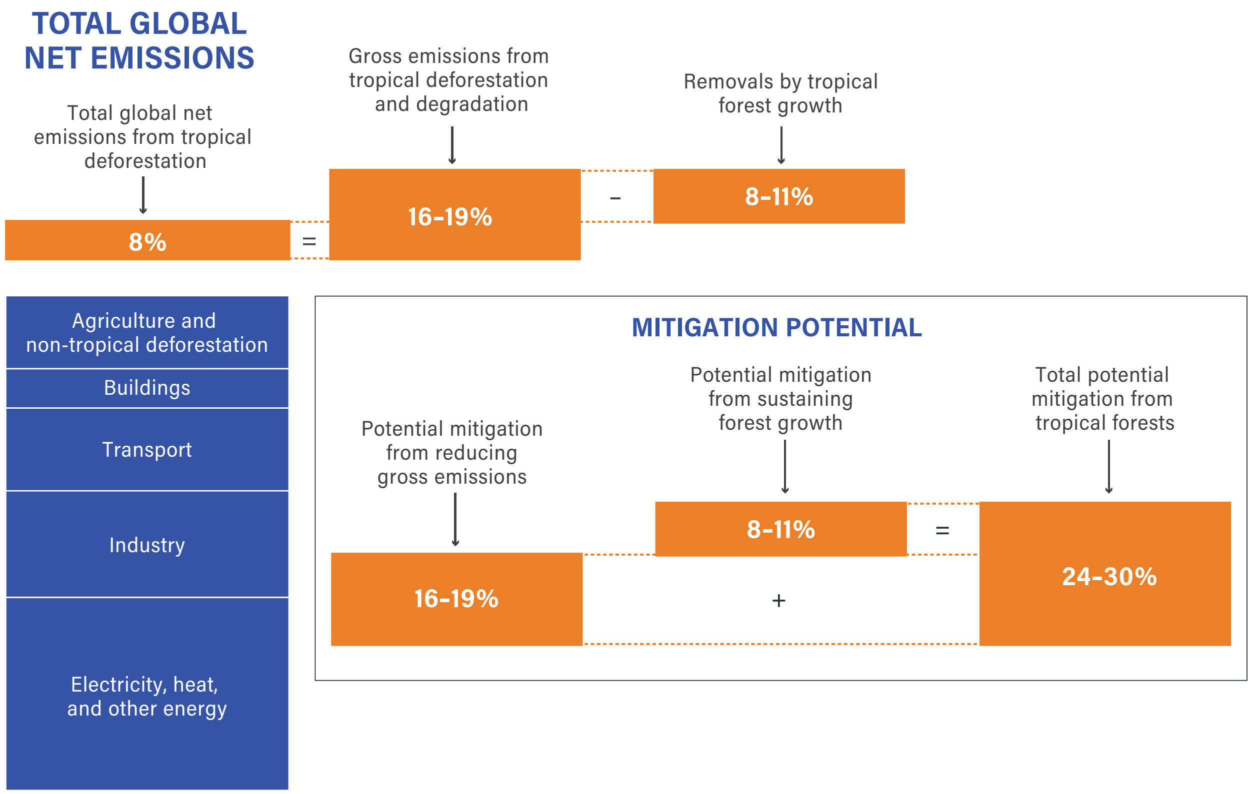
Once cleared, it can take forests decades or even centuries for carbon storage to fully recover. Standing forests store vast amounts of carbon and, if left intact, will generally continue to sequester and store carbon indefinitely.[j] Deforestation and forest degradation release this stored carbon into the atmosphere as CO_2 and eliminate a powerful, natural carbon sink.[k] Recovery of soil carbon stores is particularly slow. On average, resequestration of soil carbon takes around 60 years in tropical rain forests, 100 years in boreal forests, 150 years in mangroves, and more than 200 years in tropical peatlands.[l] Regrowth of forests following disturbance represents an important segment of the current global forest sink.[m]

Deforestation in tropical regions is proceeding at alarming rates.[n] Globally, net forest loss has decreased in recent decades, to about 4.7 million hectares (ha) per year from 2010 to 2020, and total net deforestation rates have declined to 10.2 million ha per year.[o] But tropical forests continue to experience much higher gross deforestation rates (at about 9.3 million ha per year lost annually from 2015 to 2020, an area the size of Hungary) than boreal (0.06 million ha per year), subtropical (0.50 million ha per year), or temperate regions (0.31 million ha per year).[p] Primary tropical rain forest is quickly disappearing—from 2002 to 2020, 64.7 million ha of tree cover was lost in these valuable ecosystems, an area larger than the entire country of France. In 2020 alone, this resulted in 2.6 $GtCO_2e$, which is more than double the amount of emissions from cars on roads in the United States in 2020.[q]

The world is unlikely to meet atmospheric CO_2 targets without reducing emissions from land use and land cover change.[r] Nature-based climate solutions around improved land use could offer 37 percent of necessary climate change mitigation—and in a cost-effective manner, from about US$100 per metric ton (t) of CO_2e to below $10/$tCO_2e$, in comparison to higher costs for emerging technologies, such as bioenergy with carbon capture and storage, which are estimated at about $40/$tCO_2e$ to over $1,000/$tCO_2e$ (Figure B1.2.1 and Figure B.1.2.2).[s] Forests, in particular, could provide a way to achieve 23 percent of necessary mitigation.[t] Unlike many other strategies to mitigate carbon emissions, such as geological carbon storage, better forest management, protection, and restoration can provide cascading social and environmental benefits[u] as well as benefits for biodiversity and climate adaptation.[v] Forests at the inner, nearby, and faraway level can all contribute to climate change mitigation, although the vast majority of forests and areas suitable for reforestation are represented by the faraway forests.

Internationally, tree planting is gaining momentum as a way to combat climate change, but it is still less effective than conservation at mitigating climate change.[w] Restoring forest cover to degraded and formerly forested lands can have significant climate benefits,[x] but conserving native forests is a more effective and cost-effective way to mitigate climate change. Intact and primary forests offer enormous carbon benefits: Tropical primary forests have a higher carbon density (282 tC per ha) than tropical secondary forests (139 tC per ha).[y] Although they account for only 20 percent of forests in the tropics, intact primary forests (i.e., contiguous expanses of primary forests with minimal degradation) store nearly 40 percent of aboveground forest carbon of all primary tropical forests.[z] Avoiding tropical deforestation is also about seven to nine times more cost-effective than restoration or reforestation in many contexts.[aa] Modeled data suggest that avoiding conversion and deforestation of tropical forests is estimated to offer significantly greater benefits (100 tCO_2e per ha per year sequestered globally) than reforestation could (3 tCO_2e per ha per year sequestered globally).[bb]

FIGURE B1.2.1 | The Potential Net Reduction of Emissions by Tropical Forests

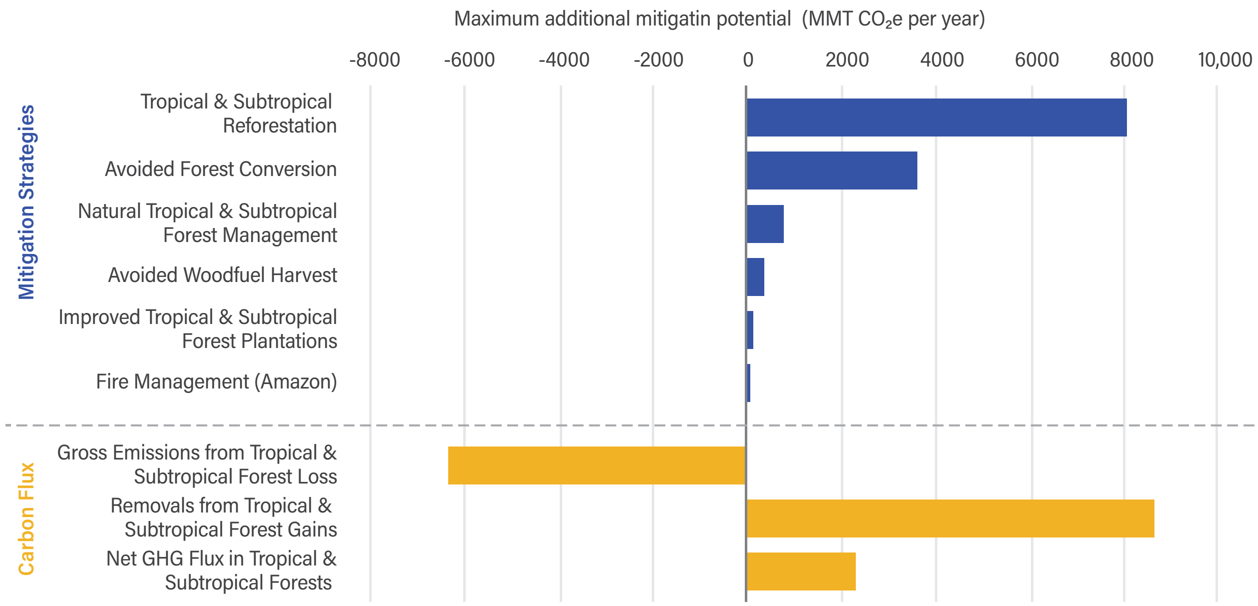


Notes: Net tropical deforestation produces 8 percent of net emissions, but halting and reversing tropical deforestation could reduce total net emissions by up to 30 percent.

Source: Authors. Adapted from Pan et al. (2011).

BOX 1 | The Important Role of Forests in Mitigating Global Climate Change (Cont.)

FIGURE B1.2.2 | The Carbon Flux of Tropical and Subtropical Forests



Note: The carbon flux of tropical and subtropical forests is a net carbon sink, but prevented deforestation and restoration in the tropics could provide significant necessary climate change mitigation.

Source: Authors. Data from Griscom et al. (2017) and Harris et al. (2021).

Restored, or secondary, forests may take centuries to recover the carbon stocks of an intact forest, even though they can have greater carbon sequestration rates.[cc] In the Amazon, for example, the rate of carbon sequestration in young forests (3.05 tC per ha per year) can be 11 times greater than that of old-growth forests (0.28 tC per ha per year), but it still took more than 60 years before aboveground forest carbon stocks recovered to 90 percent of the size of old-growth stocks following deforestation.[dd] Restoration is nonetheless an important opportunity in places where conversion has already occurred; however, due to the immediate urgency of climate action, there is not enough time to rely on restoration projects alone to regain all the potentially lost carbon from continuing to deforest mature forests.

Sources: a. Pan et. al. 2011, FAO 2020; b. Le Quéré et al. 2018; c. Federici et al. 2018; d. Seymour and Busch 2016; e. Pan et al. 2011; f. Harris et al. 2021; g. Don et al. 2011; h. Wolosin and Harris 2018; i. Harris et al. 2021; j. Pregitzer and Euskirchen 2004; k. Seymour and Busch 2016; l. Goldstein et al. 2020; m. Pugh et al. 2019; n. Seymour and Busch 2016; Anderson, C.M., et al. 2019; Weisse and Goldman 2021; o. FAO 2020; p. FAO 2016; Olsson et al. 2019; q. Weisse and Goldman 2021; r. IPCC 2019; s. Nabuurs et al. 2007; Griscom et al. 2017; t. Wolosin and Harris 2018; u. Waring et al. 2020; v. Nabuurs et al. 2007; w. Holl and Brancalion 2020; x. Griscom et al. 2017; Bastin et al. 2019; y. Pan et al. 2011; z. Popatov et al. 2017; aa. Griscom et al. 2017; Busch et al. 2019; bb. Griscom et al. 2017; Busch et al. 2019; Griscom et al. 2020; cc. Waring et al. 2020; dd. Poorter et al. 2016.

FORESTS INSIDE CITIES AND CLIMATE CHANGE: URBAN COOLING AND CARBON SEQUESTRATION

Context

The urban environment creates challenging microclimates. Dense developments stifle airflow; steel, cement, and asphalt absorb heat from the sun and elevate city temperatures; and tall buildings create wind tunnels, causing discomfort in winter. When vegetation and open water are replaced with concrete, asphalt, and other materials, temperatures increase significantly (Mohajerani et al. 2017). These conditions can increase urban demand for energy for cooling (and in some cases, heating in winter), increasing emissions and further accelerating climate change.

Cities should consider strategies to limit or reduce the urban heat island effect as a way of reducing emissions. Cities are responsible for the bulk of the world's GHG emissions (Seto et al. 2014). Transportation and industry play important roles, but maintaining habitable and comfortable indoor environments also contributes significantly. Emissions related to cooling are particularly noteworthy: urban heat islands can increase the demand for air-conditioning (Lundgren and Kjellstrom 2013) and air conditioner use—already responsible for 2 trillion kilowatt-hours of electricity annually, nearly 10 percent of global energy consumption—is expected to skyrocket in a warming world, especially in Asia (Dahl 2013; IEA 2018).

First, we examine the role of inner forests for microclimate regulation and carbon capture, following each with caveats and limitations. Then we do the same with forests outside cities.

Inner forests for microclimate regulation: What roles can trees and forests play?

Urban forests offer significant energy- and cost-saving benefits because they reduce extreme heat in summer, shade buildings, and in some settings buffer against strong winter winds. In this way, urban forests can help residents adapt to rising global temperatures—magnified by urban heat island effects—while simultaneously reducing urban emissions related to the heating and cooling of buildings.

By creating shade and lowering ambient air temperatures, trees can keep buildings cooler inside (Bowler et al. 2010a; Ko 2018). When trees shade buildings or evapotranspire, they reduce surface and ambient air temperatures, indirectly reducing the need to cool building interiors. On fossil fuel–powered electricity grids, a reduction in electricity use means a reduction in GHG emissions (Pataki et al. 2011; Roy et al. 2012; Mullaney et al. 2015). A 2018 systematic review of studies from North America suggests that cooling by trees can generate savings from 2.3 percent to as high as 90 percent of residential energy costs (Ko 2018), and another global review reported annual energy reduction benefits ranging from $2.16 to $64.00 per tree per year (Mullaney et al. 2015).

These reductions can produce significant cost savings. In the United States alone, urban forests reduce electricity use by 38.8 million megawatt-hours at a savings of $4.7 billion annually, with reductions in heating use estimated at 246 million British thermal units (savings of $3.1 billion annually) and avoided emissions savings valued at $3.9 billion annually (Nowak et al. 2017). Research from several Korean cities suggests that trees planted around multiresidential homes (totaling 32 percent of land used in Korean cities) reduced 0.367 million tCO_2 per year of emissions both directly and indirectly, offsetting the emissions of these homes related to heating and cooling by 3.3 percent, and the economic benefits of these trees related to carbon reductions and cost savings totaled $51 million per year (Jo et al. 2019).

When trees shield buildings from cold winds, they may also reduce the need to heat buildings. The evidence to support this, however, remains more limited. Cost savings for heating may range from 1 percent to 20 percent of energy costs for residential buildings in North America (Ko 2018). Reducing wind speeds may reduce winter heating costs but could conversely increase summer cooling costs in temperate climates (Ko 2018).

Inner forests for microclimate regulation: Caveats and considerations

Urban forests can provide meaningful microclimate moderation to reduce urban emissions, residential and commercial cooling and heating costs, and demand on energy generation facilities, all while creating other desirable cobenefits (Case Study 6). However, potential interactions should also be considered:

- *The cooling effects of urban forests will vary between and within cities.* Shading may produce only negligible reductions in indoor temperatures in areas where most residents inhabit tall multistory, multiunit residential buildings, as in many Chinese cities (Jim and Chen 2009). But in this context the cooling effects of evapotranspiration by trees can still be significant (Jim and Chen 2009).
- *Tall urban trees can conflict with solar access for rooftop solar panels* (Ko 2018). But this can largely be avoided with careful species selection and proper pruning (Ko 2018).
- *In areas where water is scarce, the costs of irrigating urban trees may exceed the climate benefits provided* (e.g., Pataki et al. 2011). In these contexts, selecting drought-resistant species with the ability to cool via shading may be especially important (Cameron and Blanuša 2016).
- *Interactions with the built environment matter.* For example, trees and shrubs very close to buildings may prevent the nighttime radiative cooling of buildings (Bowler et al. 2010a; Wang et al. 2014; Ko 2018). By blocking solar radiation in winter months, evergreen trees near buildings can actually increase energy demands (Lyytimäki and Sipilä 2009; Ko 2018).

Inner forests for carbon storage and sequestration: What roles can trees and forests play?

Canopy cover varies greatly among cities and is on the decline globally. Canopy cover varies with climate (Endreny et al. 2017) and between continents (Nowak and Greenfield 2020). Cities in forested regions typically have the greatest tree cover (averaging about 30 percent), followed by cities in grassland regions (18 percent) and cities in desert regions (12 percent; Nowak and Greenfield 2020). For example, the city of Atlanta contains 54 percent cover, compared to 8 percent in Cairo (Nowak et al. 2013; Endreny et al. 2017). Globally, urban tree cover is currently declining at a rate of 0.04 percent (about 40,000 ha) per year (Nowak and Greenfield 2020). The worst losses are occurring in Africa (1.5 percent lost per year) and modest gains are occurring in Europe (0.3 percent gained per year; Nowak and Greenfield 2020). Canopy cover is often used to estimate carbon storage in urban environments, and changes in canopy cover are used to estimate changes in carbon storage (Birdsey et al. 2019; Gibbs et al. 2022).

CASE STUDY 6 | The Value of Urban Forests in California

FIGURE CS6.1 | Urban Forests Near San Francisco

Source: Kevin Wolf.

Calculating the economic value of carbon sequestration can offer incentives for cities and states to invest more heavily in these strategies. In California, the value from carbon sequestration and emissions reductions from urban forests added up to 9.8 million metric tons of carbon dioxide ($MtCO_2$) per year (equivalent to removing 1.8 million cars and eliminating emissions from 210,280 households each year), with energy savings providing a meaningful 13 percent of this reduction.[a]

Using a standard price of US$12.02 per tCO_2 (based on the California Carbon Allowance Futures annual average in 2014), California's urban forest provides the state $102.35 million in carbon sequestration values.[b] Since 2014, the California Carbon Allowance has increased to $17.70 per tCO_2 (as of January 2021), and the national social cost of carbon has increased to $51.00 per tCO_2. Using these metrics, California's urban forests would render at $145.35 million and $434.26 million, respectively. The value derived from carbon sequestration is relatively small compared to other ecosystem benefits; for example, energy savings from reduced heating and cooling totaled $568.70 million, a financial benefit that often goes straight to residents.[c]

Urban trees provide substantial cobenefits for local communities, yet they tend to be expensive to plant and maintain. A recent survey found that California annually spends $19.00 on maintenance for each municipal tree.[d] However, when accounting for an average $47.83 benefit—derived from reduced energy costs, sequestered carbon, improved air quality, intercepted rainfall, increased property value—this means that the trees still represent a good investment. In fact, for every $1 spent on tree management, Californian cities receive $2.52 in benefits. Moreover, those dollars going to tree maintenance help fuel strong local forestry economics. In California, revenues directly associated with urban forestry in 2009 totaled $2.97 billion and created 40,206 jobs.[e]

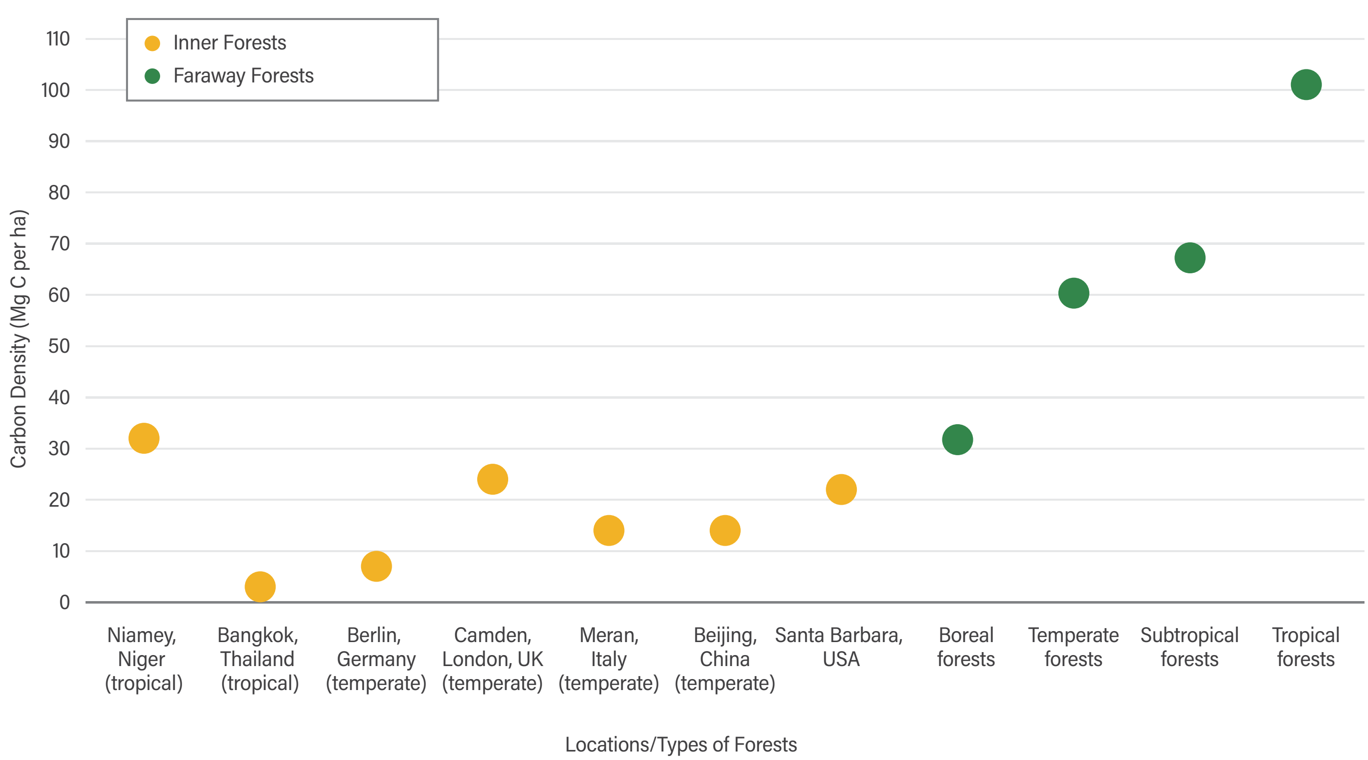
Sources: a, b, c. McPherson et al. 2017; d. Thompson 2006, found in McPherson et al. 2017; e. Templeton et al. 2013, found in McPherson et al. 2017.

Total carbon storage and sequestration rates in urban forests vary with climatic and social contexts (Nowak and Crane 2002; Strobach et al. 2011; Nowak et al. 2013; Dobbs et al. 2014; Chen 2015). Cities with favorable growing seasons, robust urban forest management programs, or ample water supplies for vegetation may store more carbon than their counterparts lacking those characteristics. Variation also exists within individual cities. For example, tree-covered spaces such as urban parks and woodland patches typically store more carbon than street trees (Fares et al. 2017). More research is needed to understand carbon storage in cities globally, but some work has been conducted to date:

- In Beijing, street trees store an estimated 0.29 $MtCO_2$ and sequester an estimated 11,400 (+/- 6,600) tCO_2 annually (Tang et al. 2016), and that sequestered CO_2 is estimated to be equivalent to emissions of approximately 2,500 gasoline-powered passenger vehicles driven for one year.
- Urban forests in the United States store approximately 3,300 $MtCO_2$ and sequester 135 $MtCO_2$ annually (gross) in their aboveground and belowground biomass (Nowak and Greenfield 2018b), with that sequestration equivalent to emissions from energy use in more than 17 million homes in the United States.

Carbon stored in urban forests per unit area varies widely but is nearly always lower than in forests outside cities (Figure 14). Aboveground carbon density varies from about 3 tC per ha in Bangkok to about 34 tC per ha in Camden, United Kingdom, to about 32 tC per ha in Niamey, Niger (Intasen et al. 2016; Wilkes et al. 2018; Moussa et al. 2019). Carbon

FIGURE 14 | Aboveground Carbon Density of Urban Forests in Selected Cities Compared with Various Faraway Forest Types



Note: For the most part, aboveground carbon density of urban forests in cities is only a fraction of the average aboveground carbon density of forests outside cities (Pan et al. 2011; Goldstein et al. 2020; Harris et al. 2021).

Source: Authors, with data from Nowak et al. (2013), Intasen et al. (2016), Tang et al. (2016), Tigges and Lakes (2017), Wilkes et al. (2018), Moussa et al. (2019), Goldstein et al. (2020), and Speak et al. (2020).

density in urban forests is consistently lower than carbon density of forests outside cities (Pan et al. 2011; Goldstein et al. 2020).

Aboveground carbon density (the amount of carbon per unit area in vegetation) has been measured for a number of urban forests; however, belowground carbon is less commonly measured. When the above- and belowground biomass for forests outside of cities is considered, these forests house far more biomass per unit area: 239–64 tC per ha for boreal forests and 242–52 tC per ha for tropical forests (Pan et al. 2011; Goldstein et al. 2020).

Inner forests for carbon sequestration and storage: Caveats and considerations

Can urban forests offset city emissions? The potential of restoring the world's forests for climate change mitigation has gained prominence in the scientific literature (e.g., Bastin et al. 2019) and in innovative global initiatives such as the Bonn Challenge,[19] Initiative 20x20,[20] the African Forest Landscape Restoration Initiative (AFR100),[21] ECCA30,[22] and Trillion Trees.[23] In some cases, cities are also increasing urban forests as a way to counterbalance carbon emissions from other sources and shrink the net municipal carbon footprint. Ambitious large-scale urban tree-planting campaigns are being supported and implemented around the world, as seen in the MillionTreesNYC project[24] or in Beijing's planting of 50 million trees between 2012 and 2015 (Yao et al. 2019). Urban forests do store more carbon than many other urban land uses and provide abundant cobenefits. But expansions in urban tree canopy are unlikely to be an effective way for cities to meaningfully curb their net emissions for four reasons:

- *Urban space for trees and forests is limited and costly.* Although higher canopy cover could increase benefits related to carbon sequestration and storage (Endreny et al. 2017), pressure from development and infill can make large increases in canopy cover challenging or impossible. Urban infill does, however, provide other benefits to cities' carbon footprints, as densification in walkable neighborhoods connected to public transit reduces emissions from private transportation.
- *Urban forests can only sequester a tiny fraction—often less than half a percent—of overall city emissions* (Case Study 7; Pataki et al. 2011). Research from diverse locations show similar numbers: Throughout China, the urban vegetation in 35 of its largest cities could offset only 0.33 percent of these cities' total emissions (Chen 2015). In the United States, urban forests in cities throughout Florida mitigate between 1.8 and 3.4 percent of city emissions (Escobedo et al. 2010), whereas in Boston urban forests mitigate only 0.8 percent (Trlica et al. 2020). In Meran, Italy, forests sequester only 0.17 percent of city emissions (Speak et al. 2020). In Tabriz, Iran, urban trees currently mitigate 0.2 percent of the city's emissions and could only be tripled to 0.6 percent over 20 years through an extensive city campaign of 150,000 new trees planted each year (Amini Parsa et al. 2019). Nonetheless, these emissions reductions can still translate into meaningful savings for cities—in the United States alone, the value of urban tree carbon sequestration is roughly $4.8 billion annually, and storage by urban trees is valued at roughly $119 billion (Nowak and Greenfield 2018b).[25]
- *Many urban trees require extensive, carbon-intensive care and maintenance during their life span.* Planting, caring for, pruning, and removing urban trees using common fossil fuel–powered machinery releases GHG emissions (Nowak et al. 2002). Such emissions often outweigh the carbon sequestered by the tree, especially street trees and trees near buildings and infrastructure, which often require extensive maintenance. Many planted urban trees die young (Roman and Scatena 2011; Roman et al. 2014)—which could mean even more emissions related to removal and replacement. Urban vegetation may also be associated with biogenic emissions from soils and decomposition of plant material (see Velasco et al. 2016). Thus, trees planted in cities often only become carbon neutral decades after planting.
- *Although urban trees grow faster, they also die younger than some of their rural counterparts, especially street trees* (McPherson et al. 1994; Roman and Scatena 2011):
    - *Urban trees often grow faster.* Trees tend to receive more sunlight and warmth due to low-density spacing and the urban heat island effect (Zhang et al. 2004). Indeed, these favorable growing conditions can lead to relatively higher storage on a per-tree basis of urban trees compared to trees in rural forest stands—as

much as four times greater (Nowak and Crane 2002). Urban tree growth can also be augmented by pruning, fertilizing, and irrigation. Good management of urban forests could promote additional carbon storage (Fares et al. 2017).

- *Urban trees face uniquely challenging conditions that can shorten their life span,* including damage from construction, pollution, pests, and vandalism. Urban soils are often compacted and contaminated with salt, have low levels of nutrients, and unfavorable pHs (Velasco and Chen 2019).
- *The estimated average life expectancy of a street tree in temperate zones is 19–28 years,* although trees in yards and parks tend to live longer (Roman and Scatena 2011).

Interventions in transportation or other sectors may be more impactful (Case Study 7). Because of the challenges that urban environments pose to tree growth, the necessary carbon inputs for many urban trees, and the premium placed on urban space, carbon sequestration by urban trees is not nearly as effective or cost-effective as sequestration in rural forests. Yet unlike most carbon sequestration and storage methods, urban trees can provide myriad cobenefits (Case Study 6).

In conclusion, reducing emissions by decarbonizing the energy and transportation sectors remains essential for cities serious about reducing their net carbon footprint. Although urban forests offset only a tiny fraction of total city emissions and the overall potential for carbon sequestration or local emissions offsetting is generally low (Pataki et al. 2011; Case Study 7), their potential for reducing urban heat islands and emissions from other sectors (such as the need for energy for air-conditioning) is considerable. Forests outside of cities, on the other hand, provide significant opportunities for cities looking to go further. Climate benefits achieved by preserving or restoring tropical forests far exceed the benefits that any amount of urban tree planting can provide.

CASE STUDY 7 | Mitigating Urban Emissions in a Tropical City: Medellín, Colombia

FIGURE CS7.1 | Medellín's Location among the Surrounding Forests

Source: Natarajan 2017.

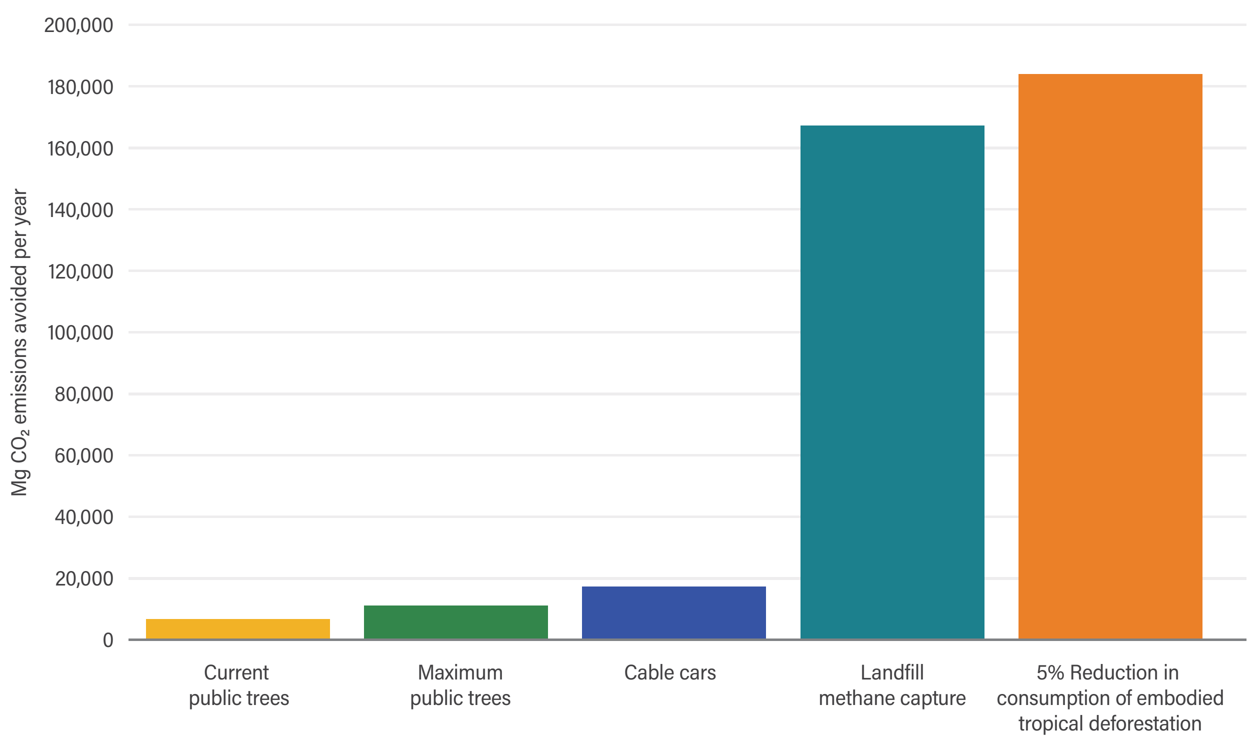
CASE STUDY 7 | Mitigating Urban Emissions in a Tropical City: Medellín, Colombia (Cont.)

Carbon sequestration by the urban forest generally only represents a small percentage of cities' total emissions. Researchers in the Metropolitan Area of Aburrá Valley in Medellín, Colombia, used a tool from the i-Tree suite (developed by the USDA Forest Service)[a] to measure carbon dioxide (CO_2) offsets from public trees—such as trees in parks, along roads, and along riverbanks—to compare them with other climate change mitigation strategies being pursued by the city: a new cable car transit system and two landfill gas management projects (Figure CS7.2).[b]

Annually, the landfill methane capture system reduced 5.84 percent of the city's emissions, compared to 0.6 percent from cable cars and 0.23 percent from public trees. Avoided emissions from cooling alone contributed about one-third of the total reduction in emissions due to street trees. Even if street trees were planted in all feasible locations (i.e., in an additional 8 percent of the city's area that could support more trees), this option would still not provide the same climate mitigation benefits as cable cars.[c]

This does not mean the urban forest is not an important asset to the city. Urban forests store a considerable amount of carbon as they provide multiple valuable services. In Medellín, public trees alone were estimated to store more than 100,000 million metric tons of CO_2 ($MtCO_2$) and are responsible for avoided emissions of 6,712 $MtCO_2$ per year[d]—roughly equivalent to removing 2,000 passenger vehicles from the road every year. Holistic urban forest management and tree maintenance is vital to protect these important carbon stores.

FIGURE CS7.2 | Potential Carbon Reduction Solutions in Medellín



Source: Authors. Adapted from Reynolds et al. (2017) and Phillips et al. (in press).

Sources: a. USDA Forest Service n.d., b–d. Reynolds et al. 2017.

CLIMATE CHANGE AND FORESTS OUTSIDE CITIES, NEAR AND FAR

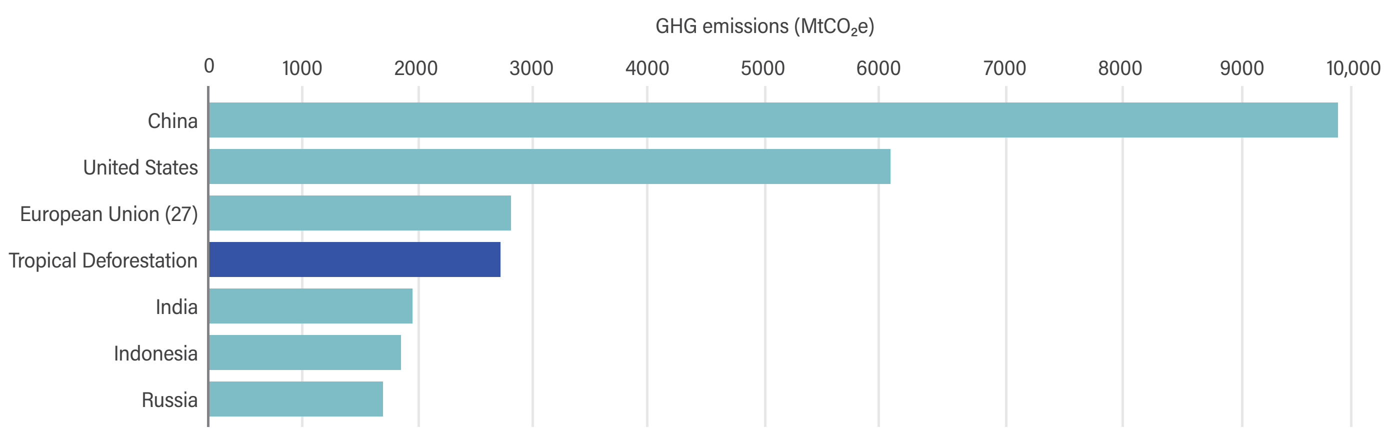
Context

Forest carbon storage and sequestration potential outside of cities far exceeds the potential within city boundaries. Globally, these forests cover approximately 30 percent (FAO 2018) of Earth's land surface (down from an estimated 55 percent at the dawn of the agricultural revolution), whereas urban areas cover only around 3 percent in total (UNSD n.d.). Investing in forest conservation outside of cities also has many cobenefits enjoyed by all people, including conserving global biodiversity, ensuring availability of future medicinal compounds, and helping to maintain global hydrological cycles, as described in the other sections of this report.

Tropical forests hold massive amounts of carbon.[26] Globally, tropical forests store approximately 470 GtC, primarily in living plant tissue (Pan et al. 2011). The tropics also contain two particularly important ecosystems for carbon storage: tropical mangroves, which line the coasts of more than 110 tropical nations (FAO and UNEP 2020b), and forested peatlands, which are especially prevalent in Southeast Asia and have been subject to conversion to palm oil plantations in recent decades (Cazzolla Gatti et al. 2019). These forests store vast amounts of carbon, which is vulnerable to loss (Donato et al. 2011; Goldstein et al. 2020).

Tropical forests are being cleared at much higher rates than boreal and temperate forests, emitting vast amounts of carbon. If tropical deforestation were a country, it would rank third in annual CO_2e emissions, only behind China and the United States (Figure 15). From 2015 to 2020, an average of 9.3 million ha of tropical forest was lost annually, compared to 0.06 million ha of boreal forest and 0.31 million ha of temperate forest (FAO 2020). However, on a net basis, temperate forests actually gained 2.2 million ha per year from 2010 to 2015, boreal and subtropical forests had little net change, but tropical forests experienced a net loss of 5.5 million ha per year (Keenan et al. 2015; FAO 2016). According to data from Global Forest Watch, from 2002 to 2020 the extent of primary tropical humid forests decreased by 6.3 percent, with losses of 4.2 million ha—an area roughly as large as the Netherlands—in 2020 alone. Brazil, the Democratic Republic of the Congo, Bolivia, and Indonesia continue to see the largest losses of irreplaceable primary rain forest (Weisse and Goldman 2021).

FIGURE 15 | If Tropical Deforestation Were a Country It Would Have the Fourth Highest Carbon Emissions Globally



Notes: GHG = greenhouse gas; $MtCO_2e$ = million metric tons of carbon dioxide equivalent.

Source: Authors. Based on data from Climate Watch (database), https://www.climatewatchdata.org/; and Pendrill, Persson, Godar, Kastner, Moran, et al. (2019).

The impact of cities on tropical forests around the world

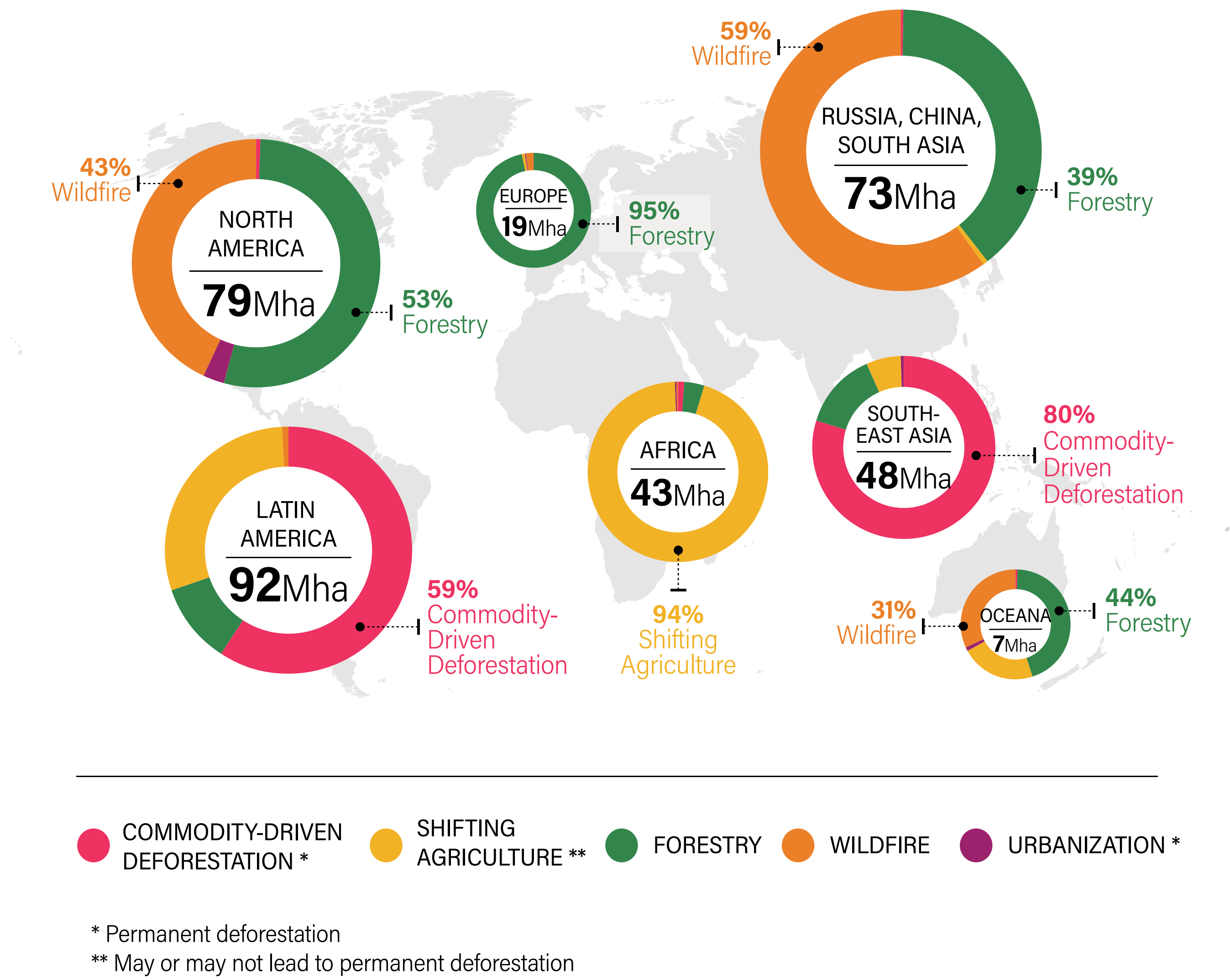
Cities may cover only a tiny fraction of Earth's surface, but they consume the majority of the world's natural resources when factoring in the goods consumed in cities but produced elsewhere (UNSD n.d). Beef, soy, palm oil, wood fiber, coffee, and rubber are just a few examples of commodities extracted from forests or cultivated in formerly forested landscapes—often illegally—that have been associated with significant forest loss (Pendrill, Persson, Godar, and Kastner 2019).

Commercial production of key agricultural commodities—including soy, beef, and palm oil—is the largest contributor to tropical forest loss (Hosonuma et al. 2012; Seymour and Busch 2016; Weisse and Goldman 2021). Much of this goes to feed consumers in cities. Deforestation in the tropics to make space for agriculture, livestock, and establishing plantation forests is estimated to emit 2.6 $GtCO_2$ (about 0.71 GtC) per year—around 5 percent of 2017 global emissions (Pendrill, Persson, Godar, Kastner, Moran, et al. 2019).[27] Of this deforestation, roughly a quarter to a third is attributable to international demand for commodities; for example, when Brazilian beef is exported to Europe or the United States (Pendrill, Persson, Godar, and Kastner 2019; Pendrill, Persson, Godar, Kastner, et al. 2019). From 2001 to 2015, deforestation to make space for agricultural commodities was responsible for an estimated 27 percent of global tree cover loss (Curtis et al. 2018). Expansion of small-scale, often shifting agriculture, accounted for an additional 24 percent of global loss, and 93 percent of total tree cover loss in Africa (Figure 16; Curtis et al. 2018).

Beyond agricultural commodities, increased demand for timber or woody biomass for energy may also place pressure on tropical forests—now or in the future. Timber harvests can also lead to deforestation and ecological degradation, as when primary forests are replaced by fast-growing plantation forests, new logging roads are created, or forests are targeted by illegal logging (Shearman et al. 2012; Seymour and Busch 2016). Wood fuel is also implicated in the struggle to maintain tropical forest cover (Sassen et al. 2015; Pearson et al. 2017) and, as with other biofuels, can create land-use competition with food production at a global level, potentially jeopardizing a sustainable food future (Searchinger et al. 2018).

The linkage between deforestation and the urban consumption patterns that drive demand for these commodities reveals an important pathway for cities to reduce their carbon footprints. Avoiding deforestation is one of the most cost-effective ways to reduce emissions while conserving a carbon sink. Cities can act on this by practicing more sustainable sourcing of the commodities responsible for much of the world's tropical deforestation, such as beef, soy, palm oil, coffee, and wood fiber; insisting that the countries those commodities come from stop deforesting land; and reducing the consumption of commodities such as beef. Because cities tend to use more resources than rural populations (Baabou et al. 2017) and are densely populated, changing urban consumption patterns can have a big impact on reducing deforestation (Defries et al. 2010). In the last decade, many multinational companies have committed to deforestation-free supply chains (Lyons-White and Knight 2018). Tropical timber, coffee, and chocolate can all be sourced in ways that do less harm to forests (Hylander and Nemomissa 2009; De Beenhouwer et al. 2013; Böhnert et al. 2016). Although deforestation-free sourcing has been implemented by some companies and at national levels, this strategy has yet to be widely adopted by cities. But cities can contribute meaningful action on this front, as evidenced by Oslo's palm oil campaign and biofuel ban (Case Study 8). Promoting awareness is the first step cities can take towards these goals, as the World Wide Fund for Nature's Earth Hour City Challenge has shown (Khan and Borgstrom-Hannson 2016).

FIGURE 16 | Commodity-Driven Tree Cover Loss by Driver for the Period 2001–2018



Note: Certain types of deforestation may not be permanent—for example, forests may be able to grow back after a fire or following logging. But clearing for commodities represents a "permanent"' transition from forest to nonforest land use, making it a much more significant source of climate-changing emissions. Within the context of this study, forest loss was categorized as shifting agriculture if the cell contained clearings that "showed signs of existing agriculture or pasture in most recent imagery as well as past clearings that contained visible forest or shrubland regrowth (gain) in historical imagery spanning the study period" (Curtis et al. 2018).

Source: Harris et al. 2020.

CASE STUDY 8 | Oslo and Palm Oil

What do cookies, cleaning supplies, and cosmetics have to do with rain forests? All can contain palm oil. To produce these consumer goods, rain forests—largely in Southeast Asia—have been cleared at alarming rates (which have declined slightly in recent years).[a] Palm oil is produced by the oil palm (*Elaeis guineensis*), an agricultural crop that grows well in the same climatic regions as tropical rain forests. From 2000 to 2011, approximately 270,000 hectares were deforested annually for palm oil production, much of this in Indonesia and Malaysia.[b] Indonesia's and Malaysia's tropical forests are home to some of the world's last orangutans as well as the Leuser ecosystem—the only place on Earth where rhinoceroses, elephants, tigers, and orangutans are found in the same place along with countless other species.[c] They also store vast amounts of carbon—many are "peat forests," which hold up to 20 times the amount of carbon in the soil as regular rain forests.[d]

People around the world unwittingly consume palm oil every day. And as most of the world's population lives in cities, that is where most of this consumption happens. Measures at national and international levels are under way to stop the import of "deforestation palm oil" and to develop protocols and certification standards for sustainably produced palm oil. But these mechanisms only go so far in addressing the problem, their effectiveness is questioned by some, and they take time to implement.[e]

In 2012, the Oslo-based Rainforest Foundation Norway broadcast a message to consumers across Norway: "Don't Eat the Forest." The campaign spread the message that consuming palm oil in edible products is causing deforestation abroad—and encouraged businesses and individuals to reassess their consumption habits.[f] In less than a year, it swayed opinion so much that national palm oil consumption dropped by 66 percent from 2011 to 2012.[g] The campaign influenced the city to update its procurement policy to ban biofuels based on palm oil and tropical wood species from unsustainable sources.[h]

The Don't Eat the Forest campaign coincided with a European-led effort to switch to renewable energy for transport, which increased demand for biofuel feedstocks, including palm oil. Up until 2015, Norway did not consume palm oil for biofuel; by 2017, it consumed 317 million liters.[i] Once again, a grassroots movement formed to change procurement policies: Indonesian Indigenous communities made their case to the European Commission, and Rainforest Foundation Norway spread the message to petroleum funds and the government. As a result, the Norwegian Government Pension Fund Global divested from unsustainable palm oil companies. The Norwegian parliament became the first in Scandinavia and Europe to eliminate palm oil–based biofuels from the government's supply chain through the Public Procurement Act.[j] Shortly after, the European Commission drafted an act to phase out palm oil–based biofuel by 2030.[k]

This reduction in palm oil biofuel feedstocks comes at a time when countries such as Norway have also committed to increasing the domestic use of biofuels. In the Norwegian case, other feedstocks will be needed to fill the gap left by palm oil. Because the large-scale use of biofuels has been criticized,[l] it is important for cities to be aware of the negative impacts of biofuel feedstocks on global forests.[m] This example shows that although grassroots campaigns, private companies, and individuals are necessary to help raise awareness to impact collective behavior, cities such as Oslo are necessary to amplify the message and supported policies that lead to change.

Note: While palm oil is a deforestation-risk commodity, research shows that it is far more efficient (yield per hectare) than almost any other oil. The reduction in demand for palm oil by Oslo residents likely means they started buying similar goods with different oils, which may result in more land conversion than for oil palm, potentially leading (and possibly indirectly) to more deforestation than if they bought products with palm oil.

Sources: a. Vijay et al. 2016; b. Henders et al. 2015; c. Swarna Nantha and Tisdell 2009; UCS 2016; CBD Secretariat n.d.; d. Jaenicke et al. 2011; e. Dalton 2018; Gatti et al. 2019; f. Alfsen n.d.; g. Rainforest Foundation Norway 2012, 4; h. City of Oslo 2017; i. Miljø-Direktoratet 2019; j. Alfsen n.d.; k. Jong 2019; l. Searchinger and Heimlich 2015; m. Seymour and Morris 2018.

When used in concert with conserving forests, forest restoration and integrating trees into farmland through agroforestry and silvopastoral systems can also serve as important tools for climate change mitigation. Conserving forests is a more effective, and more cost-effective, means of reducing the accumulation of carbon in the atmosphere (Box 1) than forest restoration alone. But as a complementary strategy, forest restoration often increases the carbon storage in forest ecosystems (Shimamoto et al. 2018). Land can be left to regrow forests on its own (Cook-Patton et al. 2020), whereas tree planting is important to reforest areas that are too degraded or severely disturbed to recover naturally, such as degraded pastureland and areas affected by catastrophic wildfires that destroy nearby sources of seed (Wilson and Rhemtulla 2016; Holl and Brancalion 2020). Where ecological conditions allow, letting forests regenerate naturally on previously forested land can regain some of their former functions in a cost-effective way (Crouzeilles et al. 2017; Cook-Patton et al. 2020). For example, there are currently 2.4 million square kilometers of secondary-growth forests in Latin America. If allowed to continue growing, these forests could sequester 8.48 GtC from 2008 to 2048—an amount equivalent to all emissions from fossil fuel use and industrial processes from countries in Latin America and the Caribbean from 1993 to 2014 (Chazdon, Broadbent, et al. 2016). Research suggests that if the full 350 million ha pledged for restoration under the Bonn Challenge were allowed to regenerate naturally, it could provide about 42 GtC storage (about three years of current global GHG emissions) by 2100, compared with 1 GtC storage if the same volume of land were turned into plantations (Lewis et al. 2019).

Caveats and considerations

Not all forests provide the same carbon benefits: forest biodiversity creates more reliable carbon sinks and a safer investment for cities.

- *More biodiverse native forests tend to store more carbon than simplified/less biodiverse forests under similar climatic and geographic conditions* (Cavanaugh et al. 2014; Poorter et al. 2015). This has been attributed to higher resource capture, more efficient resource use, and higher productivity (Poorter et al. 2015).
- *Mixed-species plantations can store greater amounts of carbon than monoculture* (Díaz et al. 2009; Piotto et al. 2010; Potvin et al. 2011; Huang et al. 2018; Jactel et al. 2018; Waring et al. 2020). Carbon storage can be further increased by incorporating species with desirable traits, such as nitrogen-fixing species (Jactel et al. 2018; Marron and Epron 2019).
- *To offer long-term climate benefits, forests must be resilient.* Biodiverse forests are likely to be more productive and offer more carbon benefits and other cobenefits due to increased resilience to disturbance and climate shocks (Liang et al. 2016; Jactel et al. 2018; Waring et al. 2020). But most planted forests in the tropics are planted with only one species, leaving them more vulnerable to disease and climatic disturbance (Payn et al. 2015; Seddon et al. 2019; Waring et al. 2020). Research shows that forests planted with mixed native species and mature native forests are more resilient. Whether planted, mature, or secondary, biodiverse forests are likely to be more productive. For example, intact tropical forests—which tend to be more biodiverse than degraded forests or monoculture plantations—create desirable traits by hosting nitrogen-fixing species (Jactel et al. 2018; Marron and Epron 2019) and establishing their own microclimates that reduce the risk of fire and protect them from droughts (Thompson et al. 2009).

With increasing climate uncertainty and risks as a result of climate change, it is not enough to maintain a certain area of forest; rather, maintaining forest quality and resilience will be essential to protecting forests to ensure they continue to store and sequester carbon.

Without immediate action to stop tropical deforestation and degradation, and encourage forest regrowth, these ecosystems could reach a "tipping point" where once-carbon-rich forests become drier savannah-like ecosystems (Lovejoy and Nobre 2018). Warming climates mean more drought and fires, which could double the area of land in the Amazon consumed by wildfires alone by 2050 (Brando et al. 2020). In a downward spiral, climate change harms tropical forests, inhibiting their ability to sequester carbon and releasing emissions that accelerate the rate of climate change (Baccini et al. 2017; Hubau et al. 2020; Anderegg et al 2020; Goldstein et al. 2020). When severely degraded or disturbed, forests may approach a tipping point, a threshold beyond which forest function deteriorates and becomes more vulnerable to human impact (Goldstein et al. 2020). The ability of tropical forests to sequester carbon in both Latin America and Africa is already being compromised due to degradation and the effects of climate change (Baccini et al. 2017; Hubau et al. 2020). Similarly, Harris et al. (2021) show that some of the largest tropical forests in the world are close to flipping from carbon sinks to carbon sources, with disastrous consequences for global CO_2 levels. Of the three largest tropical rain forests, only the Congo's tropical forests remain a strong carbon sink, with the Amazon teetering on the edge of becoming a source and forests across Southeast Asia becoming a net source of carbon emissions over the past 20 years (Harris et al. 2021).

Achieving carbon-neutrality commitments will require cities to integrate forests and trees into climate strategies. Conserving and restoring forests are currently some of the only natural, proven, and potentially cost-effective solutions to sequestering carbon and achieving net-negative emissions. Several cities are also exploring a number of innovative (and contested) strategies to harness the climate mitigation potential of forests, each with their own caveats and considerations (Box 2).

BOX 2 | Three Contested Innovations Integrating Forests into City Climate Strategies

Timber Buildings

Many cities are exploring the use of wood to build large urban buildings in place of steel and concrete to reduce embodied emissions and store carbon. But the climate impact of using wood in long-life urban construction is based on a number of key factors, and unless very high targets are met, will more often lead to negative climate impacts.

Building construction and operations (such as home electricity consumption) are responsible for 38 percent of total global carbon dioxide (CO_2) emissions.[a] Concrete and steel production alone accounts for 9 percent of all global CO_2 emissions.[b] The search for low-carbon alternative building materials has become a critical aspect of urban climate strategies. Some have proposed wood as a renewable building material that could be used in place of concrete or steel for high-density urban buildings.[c] The technology of "mass timber" employs various lamination technologies, such as cross-laminated timber, to provide increased fire resistance and structural capacity and makes use of smaller solid wood components to increase efficiency of wood harvests.[d] Practitioners are positing the role of mass timber construction as a potential avenue for climate mitigation through displacement of other higher greenhouse gas (GHG) emitting materials, and as a long-term mechanism for storing terrestrial carbon.

However, the question of the net-carbon profile of wood as a building material is contentious.[e] Several important criteria must be considered in assessing potential climate benefits or downsides of using wood for long-life urban construction, and benefits may be difficult to achieve:

- Most studies showing a positive climate benefit of mass timber inaccurately assume that using wood is "carbon neutral." For example, such calculations do not factor in the forgone carbon that would have been sequestered by the trees if they had not been harvested. Once the opportunity cost of this carbon is factored in, most calculations show that using wood for mass timber is not climate friendly.
- Increased demand for timber will result in increased "land-use competition" in lieu of other types of land use, such as conservation forests, food production, pasture, and so forth. The world is already projected to have an increase in wood demand of 50–70 percent by 2050 for "traditional" uses of wood. Mass timber represents an additional demand, further putting pressure on forest extent and forest density, especially in the context of the global land squeeze (competition for land for food, urban areas, climate protection, forest conservation, forest restoration, and so forth.).[f]
- Conversion efficiency must be considered. When trees are harvested and then processed to make wood, often less than half—and sometimes as low as 5–10 percent—of the carbon is stored in building materials or products. Roots and slash left to decompose release significant amounts of carbon. The conversion from roundwood into sawnwood ranges from 45 percent to 66 percent.[g] This is often a function of processing technologies (e.g., logging, sawmilling) and the type of timber products (e.g., plywood versus solid sawn).

Modeling indicates that for mass timber to be climate beneficial, very high bars must be met (Searchinger et al. forthcoming):[h]

Conversion efficiency must be improved such that the utilization rate of the harvested timber is above 70 percent in secondary forests and above 40 percent in plantations, thereby reducing the amount of biomass residue that is left over in the forests to decompose.

BOX 2 | Three Contested Innovations Integrating Forests into City Climate Strategies (Cont.)

Substitution rates, which refer to the climate impacts of a unit of concrete or steel versus the climate impacts of the equivalent units of timber used in a particular application, must be high. Net climate benefits from using timber are more likely when it replaces concrete or steel that has high climate impacts. Life cycle analysis tools can assist in comparing different building systems and materials, although to date most substitution rates are below threshold levels needed to be considered climate positive.

In the area where trees are harvested within a forest, the rate of regrowth must be rapid. Carbon sequestration rates will decrease while the forest regrows, so it is important that regrowth of the trees in the forest quickly returns to preharvest sequestration rates.

The longevity of forest products remaining in timber buildings is also a key factor. The length of time wood carbon is stored "in use" (i.e., not decomposed or burned) is an important factor in evaluating whether mass timber is climate beneficial or not. Perpetually reusing, upcycling, and recycling wood will help to store carbon longer.

Wood Biomass for Energy

In further efforts to reduce GHG emissions from operational energy, some cities have explored wood-based biomass energy as a substitute for fossil fuels because it is purported to be renewable and sustainable. However, this strategy has the potential to do the opposite and has become the focus of contentious debate.[i] Growing and clearing trees for fuel

- may drive conversion to plantations, which can displace or compete with other important land uses such as agriculture or intact forest, leading to net deforestation and habitat loss;[j]
- requires considerable carbon inputs for processing wood for biofuel;[k]
- creates a carbon debt that takes decades to centuries to be resequestered by forests;[l]
- requires the combustion of wood, which can result in the release of harmful air pollutants such as ultrafine particulate matter, carbon monoxide, and nitrogen oxides,[m] with health implications for communities near sites of combustion; and
- detracts from investments and research in low-pollution, low-carbon renewable energy sources.

Wood-based biomass only has carbon benefits when it uses waste residues as feedstock, but problems arise when waste residue sources are exhausted and wood is used instead to meet energy demand, which comes at the expense of forests. If forests are allowed to regrow, evidence suggests that large-scale woody bioenergy will increase atmospheric emissions in the near to medium term before potentially decreasing them relative to emissions expected from fossil fuel combustion[n]—but this may be too late to avoid irreversible climate tipping points.

Carbon Credits, Nature-Based Solutions, and REDD+

Cities are exploring the purchase of carbon credits to "offset" their unabated emissions. Nature-based solutions (NBS) can be one source of carbon credits, including the purchase of credits that conserve, manage, and restore inner, nearby, and faraway forests, especially in the tropics. However, not all carbon credits are equally beneficial to forests, climate, biodiversity, and people, and some may have adverse outcomes.[o] To ensure that the use of NBS credits helps to deliver the goals of the Paris Agreement, the credits must have high environmental integrity and adhere to robust social and environmental safeguards. Ensuring environmental integrity requires that all credits are additional (i.e., the GHG mitigation would not have been implemented without the purchase of the carbon credits) as well as address risks of leakage (when an activity is displaced to another location—for instance, if forests are grown on agricultural lands and that results in the clearing of other forests to replace that demand for agriculture), reversals (when an emissions reduction or removal is reemitted—for instance, when a forest is grown on barren land but is then cut for fuel wood many years later), and double counting (when the credit is counted by more than one entity).[p] In addition to high environmental integrity, all credits need to have high social integrity as well. Cities purchasing NBS credits should ensure that the credits respect and project human rights and that Indigenous peoples and local communities receive a fair and equitable share of the benefits.[q]

One of the most prevalent types of NBS credit is called REDD+ (reducing emissions from deforestation and forest degradation, plus the sustainable management of forest and the conservation and enhancement of forest carbon stocks). Under the United Nations Framework Convention on Climate Change, REDD+ encourages developing countries to reduce forest-based emissions in return for performance-based payments from industrialized countries. Utilizing the voluntary carbon market, cities can counterbalance their unabated emissions through the purchase of NBS credits, including REDD+. More than 50 countries have launched national REDD+ initiatives, and although there is some evidence from Brazil, Indonesia, and Guyana—the first recipients of re-

BOX 2 | Three Contested Innovations Integrating Forests into City Climate Strategies (Cont.)

sults-based finance—that REDD+ can be an effective strategy for reducing emissions from deforestation, additional finance and a transition to jurisdictional scale approaches are both urgently needed to combat underlying drivers of deforestation and provide the incentives for jurisdictional governments to act. The voluntary carbon market is one venue that can drive a significant amount of investment into NBS and at the needed scale. However, any purchase of NBS credits must be supplementary to a city's own actions to decarbonize and not reduce the pace of its own emissions reductions.

Note: A jurisdictional approach refers to a government-led, comprehensive approach to forest and land use across one or more legally defined territories (Boyd et al. 2018).

Sources: a. UNEP 2020; b. IEA and UNEP 2018; c. Buchanan and Levine 1999; Gustavsson et al. 2006; Oliver et al. 2014; Churkina et al. 2020; Waring et al. 2020; d. Harte 2017; Milestone and Kremer 2019; e. Law et al. 2018; f. Hanson and Ranganathan 2022; g. FAO et al. 2020; h. Searchinger et al. forthcoming; i. Cornwall 2017; Searchinger et al. 2018; j. Searchinger et al. 2009; k. Sterman et al. 2018; l. Buchholz et al. 2016; m. Nussbaumer 2003; Williams et al. 2012; n. Sterman et al. 2018; IPCC 2019; Favero et al. 2020; o. Seymour and Langer 2021; p, q. Burns et al. 2022.

CONCLUDING THOUGHTS

Dramatic changes in key sectors are needed to reduce global emissions and atmospheric CO_2 emissions. Yet achieving these transformations in transportation, agriculture, or industry remains challenging—even politically contentious. Natural climate solutions can offer a broadly appealing and complementary pathway to avoid catastrophic damage from climate change and accrue cobenefits related to health and biodiversity.

Agile and wielding immense political power, cities are poised to be leaders in addressing climate change by reexamining their connections to forests. Although tropical forests may seem far removed from the activities of the city, consumption patterns in urban areas drive deforestation and degradation that releases massive amounts of carbon—and threaten our ability to avoid overshooting climate targets. Forests are the only natural, proven, and cost-effective carbon solution that can actually sequester carbon and produce negative emissions. And cities have the ability to protect and support these ecosystems, both directly and indirectly.

City actions that protect the world's forests, especially tropical forests, can go a long way towards mitigating climate change. This commitment requires a multipronged approach that includes a shift towards sustainable, deforestation-free products and materials; shifting the diets of residents to more plant-based foods; and reducing food loss and waste. Forest-based approaches should not replace cuts to anthropogenic emissions—reducing emissions and sequestering carbon are both needed to meet global emissions reduction targets (Anderson, C.M., et al. 2019).


CHAPTER 5

Biodiversity

Biodiverse forests are more resilient and often provide more reliable water and climate services than depleted or monoculture forests. Biodiverse forests can help to improve mental health, support key ecosystem services, and provide the blueprints for medicine. Forests in cities can be highly biodiverse, but many species will only thrive in forests outside of cities. City action on both fronts is critical.

BACKGROUND

Cities gain tremendous benefits from biodiversity (Box 3) inside and outside their boundaries (Figure 17). Biodiversity is a key feature of resilient ecosystems (Yadav and Mishra 2013), and cities rely on resilient systems for a wide range of services. Within cities, biodiversity can have positive impacts on mental health (Fuller et al. 2007; Wood et al. 2018). Around cities, biodiversity supports key regulating and provisioning ecosystem services, such as pollination (Cardinale et al. 2012; IPBES 2016; Alvarez-Garreton et al. 2019; Yu et al. 2019). Outside city boundaries, global biodiversity directly supports human health, food security, and climate regulation and provides the blueprints for new medicines (Chivian and Bernstein 2010; Hisano et al. 2018). The value of services from natural ecosystems, which rely on biodiversity to function, has recently been estimated at $44 trillion, or over half the global economy (World Economic Forum 2020).

Biodiversity is becoming a major topic in cities around the world. Activist groups, such as Extinction Rebellion, are demanding action to protect Earth's species. Often, young and deeply engaged leaders are at the forefront of the charge, creating action plans and mobilizing political support and resources (Bagley 2019; Nwanevu 2019). Despite their distance from many of the world's natural ecosystems, it makes sense that grassroots action is originating among city residents: cities have both a lot at stake and the strongest foothold to effect change in the cultures, regulatory frameworks, technologies, and market systems that are currently responsible for global biodiversity loss. The future of cities relies on a collective ability to keep natural ecosystems functioning. Cities contain highly concentrated populations that depend almost entirely on resources and ecosystems far outside their boundaries. Partly because of this, biodiversity is increasingly appearing on city agendas, although mainly at the inner forest level (Brende and Duque 2021).

But global biodiversity is rapidly declining. Because of the importance to human well-being everywhere, including within cities, multiple international agreements exist to support biodiversity conservation via sustainable development, including the Convention on Biological Diversity and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES n.d.). Yet despite these efforts, the world is already in the midst of the sixth "global extinction" (Kolbert 2014). Around 1 million species are at risk of going extinct, many within the next few decades (IPBES 2019), mainly from habitat loss and climate change. Up to 150 species are estimated to go extinct every day (CBD Secretariat 2007), and current extinction rates are 100–1,000 times greater than the "background" rate of extinction (Pimm et al. 2014; Ceballos et al. 2015). Unlike past mass extinctions, the current extinction event is being driven by humans, through habitat loss, climate change, overexploitation, and invasive species (Tilman et al. 2017; Mazor et al. 2018).

Reduced biodiversity could have widespread impacts on the functioning of ecological support systems on which cities rely (Ceballos et al. 2017; Tilman et al. 2017). When native biodiversity is lost, ecosystems often become more vulnerable to disturbance and become less reliable—and less effective—at providing vital services. Habitat fragmentation in highly biodiverse areas can even lead to spillover of pathogens from wildlife reservoirs to human hosts (Borremans et al. 2019; Evans et al. 2020). It is uncertain how much biodiversity loss can be sustained before ecosystems see major loss of function (Dirzo et al. 2014; Moore 2018).

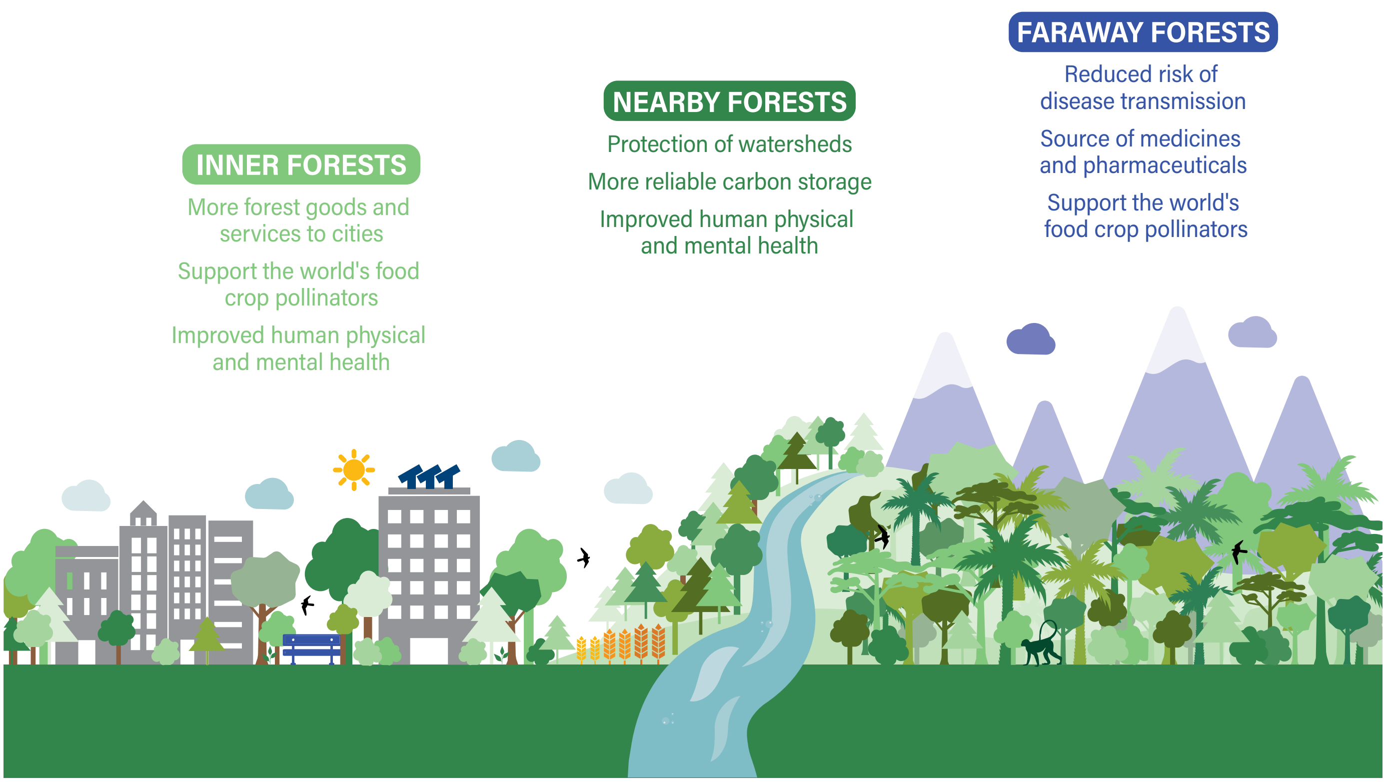
Forests are bastions of biodiversity, and biodiverse forests also provide more reliable, plentiful benefits across health, water, and climate. Forests are estimated to hold well over 60 percent—to perhaps 90 percent—of Earth's terrestrial biodiversity[28] (Erwin 1982; Wilson 1988; Reid and Miller 1989), and forest conservation is essential to maintaining the diversity of life on Earth (Wilson 1988; Brooks et al. 2006; Mittermeier et al. 2011). But forests are being rapidly cleared, and deforestation is a leading cause of global extinction (Tilman et al. 2017)—a widely reported estimate states that 135 species a day are lost through deforestation alone, but this is difficult to pinpoint as the total number of forest species and their ranges are unknown (Wilson 1988). In 2020, 12.2 million ha of tropical forest were lost, of which over a third—4.2 million ha—were in humid tropical primary forests, which are extremely important sources of biodiversity (Weisse and Goldman 2021). People in cities are responsible for an astounding 75 percent of tropical deforestation per year through their consumption. Their direct choices and indirect influence are key to conserving forest biodiversity globally and, with it, important benefits upon which they rely.

Maintaining urban forest biodiversity is increasingly appearing on urban agendas, but municipal policies and practices to protect forest biodiversity in forests outside their boundaries are rare.[29] In this section, we highlight nine key ways—based on the authors' synthesis of the literature review—that forest biodiversity near and far supports cities and city residents—and, in turn, how cities can work to support and conserve global biodiversity.

NINE THINGS CITIES NEED TO KNOW ABOUT BIODIVERSITY

Cities benefit from biodiversity and can also support it. The following nine points outline how biodiverse forests are vitally important to cities and what benefits they deliver to cities (Figure 18).

FIGURE 17 | The Biodiversity Benefits of Forests at Three Levels



Source: Authors. Adapted from Cities4Forests n.d.a

BOX 3 | What Is Biodiversity?

Biodiversity is the variation among genes, species, and communities of living organisms on Earth.[a] Species-level diversity is commonly used to assess biodiversity in forests and other ecosystems, and it is the main metric used in this section. Biodiversity can be measured at many scales, from local to global.[b] At the patch scale, promoting biodiversity could mean ensuring many native species are present; at the city scale, it could mean protecting native habitats and increasing connectivity. On the global scale, biodiversity conservation requires conserving a wide range of species and habitats, especially those that are rare, threatened, and/or species that have restricted ranges.

Endemic species—those with very limited ranges—are especially vulnerable to extinction, and the number of endemic species in an area often shapes global efforts to conserve biodiversity.[c] Many of the world's tropical cities are in areas with high levels of endemic species, especially tropical islands and mountains. An area with many non-native species can also be considered "biodiverse," but because many non-native species used in human environments are widespread, these areas contribute less to overall global biodiversity.

Sources: a. Chivian and Bernstein 2010; b. NRC 1999; c. Brooks et al. 2006; Mittermeier et al. 2011.

FIGURE 18 | Nine Things Cities Need to Know About Biodiversity

- Biodiverse forests provide more goods and services to cities
- Biodiverse forests store more carbon, more reliably
- Biodiverse, intact forests protect watersheds
- Forest biodiversity provides a template for new medicines and pharmaceuticals
- Biodiverse forests support the world's pollinators—and urban food supplies
- Protecting biodiverse forests can reduce risk of diseases and pandemics
- Access to biodiversity in urban areas benefits physical and mental health
- Urban forests can support biodiversity
- Tropical forests hold the vast majority of earth's terrestrial biodiversity

Source: Authors.

1. Biodiverse forests provide more goods and services to cities

Biodiverse forests are more resilient and have higher ecosystem function—key for climate change mitigation, water purification and regulation, and maintaining other forest benefits over time.

Biodiverse forests produce and sustain more ecosystem services on which city residents rely (Fischer et al. 2006; Flynn et al. 2011; Cardinale et al. 2012; Oliver et al. 2015). People in cities rely on forests for a large suite of different services, including mental and physical health, clean water, and climate regulation on many scales. To provide benefits, forests must be able to persist and recover from changes in the environment, including storms, droughts, and a changing climate. Maintaining higher levels of biodiversity can help them do that. "Higher biodiversity can be thought of as biological insurance": when an ecosystem has many species fulfilling similar roles, it can continue to function even if some of those organisms are lost because the roles overlap (Yachi and Loreau 1999; Brandon 2014, 3). Biodiverse forests have high function and high "resilience," or the ability to resist and rebound from shock, especially in comparison to monoculture plantations (Holling 1973; Folke et al. 2004; Thompson et al. 2009; Isbell et al. 2011; Brandon 2014; Liu et al. 2018).

Resilience is especially important for delivering forest benefits to city residents in the long term. Resilient forests persist for longer time periods. In cities, planting and maintaining a diversity of trees can prevent widespread tree loss when a new pest or disease is introduced (Santamour 2004; Raupp et al. 2006; Guyot et al. 2016). For example, in the United States, the introduction of Dutch elm disease and the emerald ash borer decimated millions of elm and ash trees, with extensive losses in urban areas (Santamour 2004; Raupp et al. 2006). Larger urban trees provide greater benefits (e.g., shade and cooling), so structurally diverse forests (with large, old trees and small, young trees) can provide additional resilience against environmental threats. Biodiverse forests in and out of cities can better weather storms, species invasions, weather fluctuations, and often human disturbance (Fischer et al. 2006; Flynn et al. 2011; Cardinale et al. 2012; Oliver et al. 2015).

2. Biodiverse forests store more carbon, more reliably

Conserving forests with high native biodiversity is a climate-biodiversity win-win for cities looking to take action on either front.

Having cities invest in forests is vital to climate change mitigation efforts. Intact and native forests sequester more carbon, store carbon longer, and provide much greater biodiversity conservation benefits than degraded forest or monoculture plantations (Holl and Brancalion 2020; Watson et al. 2020). A greater diversity of species and functional traits leads to more thorough carbon capture and storage throughout the ecosystem (e.g., aboveground versus belowground carbon; Díaz et al. 2009; Seddon et al. 2020). The higher resilience of biodiverse forests makes them a more reliable carbon sink—especially in the face of climate change, which increases extreme weather events and the need for forests to adapt to changing conditions (Turner et al. 2009; Brandon 2014; Seddon et al. 2019). Cities looking for cost-effective ways to action on climate change should consider integrating intact, biodiverse forest conservation efforts outside of cities into their climate change agendas—especially when considering procurement and sourcing options.

3. Biodiverse, intact forests protect watersheds

Native, biodiverse forests in watersheds are more effective than planted monocultures at supplying key water resources to downstream cities (Box 4; Case Study 5; Alvarez-Garreton et al. 2019; Yu et al. 2019).

The structure, impact on soils, and greater resilience of native forests create better conditions for storing and filtering water and are more likely to persist than many alternative land uses and monoculture tree plantations. For example, in south-central Chile, converting native forest to pine plantations had a negative impact on water availability, resulting in reductions in runoff (Little et al. 2009) and streamflow in the summer dry season (Box 4; Lara et al. 2009). Conversely, increases in native forest cover were linked to increases in streamflow in the dry season, when water was most needed.

BOX 4 | How Non-native Trees and Plantations Decreased Water Yield in the Andes Mountains

In the Andes, millions of city residents rely on functioning paramos (tropical high-altitude ecosystems), alpine grasslands, and cloud forests for their water supplies.[a] In the last fifty years, the Andes have undergone both extensive deforestation and planting of non-native trees species.[b]

An extensive review showed that plantations of non-native trees had negative effects on water yields in nearly every situation, except when they were planted on highly degraded soils.[c] Non-native tree plantations reduce downstream water yields compared to native grasslands and native forest.[d] Cloud forests—which capture mist from passing clouds and convert it into precipitation—are especially important for supplying water year-round. Andean cloud forests are also the most biodiverse forests in the world.[e]

Sources: a–d. Bonnesoeur et al. 2019; e. Bruijnzeel and Proctor 1995; Myers et al. 2000; Bruijnzeel et al. 2011.

4. Biodiversity in the world's forests provides the blueprints for new medicines and pharmaceuticals

Even though only a small percentage of Earth's plants have been tested, medicines in wide use come from plants—many of which come from highly biodiverse tropical forests.

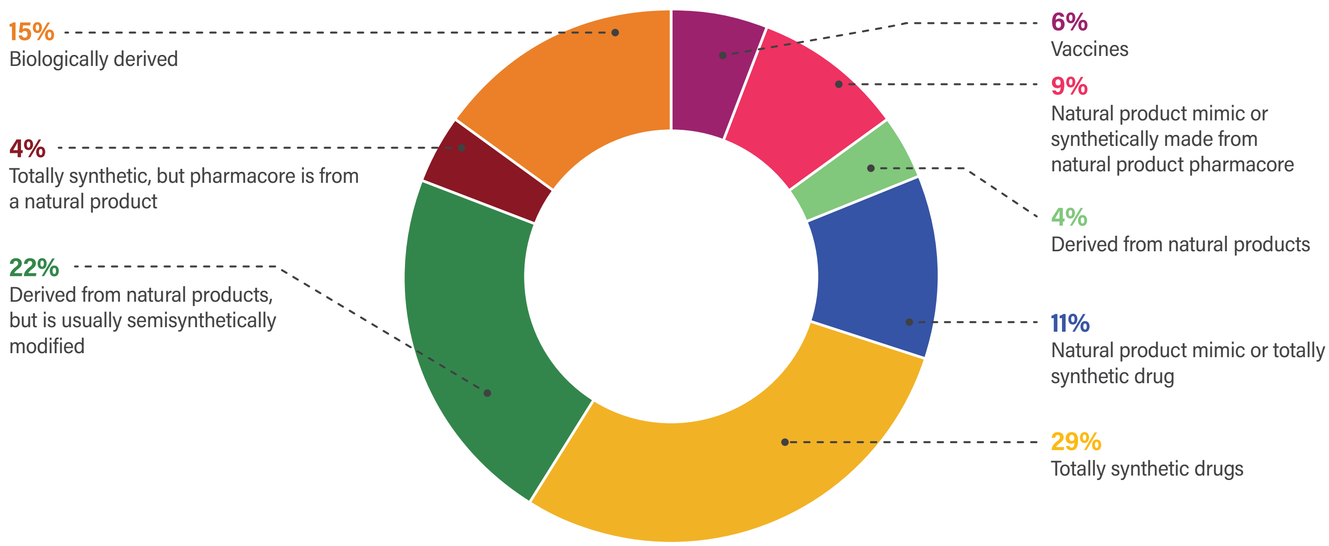
Medicinal compounds from forests are commonly used by city residents around the world. More than half of all commercial medicines are based on compounds derived from species in the wild (Figure 19; Chivian and Bernstein 2010). More than 28,000 plant species have been recorded as having a medicinal use (Allkin 2017), and an estimated 25 percent of modern medicines are derived from plants (Farnsworth and Morris 1976; Robinson and Zhang 2011).

Medicines derived from forest products include antibiotics, anticancer agents, anti-inflammatory compounds, and analgesics (Sen and Samanta 2015). Examples include morphine, aspirin, vinblastine (a lifesaving treatment for Hodgkin's disease), and vincristine (which treats acute childhood leukemia; Chivian and Bernstein 2010). In the developing world, 70–95 percent of the population—including many people living in cities—rely on traditional medicines, such as herbal medicines derived from natural environments such as forests, for primary care. These medicines make up an $83 billion per year industry (Robinson and Zhang 2011).

And this is just the tip of the iceberg—fewer than 1 percent of plant species on Earth have been examined for medicinal potential (IUCN 2011). As forests—and tropical forests, in particular—house a disproportionate share of the world's biodiversity, conserving forest is critical for future medical discoveries.

As the world's biodiversity declines, opportunities to discover new medicinal compounds decrease. "As species vanish, so too does the health security of every human. Earth's species are a vast genetic storehouse that may harbor a cure for cancer, malaria, or the next new pathogen—cures waiting to be discovered" (Mittermeier et al. 2011). A telling example comes from Australia. In 1980, two frog species were discovered in the rain forest with a unique reproductive strategy: they would ingest their own eggs to protect them and later regurgitate their young. A unique compound around the eggs prevented them from being digested—exactly the type of compound that would be useful in treating peptic ulcer sores on the stomach lining that cause burning pain. But before studies could be completed, *both* species went extinct due to habitat loss and other human activities (Chivian and Bernstein 2010). Peptic ulcers affect over 4 million people in the United States alone—and 1 in 10 people suffer from them (Harvard Health Publishing 2014). Extinctions like this happen more frequently than we would like to imagine (Wilson 1992). As forests are cleared, "hidden extinctions"—where undiscovered species disappear through extinction—reduce the biological bank that medicinal researchers have to draw from, and the possibilities for future medical advances.

FIGURE 19 | New Approved Drugs between 1981 and 2010



Notes: Twenty-two percent derived from natural product, 4 percent natural products, 15 percent biologics (derived from mammals), 6 percent vaccines, 29 percent synthetic, 24 percent from synthetic sources but modeled or mimicking a natural product (Newman and Cragg 2012). This means that 26 percent of drugs are either natural products or are directly derived from them. If including direct and indirect sources (and not including biologics and vaccines), 50 percent of drugs come from plants.

Source: Authors. Adapted from Newman and Cragg (2012).

5. Biodiverse forests support the world's pollinators—and urban food supplies

Pollinators are considered essential for an estimated 35 percent of global food production *(Klein et al. 2007). Many of these pollinators require native ecosystems—and biodiverse forests—to thrive.*

Cities import 99 percent of their food—and are almost completely reliant on pollination services outside their boundaries. Within cities, pollination is important for urban trees, gardens, and so forth. But currently only an estimated 1 percent of global food production comes from urban agriculture[30] (Clinton et al. 2018), and urban croplands account for only 5.9 percent of total croplands globally[31] (Thebo et al. 2014). Most cities rely almost entirely on agricultural lands outside of cities and import the majority of their food.

Global food production relies on both wild and managed pollinators. Seventy-five percent of the 115 leading global food crops depend, to some extent, on animal pollination, accounting for 35 percent of food produced globally (Klein et al. 2007). The Food and Agriculture Organization of the United Nations estimated that pollination services in the countries responsible for 60 percent of the world's agricultural production (Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, New Zealand, Portugal, Spain, Sweden, the United Kingdom, and the United States) were valued at between $20 and $35 billion—per year. Some estimates at the global scale put this value higher: one study[32] estimated that all pollination services had a value of $153 billion for global agriculture in 2005 (Gallai et al. 2009). Diversity of both wild and managed pollinators is important for providing more stable and effective crop pollination (Brittain et al. 2013; IPBES 2016).

But the world's pollinators are in trouble. Land-use change (including deforestation), pesticide use, climate change, and diseases and parasites are affecting pollinators around the world (Mburu et al. 2006; Vanbergen 2013; Potts et al. 2016; Sritongchuay et al. 2019; Frick et al. 2020). Wild pollinators, which include insects and bats, and are important for both crops and wild plants and are in decline (Biesmeijer et al. 2006; Potts et al. 2010; Vanbergen 2013; Martin 2015). Wild bees and butterflies are especially threatened (IPBES 2016). Beekeepers in the United States and Europe have also reported annual hive losses of 30–50 percent for the past 10 years (10 percent is considered normal; Grossman 2013; Martin 2015).

Forests, along with other natural ecosystems, directly enhance pollinator populations in both temperate and tropical regions (Öckinger and Smith 2007; Nicholls and Altieri 2013; Bailey et al. 2014). For example, the Brazilian Atlantic Forest supports pollination processes for valuable crops, including coffee (Hipólito et al. 2019). Native pollinators tend to increase with proximity to natural habitat (Kremen et al. 2004). In many contexts, agricultural landscapes with natural areas or remnants near fields have more pollinators and higher crop yields (Morandin and Winston 2006; Monasterolo et al. 2015; Cusser et al. 2016). For example, in Japan native forests were shown to support native bee pollinators, whereas plantations did not (Taki et al. 2011), and in China, majority monoculture stands had 49–91 percent fewer bee species than native forests (Hua et al. 2016). Conserving, restoring, and maintaining the biodiversity of native forests outside of cities is crucial for maintaining pollinator populations and therefore food security within cities (Krishnan et al. 2020).

Forests, too, require native pollinators to function and provide ecosystem services. Over 85 percent of wild flowering plants are animal pollinated (tropical species, 94 percent; temperate species, 78 percent; Ollerton et al. 2011; FAO and UNEP 2020b). In tropical forest environments, for example, where wind pollination is rare, flowering plants are almost exclusively pollinated by a wide variety of animal pollinators (Bawa 1990). Nonagricultural forest benefits are rarely included in global valuation of pollinator services but are essential for people everywhere, including city residents (Mburu et al. 2006). Pollinators also make forests more resilient by maintaining genetic diversity of plant species (FAO and UNEP 2020b; Krishnan et al. 2020). Plant and pollinator diversity are inextricably linked and are essential for the provision of a wide range of ecosystem services (Kearns et al. 1998; Ollerton 2017). Losing pollinators via the loss of forest biodiversity is a negative downward spiral with serious implications for forests and agriculture.

6. Protecting biodiverse forests can reduce risks of zoonotic and vector-borne diseases and pandemics

Tropical deforestation can increase the transmission of infectious diseases—including novel ones—to humans.

In 2020, the COVID-19 pandemic spread around the world, with profound social and economic consequences and devastating loss of life. In many nations, cities were the hardest hit. Like many emerging infectious diseases, researchers suspected the virus responsible (SARS-CoV-2) was animal borne (*zoonotic*), and that it may have jumped from bats, civets, or pangolins (Mallapaty 2020).

The novel coronavirus is not an outlier: 61 percent of infectious diseases and 75 percent of new and emerging pathogens originate in animals (Taylor et al. 2001; Karesh et al. 2012). Although many of these pathogens persist among animal hosts for ages, deforestation, environmental degradation, agricultural intensification, and increased human presence in biodiversity hotspots—especially in the tropics—can increase human-wildlife interactions and allow contagious viruses and bacteria to leap from animals to humans (Wolfe et al. 2007; Karesh et al. 2012; Jones et al. 2013; Borremans et al. 2019).

Deforestation may play a role in the spread of emerging infectious diseases as well as outbreaks of established vector-borne disease (Evans et al. 2020; Guégan et al. 2020):

- In West and Central Africa, clearing intact rain forest has been associated with Ebola virus outbreaks due to increased animal-to-human contacts, which promote the possibility for disease transmission (Olivero et al. 2017).
- Yellow fever has been linked to deforestation (Wilcox and Ellis 2006) because it increases ground-level activity of the virus's vectors (Monath and Vasconcelos 2015).

- Deforestation has been tied to malaria incidence via mosquito abundance in Latin America (Guerra et al. 2006; Karjalainen et al. 2010), but not in Southeast Asia (Guerra et al. 2006) or Africa (Bauhoff and Busch 2020).
- Deforestation and habitat fragmentation are also implicated in the spread of Lyme disease: as biodiversity declines, animal hosts of ticks such as mice become overabundant (Allan et al. 2003; LoGiudice et al. 2003).

Evidence suggests that maintaining high levels of biodiversity can decrease transmission of some infectious diseases (Civitello et al. 2015). Preventing deforestation and minimizing environmental degradation—especially in biodiversity hotspots such as the world's tropical rain forests—could play a role in preventing the next pandemic (Evans et al. 2020; UNEP 2020; Alimi et al. 2021).

7. Access to biodiverse nature in urban areas provides measurable benefits to urban residents

Biodiverse forests can provide more reliable and richer health benefits to urban residents.

Access to natural environments is linked to an impressive list of mental and restorative health benefits (Hartig et al. 2014). *Nature* generally implies some degree of native biodiversity and function. The few studies on nature and health that incorporate biodiversity often indicate positive relationships (or, in some cases, no effect; Fuller et al. 2007; Lai et al. 2018; Marselle et al. 2019; Ngheim et al. 2021; Wood et al. 2018). The quality and type of green space also matters; for example, a study in Australia showed that wooded areas provide more mental health benefits, and that access to nature—not just green space—is important (Astell-Burt and Feng 2019).

Urban forests can be the only source of nature for many city dwellers. For example, a survey of New York City park users in 2013–14 found that 50 percent of people who use city parks only experience nature in urban parks (Pregitzer et al. 2019). Maintaining high-quality natural areas within cities is key for many residents to access the health and other local benefits biodiverse forests provide.

Urban forests can also provide early childhood nature experiences—and may be the only source of them for many children in cities. Exposure to nature in childhood can

have lasting impacts on an individual's feelings towards the environment (Sampaio et al. 2018). Spending time in nature early in life is associated with pro-environmental behavior later in life in both developing and developed nations (e.g., Evans et al. 2018; Rosa et al. 2018). Time in nature can also be important for children's development—but children are getting less and less of it, in part because of the loss or inadequate amount of natural, biodiverse areas in cities (Louv 2005).

Biodiversity in the urban forest contributes to the distinctive character of cities around the world and can help connect people to place and encourage ecotourism (Hausmann et al. 2016). For example, Rio de Janeiro is internationally known for its astounding biodiversity and nature in the city, which is a point of pride to city residents and a major attraction for visitors worldwide. Working together to restore ecosystems can also connect people to place as well as to each other (Higgs 2003).

8. Urban forests can house high biodiversity

Urban forests can be highly biodiverse, but they also tend to have more invasive species, "generalist" species, and fewer endemic species than rural forests in the same habitat type (Concepción et al. 2015; Ducatez et al. 2018; Borges et al. 2021).

Urban areas occur in many of the world's most biodiverse landscapes. For example, 422 cities[33] are found in the world's "hotspot" regions—areas of critical importance to biodiversity conservation with both high endemic biodiversity and extensive habitat loss (Seto et al. 2011; Weller et al. 2017). Cities are highly transformed environments, but many still support surprisingly high levels of biodiversity (Box 5). Their potential as migration corridors is also key for migratory species. In some cases, moderate levels of urbanization (e.g., lower-density settlements in suburbs, less homogeneity, larger and more evenly distributed green spaces) can even increase the biodiversity of certain groups, such as plants and certain bird species (Marzluff et al. 2001; Chace and Walsh 2006; McKinney 2008).

Urban forests often support lower biodiversity and fewer endemic species than forests outside of cities (Boxes 6 and 7). Despite the ability of some urban areas to support relatively high levels of biodiversity, these areas are often different from ecosystems found outside of cities. Urbanized areas often report lower species richness (total number of species) or species density (species per unit area) than nonurbanized areas (Marzluff et al. 2001; Chace and Walsh 2006; McKinney 2008; Aronson et al. 2014).

Cities often support different types of species, including more exotic and invasive species and fewer wildlife species, than nonurban areas (specifically animals with large ranges, highly specific habitat requirements, and large mammals; Adams 1994; Marzluff et al. 2001; Chace and Walsh 2006; McKinney 2008; Aronson et al. 2014). Non-native species are often intentionally planted, sometimes because they are well adapted to city conditions (Potgieter et al. 2017) but can spread into and threaten biodiversity in nearby forests. They also limit the opportunity to conserve locally endemic or other native species. Non-native, invasive species can be detrimental to ecosystem services, spread disease, produce allergens, or lead to "biotic homogenization," where forests in different places become increasingly similar because common invasive species dominate at the expense of other species (Gaertner et al. 2017).

Both the size and connectivity of natural areas in cities are crucial for supporting urban forest biodiversity. A global meta-analysis showed that these two factors were more important than other biodiversity-friendly management

BOX 5 | Cities Can Support High Biodiversity

The Secretariat of the Convention on Biological Diversity highlights a number of key examples of high biodiversity in cities:

- More than 50 percent of the plant species found in all of Belgium can be found in Brussels.
- Mexico City supports approximately 2 percent of all the known species in the world, including 3,000 species of plants, 350 species of mammals, 316 species of birds, and many more.
- Nairobi National Park has over 100 mammal species and 400 bird species.
- In São Paulo, Brazil, 1,909 plant species and 435 animal species have been recorded, 73 of which are endemic to the Brazilian Atlantic Forest.
- Singapore has recorded many native species, including 2,145 vascular plants; 52 mammals; 364 birds; 301 butterflies; 127 dragonflies; 103 reptiles; 400 spiders; 66 freshwater fish; and 255 hard corals.

Source: CBD Secretariat 2014.

techniques or the surrounding landscape, and that areas of more than 50 ha are often needed to conserve more vulnerable species (Beninde et al. 2015).

The case studies in Boxes 6 and 7 highlight the difference between biodiversity in some of the world's best examples of biodiverse urban natural areas and the forests found outside of cities. Collectively, these studies illustrate that well-managed and cared-for urban forests can have high biodiversity and can protect threatened and/or endemic species. Nonetheless, they are unable to support all the species in a given area. Conservation efforts outside of cities are therefore essential for conserving global biodiversity.

9. Tropical forests hold the majority of Earth's terrestrial biodiversity and are therefore essential to urban well-being and sustainability

Where should cities invest in global biodiversity? Global biodiversity conservation priorities based on different metrics consistently identify tropical forests as priorities. Because cities around the world directly impact tropical forests via their consumption, they are in a strong position to improve their own biodiversity impacts through local policies that reduce negative impacts or invest in conservation.

BOX 6 | Biodiversity Comparisons between the Urban Tijuca National Park, the Rural Serra dos Órgãos National Park, and the Atlantic Forest, Brazil

TABLE B6.1 | Species Richness in Tijuca National Park, Serra dos Órgãos National Park, and the Atlantic Forest

	TIJUCA[a]	SERRA DOS ÓRGÃOS NATIONAL PARK[b]	ATLANTIC FOREST[c]
Area (ha)	3,953	20,024	~18,500,000
Birds	189	462	936
Mammals	72	105	312
Reptiles	33	81	306
Amphibians	37	102	516
Fish	NA	6	350
Plants	1,619	2,800	20,000

Sources: a. Freitas et al. 2006; Maps of World 2017; Parque Nacional da Tijuca n.d.; b. Cronemberger and Viveiros de Castro 2009; Parque Nacional da Serra dos Órgãos n.d.; c. Mittermeier et al. 2011; Ribeiro et al. 2011.

Tijuca National Park is one of the largest, most well-known, and biodiverse urban parks in the world, and it is also a major tourism attraction.[a] Encompassing 3,953 hectares (ha) of primary and secondary tropical rain forest in the city of Rio de Janeiro, Brazil, it spans an impressive elevation, from 400 to 1,021 meters above sea level, especially for its size.[b]

Yet despite this, it still supports only a fraction of the species housed in forests outside Rio de Janeiro, the extremely biodiverse Atlantic Forest. Considered a hotspot, the Atlantic Forest is estimated to hold 20,000 plant species, 8,000 of which are considered endemic.[c] For example, Serra dos Órgãos National Park, 90 kilometers outside of Rio, encompasses more than 20,000 ha (the size was increased to 20,030 ha in 2008—note that species surveys represent only 10,000 ha) of remnant Atlantic Forest, with much higher numbers of animals across all taxa (Table B6.1). Bird species diversity is especially notable, as 142 are endemic to the Atlantic Forest.[d]

Sources: a. Freitas et al. 2006; Pougy et al. 2014; b. Drummond 1996; Pougy et al. 2014; Parque Nacional da Tijuca n.d.; c. Mittermeier et al. 2011; d. Mallet-Rodrigues et al. 2007; Cronemberger and Viveiros de Castro 2009.

BOX 7 | Forest Biodiversity in New York City

New York City (NYC) is the most densely populated city in North America, with more than 8 million people in 78,000 hectares (ha).[a] Despite this, the city has 21 percent forest cover and expansive green spaces, including the iconic Central Park. These areas collectively support many species, including a relatively high proportion of native plant species (Table B7.1).[b] A study of municipal parklands found that 82 percent of natural area forest canopies are native, but that only 53 percent of the understory is native, indicating that many flowers and groundcovers are introduced exotics.[c]

NYC still only supports a small percentage of the species found in the state. This is to be expected—the state is much larger than the city—but also important because NYC both impacts and relies on nearby forests for watershed protection and recreation (Table B7.1). New York State has the greatest area of old-growth forests in the northeastern United States.[d] Intact forests support species that the city cannot—many mammals require large, intact areas of forest, and more than 20 species of birds in the state require interior forest habitat for nesting.[e]

TABLE B7.1 | Species Richness in NYC and New York State

	NEW YORK CITY	NEW YORK STATE[a]
Area (ha)	78,000	14,129,939
Plants	2,179[b]	4,253
Mammals		103
Birds	350[c]	462
Reptiles	15[d]	40
Amphibians	8[e]	32
Fish	80[f]	471

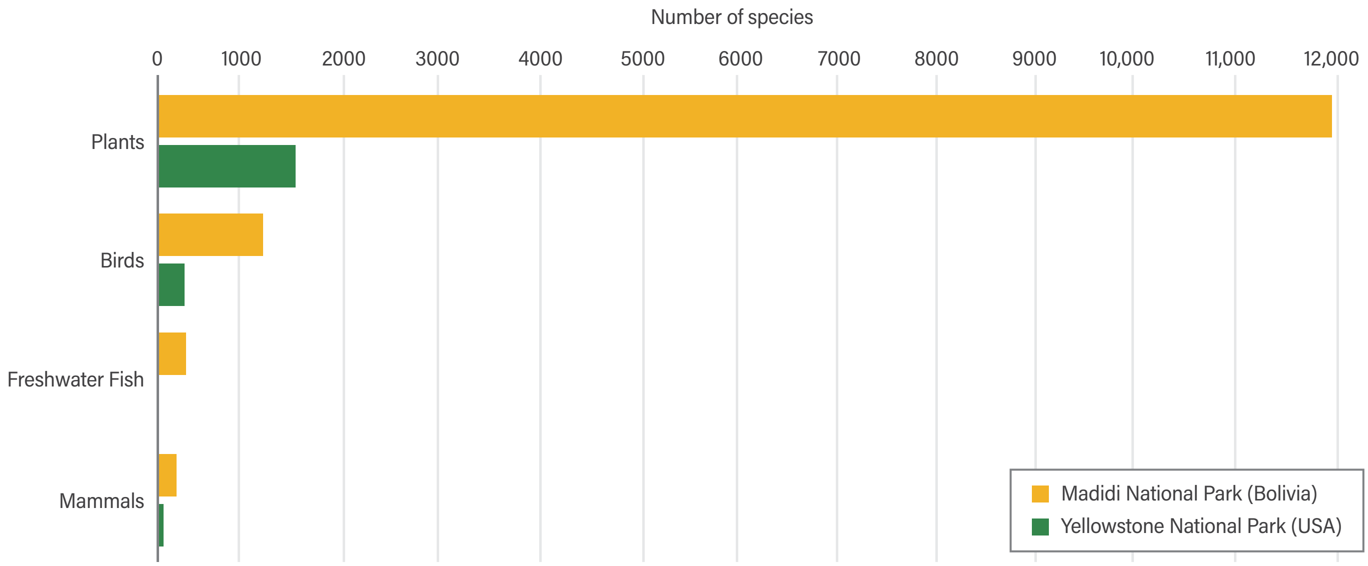
Sources: a. Johnson and Smith 2006; b. NYC Department of Parks & Recreation n.d.; Decandido et al. 2004; c. NYC Audubon n.d.; d, e. DEC n.d.; f. Encyclopaedia Britannica 2020.

Sources: a. U.S. Census Bureau 2019; b. McPhearson et al. 2013; NYC Department of Parks & Recreation n.d.; c. Pregitzer et al. 2019; d, e. Johnson and Smith 2006.

Tropical forests hold up to 90 percent of the world's land-based species. The tropics cover about 40 percent of Earth's surface but are home to over 90 percent of bird species and 75 percent of other groups, including mammals, freshwater fish, ants, and flowering plants. The species richness (total number of species) of mammals, birds, and plants increases consistently from the poles to the tropics (Barlow et al. 2018). Within the tropics, forests hold an enormous amount of this biodiversity—most (65–90 percent) of the world's land-based biodiversity is found in tropical forests, which are far more biodiverse than temperate and boreal forests[34] (Wilson 1988; Reid and Miller 1989; WRI et al. 1992).

Cities looking to conserve global biodiversity need to look both inside and outside their boundaries. Efforts to conserve biodiversity that focus only on urban areas are limited by area, degree of habitat intactness, and—critically—their geographical location. The Amazon rain forest is estimated to contain 16,000 tree species. Canada and the United States combined are estimated to hold fewer than 650 but are approximately 3.6 times the size of the Amazon. Even more impressive is that this number—650 species—can be found in one hectare of tropical rain forest, indicating both the Amazon's high level of species richness (Coley and Kursar 2014) and the potential return on investment for cities promoting biodiversity conservation in the tropics. This pattern holds true across multiple types of species as well as multiple tropical forests. Madidi National Park in Bolivia may be one of the most biodiverse areas in the world (WCS 2012; Brandon 2014). In contrast, the temperate Yellowstone National Park supports relatively high biodiversity for a temperate area but has only a fraction of the species (Figure 20; NPS 2019).

FIGURE 20 | A Comparison of the Species Found in Tropical Madidi National Park and Temperate Yellowstone National Park



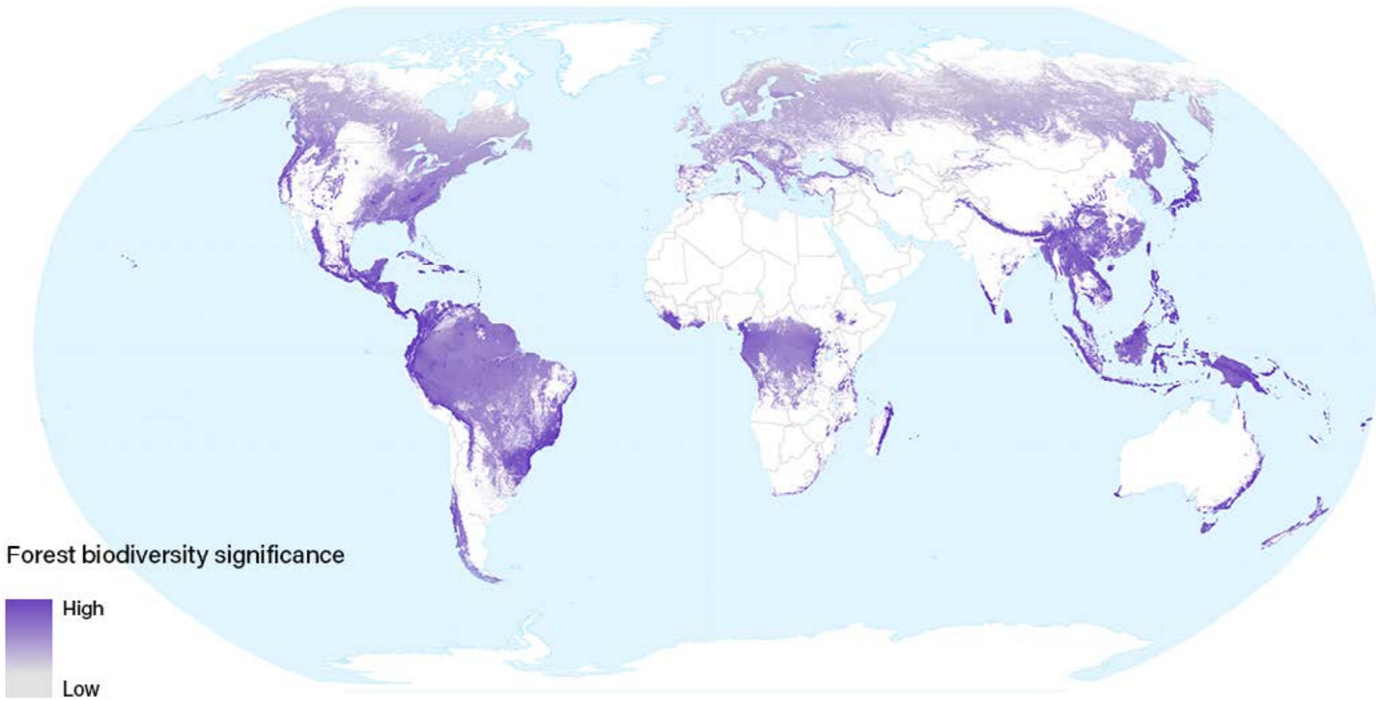
Source: Authors. Adapted from data from WCS (2012) and NPS (2019).

The Amazon, Brazilian Atlantic Forest, Congo Basin, and other parts of Central Africa contain about 50 percent of the species on Earth in only 7.5 percent of its land area and have the highest species richness per unit area in the world (Jenkins et al. 2013). That is why most of the many methods to prioritize where to invest to conserve global biodiversity point to the tropics (Myers et al. 2000; Brooks et al. 2006).

Tropical forests are home to many endemic species (Figure 21). Endemic species are critical for global biodiversity conservation because they are more vulnerable to habitat destruction in a specific place. There are *six times* more endemic species in tropical areas than temperate ones (Barlow et al. 2018). Tropical mountains (notably the Andes) and islands in particular are home to species found nowhere else (Myers et al. 2000; Kier et al. 2009).

Most global biodiversity hotspots are in the tropics. Thirty-five global biodiversity hotspots have been identified using species "irreplaceability" (endemism) and "vulnerability" (the chance that they stand of being wiped out due to habitat loss[35]; Mittermeier et al. 2011). These hotspots cover 2.3 percent of the world's land area, down from 15.9 percent originally, due to extensive habitat destruction in the last century. Yet they still house an astounding proportion of the world's species (Figure 22): the tropical Andes alone has 30,000 plant species, of which 15,000 are endemic (Mittermeier et al. 2011). Nearly all 35 hotspots are in the tropics and subtropics, and all are either completely or partially forest biomes.

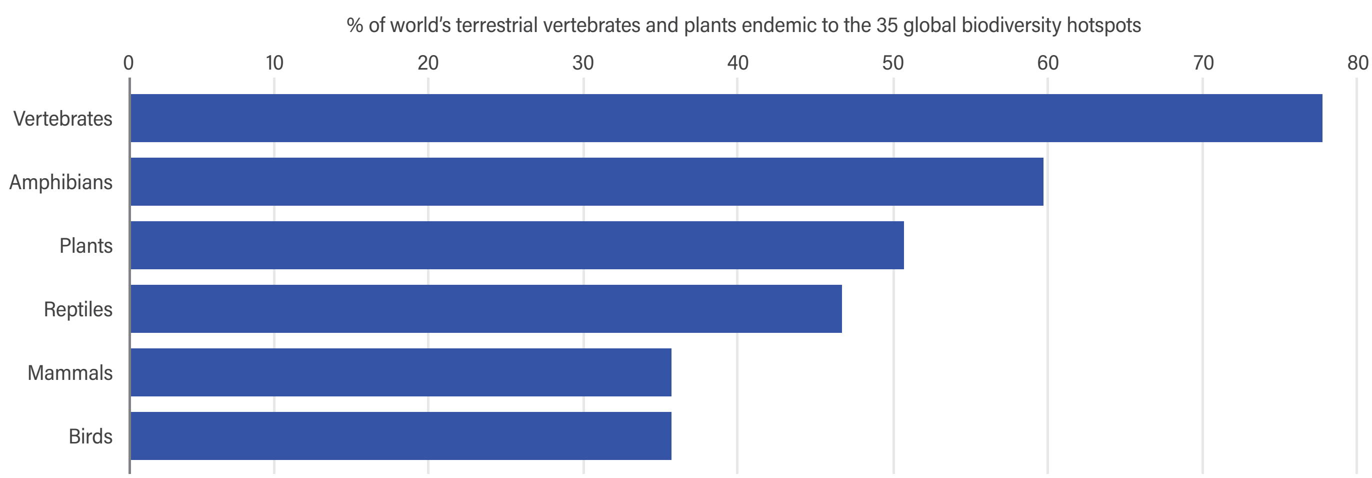
FIGURE 21 | Relative Forest Biodiversity Significance, 2018



Notes: Forest biodiversity significance is based on the "distribution of forest mammal, bird, amphibian, and conifer tree species" (Hill et al. 2019). Darker areas show higher significance values; white areas are not classified as forest.

Source: Hill et al. (2019).

FIGURE 22 | Percentage of the World's Terrestrial Vertebrates and Plants Endemic to the 35 Global Biodiversity Hotspots



Source: Authors. Adapted from Mittermeier et al. (2011).

Caveats and Considerations

Measuring biodiversity is difficult and inexact. This applies to estimates of global or regional biodiversity and global extinction rates. These numbers give a range for the vastness of biodiversity and changes over the decades but are imprecise by nature. However, they still have value and are instrumental in communicating the general trends; for example, that extinction rates are increasing or that there is higher biodiversity in the tropics, which indicate when and where action is needed.

Biodiverse forests are important for their untapped medicinal potential, but this can lead to instances of traditional medicinal knowledge being stolen or co-opted. Bioprospecting—"the exploration of biodiversity for new biological resources of social and economic value"—can be especially extractive in the context of pharmaceuticals (Beattie et al. 2011). Although the importance of biodiversity for new discoveries should not go unacknowledged, neither should the contributions of local and Indigenous peoples to building this knowledge and their rights to these resources. When exploring these topics, cities should ensure that there is equitable benefit sharing and proper recognition of intellectual property.

Debate remains around the concept that higher biodiversity decreases the risk of infectious diseases, a hypothesis known as the dilution effect (Salkeld et al. 2013; Civitello et al. 2015). When applied generally, the link between biodiversity and infectious disease transmission is less conclusive, oftentimes mitigated by the specific disease's system. However, the argument that deforestation and forest degradation contribute to the spread of infectious diseases is largely separate from the dilution effect and more strongly supported, though these mechanisms could reinforce each other. The conclusion that protecting biodiverse forests to decrease the spread of infectious diseases therefore still stands.

Some argue that biodiversity has inherent and cultural value. While not quantifiable in the same manner as the topics focused on in this section, there are arguments that biodiversity is important intrinsically and should therefore be protected. Sometimes this is described as "existence value," which does not require any direct use for there to be value but instead simply the knowledge of its existence is enough.

CONCLUDING THOUGHTS

Conserving biodiversity is critical to provide essential services that city dwellers rely on every day. Biodiverse forests are more resilient, and thus a more reliable source of forest benefits. Inside the city, biodiverse forests support improved mental health, pollination, and, in some cases, tourism. Forest biodiversity outside of cities supports services that we rely on every day, including food security (via pollination and global rainfall patterns), medicinal resources and research, climate change mitigation, and even buffering against future pandemics.

Conserving tropical biodiversity can be a double (or triple) win for cities because the world's most biodiverse forests are also critical for providing other benefits (carbon sequestration; global hydrology cycles). Cities could consider investing in biodiverse forests to which they are connected by flows, such as migratory bird routes, rainfall patterns, or in areas of high carbon density.

Although cities are far removed from the world's most biodiverse forests, they have a big impact on these environments and can play a critical role in conserving them. When it comes to biodiversity conservation, tropical forests are key. Conserving native, intact forests outside of cities in the tropics is the most important measure that cities can take because these forests contain far higher levels of native biodiversity than most secondary forests, temperate forests, and urban tropical forests. They are also especially important for conserving endemic species (Holl and Brancalion 2020). People in cities consume the majority of the world's goods and commodities, many of which currently harm diverse forests—but this impact could be greatly reduced through better sourcing and changing consumption habits. Cities can also conserve biodiversity with their boundaries, including by maintaining and expanding diverse natural areas throughout cities.


CHAPTER 6

Recommendations for Policy and Action

Around the world, cities are responding to the evidence presented in this report by increasingly using forests to address their challenges and meet the aspirations of residents. Taking inspiration from leading cities and innovative projects, this chapter describes the immediate actions that cities can take to incorporate forests into their plans, policies and investments to ensure the long-term provision of benefits they provide.

INTRODUCTION

Decades of research and on-the-ground outcomes show the untapped potential of forests to meet city needs and aspirations.

As cities face the dual challenges of growing populations and accelerating climate change, they need scalable solutions that can be implemented at relatively low cost. This report shows that forests at all three levels—inner, nearby, and faraway—can provide essential services to city residents, including improved human health, increased water security, improved microclimate regulation, climate protection, and biodiversity conservation. Forests often provide these services at lower cost than traditional infrastructure alone and can be integrated into cost-saving hybrid systems (Browder et al. 2019). Cities can use their plans, policies, and actions to harness the power of forests to build thriving, resilient communities, creating a mutually beneficial relationship between cities and forests.

What can cities do to realize the myriad benefits that trees and forests can provide them?

Our analysis has identified actions cities can take, and our synthesis of the literature and interviews categorized these under five thematic categories:

1. Measurement and monitoring
2. Planning
3. Partnerships
4. Finance
5. Markets

Under each of these categories are "no regrets" measures that allow a city to take immediate action to leverage the power of inner, nearby, or faraway forests to help meet their goals and serve their residents. Although these recommendations are not exhaustive, they provide direction for cities to take tangible action. Underpinning these measures are a set of guiding principles (Box 8)—determined by the authors based on the latest primary literature—that apply to all recommendations. These actions are intended to help deliver the benefits described in this report and raise awareness of how critical forests are to thriving, resilient cities (Box 9). The recommendations and categories of action are summarized in Figure 23.

FIGURE 23 | Forest-Positive Actions across Five City Action Categories and Three Forest Levels

	INNER FORESTS	NEARBY FORESTS	FARAWAY FORESTS
1. Measurement	1. Map, inventory, and monitor your city's urban forest 2. Quantify the benefits of urban trees 3. Align forest monitoring metrics with city goals 4. Articulate clear forest-related goals	1. Map peri-urban and watershed forests and identify where forests are being lost 2. Quantify the benefits of trees in areas around the city	1. Conduct an analysis of city-wide consumption linked to tropical deforestation 2. Identify and track local attitudes and initiatives towards promoting deforestation-free commodities 3. Articulate clear goals to guide action
2. Planning	5. Develop an urban forest management plan 6. Designate land specifically for natural areas 7. Create connectivity	3. Support the development of "nearby forest" management plans 4. Articulate clear forest-related goals	4. Calculate and develop an action plan to reduce the consumption of forest-risk commodities and city-driven carbon dioxide emissions associated with deforestation
3. Partnerships	8. Seek out organizations conducting innovative work on inner forests 9. Cultivate interagency and cross-jurisdictional collaboration	5. Articulate and amplify shared goals	5. Establish a "partner forest" 6. Establish relationships with organizations involved in forest conservation, restoration, and sustainable management to help implement faraway forest programs 7. Call on subnational and national governments as well as businesses and financiers to conserve, restore, and better manage tropical forests 8. Incentivize the use of responsibly sourced forest-risk products
4. Finance	10. Explore diverse, long-term financing mechanisms	6. Clarify that forest protection and management are eligible infrastructure expenses 7. Make the economic and business case for action on forests 8. Establish upstream-downstream partnerships to finance watershed management	9. Compensate for urban emissions by funding tropical forest conservation 10. Match conservation and restoration efforts in the city with conservation in faraway forests
5. Markets	11. Develop wood waste reuse programs	9. Implement a robust procurement policy for local, sustainably sourced wood 10. Explore the role of carbon markets to finance forest conservation or restoration	11. Establish ecotourism ventures to conserve and sustainably manage forests threatened by competing land-use pressures 12. Initiate tropical forest-positive procurement policies and campaigns

Source: Authors.

BOX 8 | Better Forests Guidance

These guiding principles apply to action at all three forest levels and will help cities realize the best outcomes from investing in forests.

- **Conserve first, restore second**. Conserving native—and especially intact—forests (through conservation or sustainable management) is a more effective and cost-effective way of sequestering carbon, conserving biodiversity, and maintaining water security than planting new forests. Conserving older and intact forests patches in and around cities gives forest interventions a "head start." Avoiding tropical deforestation is also about seven to nine times more cost-effective than restoration or reforestation in many contexts.[a]
- **Protect old and large trees**. Inside and outside of cities, large and old trees support biodiversity and provide benefits that cannot be replaced by planting new trees.
- **Define forests as essential infrastructure**. Forests are often seen as a luxury or amenity. But given the benefits they provide, they should be viewed in policy and practice as essential infrastructure for cities alongside traditional built infrastructure such as roads and bridges.
- **Create a clear vision for the role of forests**. Because forests and trees can serve so many objectives and can also imply trade-offs with others, it is important to have clarity on the ultimate purpose(s) of a program—developed in collaboration with the community—and the role that forests can play in reaching success.
- **Give voice to communities**. Engage with and empower community members and stakeholders who have a role to play in the protection, restoration, and management of forests. Including a diversity of voices and using participatory methods helps to ensure that the benefits of forests are equitably distributed and suit residents' needs. Forests that do not accommodate local needs or preferences are less likely to produce benefits that endure over time, but engaging local people can create support and even establish community stewards and advocates to champion projects and promote success over the long term.[b]
- **Emphasize equity**. In many cities, ecosystem services are distributed unevenly, further marginalizing the poorest and most vulnerable. Yet for disadvantaged populations, these services may hold disproportionate value. Conduct spatial analyses to identify under-served areas and work with local communities to plant trees, restore woodlands, and ensure that the benefits of urban greening reach the neighborhood level.
- **Collaborate across jurisdictions and city agencies**. Synergize data, resources, expertise, and policy actions on forests to help leverage the multiple benefits they can provide. Collaboration across agencies, sectors, and jurisdictions (including both other municipalities and regional and national governments) is key to increasing positive impacts on forests outside their boundaries as well as envisioning and planning for collective goals.
- **Use forests to complement measures to reduce greenhouse gas emissions**. Forests are threatened by climate change. Taking other action on climate change helps to prevent further forest degradation and other climate-induced changes, which allows them to maintain their role as carbon sinks. In this way, forests can be used to both mitigate and boost city resilience to climate change—a double win.
- **Prioritize biodiverse, native forests**. Biodiverse, native forests are more resilient to stress and provide more reliable supplies of services. Within cities, even small patches of diverse, native forest that connect fragmented landscapes provide habitat for animals, birds, and pollinators and offer access to nature for local residents. Outside of cities, native forests and areas planted with a variety of native species often produce more and more reliable forest benefits.
- **Use the "right tree, right place" approach.** When using trees and forests to achieve specific goals or benefits, cities must go beyond just increasing canopy cover. The species and placement of forest planting and regrowth should be aligned with specific goals and adapted to local conditions and a changing climate. Goals should also be aligned with appropriate metrics to monitor progress and measure success.

Sources: a. Busch et al. 2019; b. Higgs 2003; Wilson et al. 2019.

BOX 9 | Cities4Forests: A Vision for the Future

CURRENT CITY CHALLENGES/STATUS QUO		FUTURE DIRECTIONS
City planners may see urban trees and forests as luxuries, "nice to have," or sometimes liabilities	→	Urban nature seen as essential infrastructure, integral to human well-being and resilient, equitable, and habitable cities and appropriately supported by urban policy, finances, and culture
Research on urban forest expansion only uses "canopy cover" for planning and assessment	→	Urban forest expansion uses diverse metrics for high-quality natural forests and trees to deliver most-needed services in targeted areas, with community input
Urban forest management is siloed among city agencies; little communication across different departments	→	Increased coordination, cooperation, and partnership between city agencies, city residents, and private industry to support forests
City governments see nearby and watershed forests as outside the city's purview, jurisdiction, and/or concern	→	Nearby and watershed forests seen as vital to cities, supported by city regulations and incentives in collaboration with rural and municipal stakeholders outside urban limits
Consumers see forests as resources to be managed primarily for wood and paper products	→	Forests are living ecosystems managed for multiple benefits simultaneously: nontimber forest products, carbon sequestration, other climate and hydrological services, human heath, cultural services, and native biodiversity
City governments and residents see forest conservation as an impediment to growth	→	Forest conservation, restoration, and sustainable management can lead to new jobs, resilient cities, forests and landscapes, and many other benefits to the city
City governments and residents do not understand the linkage between "faraway" tropical forests and urban well-being	→	Protection and restoration of tropical forests seen as essential by city governments to efforts to maintain a livable Earth and preserve biodiversity for future generations
City governments perceive that tropical and intact forests are outside the scope of city action	→	City governments and residents empowered to take an active role in tropical forest conservation and restoration via procurement, climate action, and other direct support

Source: Authors.

ACTIONS FOR CITY PRACTICE AND POLICY

Suggested policy actions are divided by level—inner, nearby, and faraway forests—and the thematic category that each action addresses.

Inner forests: Urban trees, parks, green infrastructure, and natural areas

With planning and long-term investment, inner forests can provide multiple social, health, environmental, and economic benefits to cities and their residents. Most of the recommendations at the inner forest level can be implemented through existing city agencies, departments, and their close implementing partners directly. Making training and education available to staff of multiple city agencies will empower them to do so. In particular, having staff trained in arboculture is essential: trees are community assets that require specific skills and expertise to help them thrive in urban environments. Interagency collaboration and partnership with urban residents and stakeholder groups is also important for achieving outcomes.

Measurement and monitoring: Inner forests

- **Map, inventory, and monitor your city's urban forest**. Develop an urban tree cover baseline and land cover map as a first step towards planning and monitoring urban forests. Evaluate key urban environmental challenges—such as heat islands, urban flooding, and lack of green space (WRI Mexico 2016; Singapore-ETH Centre n.d.)—that could be improved through better forest management, and use available socioeconomic information to ensure equitable distribution of the benefits of trees to all city residents. For example, North Macedonia's Skopje Green Cadaster[36] involves a comprehensive mapping, recording, and cataloging of all public green zones in the city, including every bush and tree. Identifying areas where trees and forests are not present is also important to identify needs and opportunities (UNDP North Macedonia n.d.).
- **Quantify the benefits of urban trees, especially iconic and mature ones.** A range of tools can be used to quantify the benefits of existing trees, including large and mature ones that often have disproportionate cultural or ecological value (Pool et al. 2022; Box 10). This analysis can be used to garner political and resident support as well as guide investments in (for example, by justifying local budget decisions) and management of urban forests. For example, i-Tree Eco[37]—an online tool developed by the U.S. Forest Service to quantify and value ecosystem services provided by trees—was recently adapted, translated, and launched for Mexican cities, allowing cities across Mexico to quantify the extent and composition of urban forests and calculate their ecosystem services and monetary value. Findings from the Chapultepec Forest, a vast urban forest in Mexico City, are available via an interactive map for resident education and engagement, influencing public awareness and building the case for preserving urban forests (SEDEMA n.d.).[38]
- **Align forest monitoring metrics with city goals.** Measuring the right thing is critical to achieving and assessing specific benefits. Canopy cover is often measured to assess urban forests within cities, but it does not provide comprehensive information for all forest benefits. Using proper metrics to evaluate and track urban forests can help align goals, actions, and outcomes. In addition to canopy cover, focus on other forest qualities that improve forest function, such as biodiversity, location, forest type, dominant species, quality of the understory vegetation, location, size, and other metrics that align with the goals for these forests (Pregitzer et al. 2019).
- **Articulate clear goals.** These are a few examples:
  - *Increase forest canopy by* X *percent.* The appropriate canopy cover targets will depend on what is appropriate for local conditions (e.g., climate; natural tree canopy cover outside the city) and should be used with additional targets—such as species diversity or a mix of stand ages—to ensure forest diversity and health. In Barcelona's *Trees for Life: Master Plan for Barcelona's Trees,*[39] the city set a target to increase tree canopy by 5 percentage points for a total of 30 percent (Barcelona City Council 2017).

BOX 10 | The Value of Old, Large Trees in Cities

In cities, older and large trees can serve as important habitat and as beloved spiritual, cultural, or neighborhood landmarks. In terrestrial ecosystems, large trees are considered "keystone structures" because they occupy a small fraction of many ecosystems but have a disproportionately large impact.[a] They provide habitat for an array of animal species, from bats to insects to arboreal mammals.[b] In some communities, large "heritage" or "veteran" trees that have persisted through decades of challenging conditions become local treasures, with sentimental attachment.[c] For example, in Dakar, Senegal, the iconic baobabs, like many of the region's trees, are in jeopardy, threatened by climate change, urbanization, and population growth. Baobabs outside the city are being cleared for palm oil and cocoa plantations, but in the city the few surviving veteran baobabs serve as iconic landmarks:[d] town hall meeting spots where municipal decisions are made and resting places where city residents can find some reprieve from the day's heat.

Many cities ensure the protection of these valuable individual trees through special heritage tree ordinances.[e] Some even create dedicated registers of these urban giants to increase public awareness and facilitate their protection.[f] For example, the city of Washington, DC, requires permits and payment of hefty fees for removal of large trees and prohibits the removal of trees greater than 100 inches (254 centimeters) in circumference, which are classified as heritage trees.[g] Likewise, the city of Melbourne has created guidelines to ensure that trees are protected from damage during construction and maintains a registry of "exceptional trees" to offer additional protection from significant pruning or damage.[h] Regulations and monitoring programs such as these make it easier for trees to mature into large, attractive specimens that provide greater ecosystem services to people and urban wildlife alike.

Young trees in the understories of forests are the older trees of tomorrow. Alongside older trees, ensuring that the next generation of trees is protected by policy, sufficient new green space, and measures to protect the forest understory from foot traffic and other disturbance is also key for forest sustainability.

Sources: a. Prevedello et al. 2017; b. Stagoll et al. 2012; c. Jim 2005; d. Searcey 2018; e, f. Jim 2005; g. DDOT n.d.; h. City of Melbourne 2019.

- ☐ *Ensure every resident has green space within half a mile of home.* Cities are seeking to achieve equitable access to green space. For example, Vancouver's *Greenest City 2020 Action Plan*[40] pledged that all Vancouver residents would live within a five-minute walk of a park, greenway, or other green space by 2020 (City of Vancouver 2012).
- ☐ *Reduce heat island or stormwater threats by* X *percent.* Cities are establishing targets that address climate risks such as flooding, drought, and heat. In Australia, Western Sydney's *Turn Down the Heat: Strategy and Action Plan*[41] has set targets to reduce average peak ambient temperatures in the city by 1.5°C through greening and cool materials strategies by 2023 (WSROC 2018).

Planning: Inner forests

- **Develop an urban forest management plan.** The plan should be scientifically informed, based on nationally or internationally recognized standards, take climate change into consideration, and prioritize native species. It should also encourage education, outreach, and, if possible, support or training for private landowners—the majority landowners in many cities. Some cities have created dedicated urban forestry departments to take charge of this, but others coordinate this effort between multiple municipal agencies. Developing a robust urban forest management plan can help maximize ecosystem services from the urban forest, which includes street trees, parks, natural areas, and other urban forests (Box 11).

- **Designate land specifically for natural areas.** Even small patches of forests—in parks, vacant lots, along roadways, and in industrial areas—can provide access to nature in under-served areas. For example, the Miyawaki method, in which diverse plantings of trees and shrubs are used to create microforests, has been used to create local access to nature and increase urban biodiversity in many cities (Nargi 2019).

- **Create connectivity.** Connecting landscapes and urban green spaces supports plant and animal populations, including songbirds and pollinators. Corridors of diverse native forest can facilitate the movement of pollinators, support wildlife, provide space to alleviate stress, increase foot and bike commuting, and reduce exposure to pollution for residents. Successful examples of green corridor projects include the Medellín Green Corridors (UNEP 2019) and the Barcelona Green Corridor Network (O'Sullivan 2017).

BOX 11 | Developing a Robust Urban Forest Management Plan

Urban forest management plans take stock of the forest condition (e.g., age and species diversity; overall health), threats and challenges to existing and future trees, indicate possible protected areas, and identify areas to be restored, and/or managed. They should also define stakeholder roles and outline specific forest management actions (e.g., thinning overstocked forest stands to reduce fire risk, managing pests or invasive species, setting aside protected areas, planting trees, or managing riparian areas).

A strong urban forest management plan should contain the following:

- A vision statement for the city's canopy
- An inventory or other assessment of the urban forest
- A description of goals, objectives, measurable targets, and actions
- An implementation plan describing dates and responsibilities
- An ongoing monitoring plan
- A list of qualifications and training requirements and how these will be met
- A budgeting and funding strategy[a]

Melbourne's *Urban Forest Strategy: Making a Great City Greener 2012–2032* provides an example of a comprehensive urban forest management plan, informed by data and shaped to reflect the realities of the city. Its framing structure can be adapted and used by other cities. The strategy defines a clear, simple vision for Melbourne; describes the condition of and major challenges facing the city's trees and forests; establishes principles that address key challenges; and defines strategies, targets, and priority actions. Key cornerstones include interagency coordination, community engagement, and understanding the benefits urban forests provide to communities.[b]

Johannesburg's End Street North Park piloted an example of creating a plan through extensively engaging local stakeholders using different methods.[c] The United Nations Human Settlements Programme facilitated the use of the video game *MineCraft* as a community participation tool for public space design, and a local community organization, Sticky Situations, led participatory mapping exercises and other techniques to understand how the park is used and to engage the community in its redesign.[d]

For additional actionable information on urban forest management, see the Cities4Forests "Learning Guide: Urban Forests for Healthier Cities: Policy, Planning, Regulations, and Institutional Arrangements."[e]

Notes: For more information about the Urban Forest Strategy, see https://www.melbourne.vic.gov.au/SiteCollectionDocuments/urban-forest-strategy.pdf; to learn more about End Street North Park, see https://www.saferspaces.org.za/be-inspired/entry/inner-city-safer-parks-and-open-spaces-strategic-framework-end-street-north.

Sources: Adapted from Juno and Virsilas 2019; a. Ordóñez and Duinker 2013; Gibbons and Ryan 2015; California Urban Forest Council 2018; b. City of Melbourne 2014; c. SaferSpaces n.d.; d. Mavuso 2016; e. Juno and Virsilas 2019.

Partnerships: Inner forests

- **Seek out organizations conducting innovative work on inner forests and propose partnership models to share resources and track outcomes.** Work with credible, long-standing organizations with the capabilities and resources to conserve, create, and manage parks and other natural areas. Working with these organizations can help to both manage forests and build community-based stewardship. For example, the Natural Areas Conservancy[42] in New York City is a formalized partnership that focuses on maintaining and improving the city's vast natural areas network, integrating the city's needs with the conservation benefits these areas provide, and providing extensive community outreach.
- **Cultivate interagency and cross-jurisdictional collaboration.** Managing forests for multiple benefits that span different city agencies (including health, water, forestry, environment, and parks/recreation) can provide more benefits from the same amount of resources. Different agencies are also responsible for delivering and managing urban forestry, parks and open space, and green infrastructure in cities. The Joint Benefits Authority[43] is an example of a new mechanism that will allow multiple departments within a city to jointly plan, implement, and finance these types of transformative projects by quantifying the range of benefits that cross agency mandates (Box 12).

Finance: Inner forests

- **Explore diverse, long-term financing mechanisms to manage, protect, and expand urban forests.** Innovative financing tools include the following:
  - **Green bonds** and **climate bonds** fund projects that have positive environmental and/or climate impacts through the use of proceeds or asset-linked bonds. The Netherlands issued one of the world's largest green bonds in 2019 (about $6.8 billion) to finance natural infrastructure solutions crucial for protecting its low-lying regions from sea level rise (Anderson, J., et al. 2019).
  - **Pay for performance environmental impact bonds** (also known as pay for success bonds and social benefit bonds) allow private investors to fund specific interventions and earn a return based on performance (i.e., paying for results rather than services). In 2019 Atlanta announced a $14 million impact bond for private investors to finance innovative green infrastructure projects to address critical flooding and water quality issues, reduce stormwater runoff, and enhance the quality of life in certain neighborhoods (Water Finance & Management 2019). Investors are paid back as the green infrastructure "performs" by reducing the impacts of stormwater flooding—such as damage to public infrastructure, private houses, and people's lives—thereby saving the city money related to clean up costs.
  - **Community-based public-private partnerships** between local governments and private entities align the interests of public, private, and community stakeholders around common goals. In 2020, the Milwaukee Metropolitan Sewerage District launched a new program to capture rainfall runoff and prevent downstream flooding and sewer system contamination issues (MMSD 2020). The partnership will identify priority areas for green infrastructure based on the ability to support program goals, such as reducing overflow volumes, reducing localized flooding, and improving water quality. It reduces the risk for taxpayers as the private entity partner (a design engineering firm) is paid based on performance (i.e., the volume of water attained).
  - **Tree-planting funds** collect funds from taxes and stormwater fees. In Madison, Wisconsin, the city council has adopted a special charge—collected as part of the Madison Water Utility's municipal services bill—to support its growing urban forestry program and protect the vital services that the city's urban forest provides (City of Madison n.d.).
  - **Tree banks** collect funds from public and private developers when trees are removed and their replacement value (in terms of the ecosystem services they were providing) cannot be achieved; they also support replacements in other places throughout the city.
  - **Mitigation fees**, such as those adopted by Maryland's Montgomery County, require that development activities regulated by the county's Tree Canopy Law mitigate their impacts by planting shade trees on sites

where building disturbance occurs or pay the equivalent fees into the county's Tree Canopy Conservation Account (Montgomery County Government 2017).

- **Integrate forests into city environmental compliance plans.** Philadelphia's Green City, Clean Waters program (PWD 2011) integrated green and gray solutions based on a triple bottom line approach (Green 2013) that is already paying off (Hess 2019).
- **Incentivize city residents to support trees and forests through tax reductions**. For example, residents could be incentivized to plant trees for green stormwater infrastructure on private property via reduced stormwater fees (Berland et al. 2017). San Francisco's Urban Watershed Stewardship Grant supports similar community-based projects managing stormwater and greening the city (SFPUC n.d.).

Markets: Inner forests

- **Develop a wood waste reuse program.** Rather than disposing of waste from street and yard trees in landfills, municipalities can develop wood waste reuse programs. Dead trees can become wood chips or fuel or salvaged for timber or architectural purposes. For example, Baltimore has implemented a wood reuse program, the Baltimore Wood Project (*Room & Board* 2018), which salvages wood from demolished buildings and street trees to repurpose them into furniture and other household items, creating jobs and reducing waste (Juno and Hines 2019).

Nearby Forests: Watershed and Recreation Areas around Cities

Cities can work with other levels of government and agencies to support the conservation, sustainable management, and restoration of nearby forests; many world-class examples exist of cities working to support nearby forests. Since most nearby forests fall outside city agency jurisdiction, partnership and collaboration with state, provincial, and federal government agencies, landowners and managers, and watershed stakeholders will be necessary for recommendation implementation.

Measurement and monitoring: Nearby forests

- **Map peri-urban and watershed forests and identify where forests are being lost around a city.** Collaborate with other cross-jurisdictional stakeholders, including regional/state governments and organizations working in watershed areas. When possible, map forest type (e.g., plantation versus natural forest) as well as total forest cover. Understanding where forests are, where loss is occurring, and where restoration opportunities exist is essential for planning engagement with nearby forests (Box 12). Cities can use tools such as Global Forest Watch[44] to identify significant areas of forest loss.

BOX 12 | Mapping as a Key Tool for Watershed Restoration Planning: Jakarta, Indonesia; Extrema, Brazil

Mapping is a crucial component of watershed planning and can be used to identify the most effective course of action, inform policy, engage stakeholders, and solidify partnerships.

In Jakarta, World Resources Institute Indonesia used Global Forest Watch Water to map the extent of forest loss in Jakarta's Ciliwung watershed to assess the impact of upstream forest loss on downstream urban flooding. The analysis produced recommendations to reduce the frequency and intensity of Jakarta's floods, including reforestation, assisted natural regeneration, and agroforestry. The city has since piloted innovative solutions to protect the forested areas around the city. A payment for ecosystem services (PES) scheme in the Cidanau watershed used revenue from water pricing collected by a multistakeholder organization to fund reforestation upstream, helping to ensure clean water for the downstream residents.[a]

At a regional level, the Extrema municipality, on the border of the state of São Paulo, is located in the upper watershed basins of the Piracicaba, Capivari, and Jundiaí Rivers, a region partly responsible for supplying water to the 9 million residents of São Paulo and 3 million residents of Campinas. Officials mapped forest cover and potential sites for forest restoration and launched the Conservador das Águas program, Brazil's first successful PES scheme that has facilitated the restoration of more than 6,000 hectares of forest (more than 1.3 million native trees) in Extrema's watershed. The program increased water yield—to the tune of billions of liters of water—for downstream communities and is being scaled to other cities in the Serra da Mantiqueira region through the Mantiqueira Conservator program.

Note: For more information about Conservador das Águas, see https://www.extrema.mg.gov.br/conservadordasaguas/.

Source: a. Finlayson 2013.

- **Quantify the benefits of trees in areas around a city.** Understanding the benefits from trees can help garner support from residents and partners to support watershed management for a city's water supply. Tools such as Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) can be used to quantify and understand the current benefits and values of trees around a city (Natural Capital Project n.d.). For example, in Baoxing, China, county officials used InVEST to estimate and map annual sediment retention, water retention, and carbon sequestration provided by the city's conservation areas. Mapping results were overlaid with a biodiversity map to identify areas suitable for development with minimum negative impacts on the environment. This analysis showed that protected areas produce essential ecosystem services but that some key areas had development projects planned. The results led to local government officials reconsidering the development projects while drafting the Baoxing Land Use Master Plan in 2010.

Planning: Nearby forests

- **Support the development of a nearby forest management plan with measurable goals and success metrics.** A city could provide resources such as funding and administrative support and could participate in a goal-setting process. The plan should do the following:
  - *Be scientifically informed and climate resilient*, build on best practices, and be contextualized to the watershed.
  - *Consider the network of actors required for success.* Watershed management plans are often driven by water utilities, but they also need to take the interests of key actors such as city and community beneficiaries, landowners, and county/state/provincial governments into account (Trivedi et al. 2020). Tools such as the *Mapping Social Landscapes Guide* can help to identify the priorities and values of the suite of stakeholders involved (Buckingham et al. 2018).
  - *Be tailored to the local context.* What works in a large watershed may not work in a small one, and what works in a pristine watershed may fall short in a

highly degraded one (Postel and Thompson 2005). For example, focusing on improving forests as the key to watershed management worked well in the Kinda Dam Watershed Project in Myanmar, where population densities were low and the selective focus made it easy to implement, but this strategy was unsuccessful for the Tarbela and Mangla Dam Watershed Project in Pakistan, where population densities were higher and the limited perspective failed to integrate the greater extent of human needs and activities (Upadhyay 2005).

- **Articulate clear goals.** These are a couple of examples:
  - *Restore* X *ha by 2030.* In January 2017, Brazil's National Plan for Native Vegetation Recovery was issued as Federal Decree No. 8,972 entitled "National Policy for Native Vegetation Recovery." This policy aims to articulate and promote practices, programs, and actions that encourage forest and other native vegetation recovery on at least 12 million ha of land throughout the country.
  - *Remove invasive species from key watersheds.* For example, the city of Cape Town has begun restoring nearby water catchments, including by removing invasive exotic tree species such as pines and eucalyptus (Crawford 2020). Replacing 0.4 ha of invasive species with native vegetation could save more than 386,417 liters of water annually, allowing for accelerated replenishment of Cape Town's water storage dams and thereby preventing the next Day Zero.

Partnerships: Nearby forests

- **Articulate and amplify shared goals.** Forming collaboratives between city agencies and other forest or land management groups/levels of government to rally support can be an effective way to do this (Case Study 9). For example, an initiative between the U.S. Forest Service, Colorado State Forest Service, the Natural Resources Conservation Service, and Denver Water known as Forests to Faucets,[45] has the collective aim of reducing wildfire watershed risks and improving conditions across Colorado's Front Range. Together, they have invested over $64 million in fuel reductions and forest health across 29,500 ha (CSU n.d.).

Finance: Nearby forests

- **Clarify that forest protection and management are eligible infrastructure expenses.** Many existing funds for infrastructure have not clearly stated their ability or priority for funding NBS such as forests. Explicitly making NBS eligible for funds can open new funding sources for forest protection and management.
- **Make the economic and business case and conduct a Green-Gray Assessment.** These assessments can be used to assess the costs and benefits of green infrastructure for water supply systems and other ecosystem services (Box 13).

BOX 13 | Application of the Green-Gray Assessment in Brazilian Watersheds to Evaluate the Potential Benefits to Cities

The Green-Gray Assessment (GGA) method of World Resources Institute (WRI) allows stakeholders to value the costs and benefits of integrating green or natural infrastructure into water supply systems to improve performance.[a] It has been applied by WRI in multiple watershed systems in the United States, Mexico, Brazil, and Colombia.

In São Paulo, a GGA conducted by WRI and WRI Brasil found that restoring 4,000 hectares (nearly 10,000 acres) of priority watershed forests could reduce sediment pollution by 36 percent within 30 years, reducing turbidity by almost half and potentially boosting water supply when it is most scarce. A similar study in Rio de Janeiro's Camboriú watershed suggests that with appropriate water tariff restructuring that incorporates watershed conservation costs into water user fees (something that other studies on the average household willingness to pay for water security report is possible), up-front investment in forest conservation would be financially justified. Recognizing the potential benefits of watershed forest conservation, the Balneário Camboriú municipality undertook a review of a new water tariff structure that would incorporate watershed conservation and cover the program's full operational costs.

Sources: Ozment et al. 2018; a. Gray et al. 2019.

- **Establish upstream-downstream partnerships to finance watershed management.** These partnerships can take many forms, but all have one thing in common: an upstream stakeholder incentivized to take protective actions to conserve or restore forests by downstream beneficiaries (Boxes 13 and 14; Wunder 2005). The key to tapping into sources of financing to protect these nearby forests is to identify the beneficiaries of the services that forests offer. Arrangements between upstream land managers and downstream water users should be mutually beneficial and equitable, and they can include partnerships between upstream landholders and /or upwind landholders (those in the "precipitation sheds" of cities) who provide forest ecosystem services and downstream water to users (Postel and Thompson 2005).

BOX 14 | Funding Mechanisms for Watershed Management and Protection

Green bonds. These bonds fund projects with positive environmental and/or climate benefits. For example, Central Arkansas Water, the largest drinking water utility in Arkansas, relies on its forested watershed to offer affordable, reliable filtration services as a component of its drinking water treatment process. The utility has a dedicated watershed protection fee that goes into a fund to finance the prevention of future development of the watershed, and recently the utility bonded those fees to issue the first-ever certified green bond to acquire forestlands for drinking water.[a]

Public-private partnerships. An example of such partnerships is the Forest Resilience Bond (FRB). The FRB is an innovative collaborative financing bond that mobilizes private capital to fund the up-front costs of forest restoration work across varied landownerships and increases the pace and scale of work to improve forest health and reduce the risk of devastating wildfire in priority watersheds.[b] The FRB was first piloted in the Tahoe National Forest, where private investors invested US$4.6 million to pay for immediate restoration treatments, and beneficiaries, including the State of California, the U.S. Forest Service, and the Yuba Water Utility, repay over the tenure of the FRB.[c]

Water funds. Water funds provide a mechanism through which downstream beneficiaries of enhanced water services are able to pay for upstream investments that are essential for securing downstream security, oftentimes both in terms of quality and quantity. For example, the municipality of Quito, the city's water company, and The Nature Conservancy created the Fund for the Protection of Water (Fondos de Agua; FONAG)[d] to address simultaneously increasing water demands and watershed degradation. The FONAG board includes public, private, and nongovernmental organization watershed actors, providing a mechanism for joint investment in watershed protection, including supporting communities that live there. FONAG receives $1.5 million annually, supported in large part by Quito's water company, and to date has protected and restored more than 40,000 hectares of paramos and Andean forests with the support of more than 400 local families.[e] Since the establishment of the Quito water fund, others have been developed for Nairobi and Cape Town.[f]

Rate surcharges. These include taxes levied on top of regular water utility charges for environmental enhancement projects and are designed to establish and maintain city watershed protection programs. In North Carolina, to protect and improve drinking water quality in Raleigh, the local utility, Raleigh Water, uses a dedicated watershed protection fee to fund a partnership of land trusts through the Upper Neuse Clean Water Initiative.[g] The initiative supports projects involving nature-based solutions for stormwater management on behalf of urban communities, and upstream acquisition, easements, or payments for improved land management practices in watersheds. This consistent funding model and inclusive approach has protected 182 kilometers of stream banks on 4,246 hectares—a huge success in a rapidly urbanizing landscape.[h]

Sources: a. Fatin 2020; b. Blue Forest Conservation n.d.; c. WRI 2018; d. TNC n.d.a; e. Fondos de Agua n.d.; f. TNC n.d.b; g. CTNC n.d.; h. Upstream Matters n.d.

Markets: Nearby forests

- **Implement a robust procurement policy for local, sustainably sourced wood.** Sourcing sustainability produced wood from carefully managed forests around cities can support forest conservation. For example, the city of Barcelona recognized the power of its public procurement. It implemented its first timber procurement policy in 2004 (most recently updated in 2015) as part of the city's public procurement initiative to enrich cultural values, improve social equity, foster innovation, and support environmental sustainability through its buying power. During the policy's first four years, 76 percent of wood procured (4,673 cubic meters) was Forest Stewardship Council certified or equivalent.
- **Explore the role of carbon markets to finance forest conservation or restoration.** Carbon markets vary widely in terms of scope, design, rules, regulations, and implementation. Individual approaches to carbon markets need to be context specific to enable a sustainable carbon price, incentivize investment, and encourage transparent auditing and accountability. Cities using this strategy should ensure that supply meets the criteria in Seymour and Langer (2021). King County in Washington State established the Forest Carbon Program, providing the opportunity for local companies to purchase carbon credits and support healthy forests within the county. In the first five years, King County estimates that the program will store at least 100,000 tCO_2 that otherwise would have been emitted into the atmosphere (King County 2020).

Faraway forests: Intact and remote forests, especially in the tropics

Conserving tropical forests is essential for mitigating climate change, conserving biodiversity, and regulating the global hydrological cycle. Deforestation rates in the tropics have soared in the past several decades and remain high (Hansen et al. 2013; FAO 2020). Recommendations for faraway forests include conducting a citywide forest footprint analysis as well as establishing mutually beneficial partnerships between city leadership (especially procurement managers) and tropical forest stakeholders. Cities can explore multiple ways to integrate faraway forest outcomes into their plans for climate, biodiversity, and local resident engagement and awareness campaigns (Box 15).

CASE STUDY 9 | How the Catskills Filter Water for New York City's 8 Million Residents

New York City (NYC) conserved forest and natural landscapes in the Catskills to save on water filtration costs. The city invested US$1.5 billion to protect more than 404,686 hectares of mostly forested watershed area, ultimately avoiding $6–$8 billion on the cost of building a water filtration plant.[a]

To comply with the federal regulations of the Safe Drinking Water Act, NYC had to choose to either construct a new filtration plant (at a cost of $6 billion, with an estimated $300 million in annual operation costs) or demonstrate that it was committed to the protection of the Catskill-Delaware Watershed, a heavily forested region that supplies the vast majority of the city's water. NYC chose to meet its residents' needs via the latter, a nature-based solution.

Following negotiations with a broad array of stakeholders, in 1997 NYC signed an agreement to invest $1.5 billion over a decade in the protection, restoration, and local economy of the watershed. This included doubling the amount of protected land around the watershed's eight reservoirs and expanding the amount of watershed lands open to mixed use, including recreation, fishing, and hiking. NYC partnered with local organizations to ensure that agriculture, forestry, wastewater management, and development are implemented in ways that generate minimal erosion and pollution. Funding for this program came from bonds issued by NYC and additional taxes on residential water bills.

Sources: Summarized from Postel and Thompson (2005); a. Gartner et al. 2013.

BOX 15 | The Importance of Communications and Resident Engagement

To achieve their forest-related goals, city officials must be able to communicate effectively with city residents, political leadership, and other city departments. Investing in communications and resident engagement can help build support for forest-related policies at the ballot box, inspire volunteerism, persuade landowners to plant or maintain trees on private property, and elevate trees and forests as a city priority. The recommendations below draw from recent examples of successful communications and resident engagement strategies in cities that the authors have selected as scalable and applicable to other cities:

- **Cultivate champions and advocates to drive change and progress on urban green space.** Individuals in city agencies or local communities aligned with a given cause often drive change within their respective spheres and can be key for pushing forward new policies or actions to support forests. *Champions* are leaders within key decision-making bodies like government agencies and utilities who help partners navigate bureaucracy and gain necessary approvals of funding allocations, bond measures, and regulatory compliance. *Advocates* are leaders, often from community groups or nongovernmental organizations, who help form alliances among key stakeholders, lobby interest groups, measure public opinion, and garner public support. Both champions and advocates are critical for effective communications, both within city government and externally.
- **Articulate clear goals.** Concrete, measurable targets can serve as a powerful tool to communicate with both decision-makers and public audiences by defining what success looks like, offering a goal to rally around, and setting a baseline against which to measure progress (see the planning section for each forest level).
- **Educate urban communities about the value of trees and healthy forests.** Cities can use educational campaigns and calls to action to engage with residents and businesses to support urban forests. For example, Ontario created the Urban Forest Call to Action[a] and Toolkit,[b] and a new outreach campaign from Trees Atlanta,[c] "Learn. Do. Give.," educates residents about the benefits of trees to broaden support for the urban forest. At the faraway forest level, awareness campaigns for city residents and businesses could also focus on communicating the impact of deforestation-linked commodities on tropical forests and sustainable alternatives. For example, Oslo used a public awareness strategy on the links between palm oil and tropical deforestation to great effect, ultimately increasing consumer awareness and decreasing palm oil consumption in foods and goods (Case Study 8).
- **Engage youth through classroom education and field trips.** For example, Little Rock's drinking water utility, Central Arkansas Water,[d] engages younger generations by taking them on field tours of the forests that provision local drinking water and articulating the benefits of a healthy forested watershed for drinking water quality. It also hosts an annual "What Do You Know about H_20" public awareness event in which the utility gives out free water and educational information about its hybrid green-gray approach to drinking water treatment.[e]
- **Use storytelling and highly visible demonstration projects to garner local interest and support for faraway forest conservation and partnerships.** Faraway forests are the most geographically distant from cities, and their benefits and threats may be poorly understood by city residents. This does, however, present unique opportunities for creative communications campaigns and demonstration projects. For example, in 2020 the Brooklyn Bridge Forest project won the international Reimagining Brooklyn Bridge design competition to make the bridge safer, more accessible, and more sustainable. This proposal seeks to restore the bridge's pedestrian promenade with sustainably sourced tropical hardwood originating from a community-managed partner forest in Guatemala's Maya Biosphere Reserve. A key element of the project includes interpretive signs and cultural and educational programming linking New York City residents with Guatemala's Uaxactún community that can link people across geographic boundaries and help generate interest and empathy that supports environmental and cultural sustainability (Case Study 10).

Sources: Authors (based on a synthesis of best practices from discussions with cities and city-oriented nature-based solution projects); a. GIO 2015; b. GIO n.d.; c. Trees Atlanta n.d.; d, e. Central Arkansas Water n.d.

Measurement and monitoring: Faraway forests

- **Conduct a citywide analysis of consumption linked to tropical deforestation**. Cities consume a disproportionately large amount of the world's resources—they are where most of the world's population lives, and urban residents typically use more resources per capita than their national averages (Baabou et al. 2017). The Cities4Forests Forest Footprint[46] tool calculates a city's impact on tropical forests, and the GHG emissions associated with this deforestation (Cities4Forests n.d.b).

- **Identify local initiatives and attitudes towards promoting deforestation-free commodities.** Understanding local attitudes and behaviors related to tropical deforestation can be key to supporting political action. A poll may provide valuable insight for foregrounding action. For example, many cities polled resident opinions on climate change, but deforestation polls are uncommon. There are some national examples too: Brazil, France, and Indonesia have all undertaken surveys on attitudes towards deforestation (Copsey et al. 2013).

- **Articulate clear goals to guide action.** For example, *X* percent of tropical wood and forest-risk commodities will be sustainably procured by *Y* date. For instance, in 2004 the French national government committed that 50 percent of timber and wood products would be procured from sustainably managed and legal forests by 2007, with 100 percent procurement by 2010.

Planning: Faraway forests

- **Calculate and develop an action plan to reduce the consumption of forest-risk commodities and city-driven CO_2 emissions associated with deforestation.** Set goals for reducing deforestation and associated GHGs and track progress on reducing deforestation. For example, by using the Forest Footprint tool, Quito has identified the size of its forest impact and the key drivers of commodity consumption linked to tropical deforestation—most notably, beef. Quito's Environmental Secretariat adopted the tool in early 2020 and is currently exploring options for mitigative action. Quito is also working on integrating its Forest Footprint into its 2040 Climate Action Plan with the goal of integrating forest conservation and restoration to mitigate climate change.

Partnerships: Faraway forests

- **Establish a partner forest program.** A partner forest is a faraway (usually tropical) forest connected to a city through a mutually beneficial exchange. The city supports the partner forest by directing its purchasing power towards a product or service that the forest provides within a well-established forest conservation model (Case Study 10). The goal of the partner forest program is to visibly support a tropical forest that provides direct benefits to the city and raise awareness of those benefits among city residents (Cities4Forests n.d.c). Examples of possible connections include the following:
  - *Engage local businesses to import and market forest-positive goods* (such as coffee, timber, or chocolate) from the partner forest. For example, the Seattle Zoo is sourcing coffee from a partner forest in Papua New Guinea[47] that houses astounding biodiversity, including tree kangaroos (TKCP-PNG n.d.). Marketing this coffee in the city brings residents into the conservation story.
  - *Use products from the partner forest in city infrastructure*. For example, the Brooklyn Bridge Forest model for New York City would source wood for the pedestrian boardwalk from a community forest in Guatemala to support its forest conservation efforts (Case Study 10).
  - *Partner with a forest that has a direct link to migratory species,* such as birds or butterflies that are iconic and/or seasonally present in the city. For example, Toronto is exploring a coffee-sourcing relationship with the Birds and the Beans, a local roaster that sources only certified bird-friendly coffee. Beans sourced from Central America would help conserve forests where many North American birds overwinter.
  - *Partner with a forest in an area with cultural ties to the city*, such as a large immigrant community from Puerto Rico in New York City and the El Yunque National Forest in Puerto Rico.
  - *Create an educational exchange* involving a research center in the forest connected to a university situated in the city. For example, the United Kingdom's Sussex University has partnered with the Santa Lucia Cloud Forest reserve in Ecuador, sending classes of students each year to conduct research while providing financial support to the reserve (University of Sussex n.d.).
- **Establish relationships with organizations involved in forest conservation, restoration, and sustainable management** to help implement faraway forest programs (e.g., forest-friendly procurement; partner forest program). In particular, plan and implement faraway forest

activities with environmental organizations that work with Indigenous peoples and local communities with a good track record of sustainable forest management, conservation, and/or restoration. Be aware that the high costs of instruments, such as sustainability certifications, can be prohibitive for many local and Indigenous communities and small and medium enterprises, and that partner organizations can help to showcase their work and/or help to provide certification. For example, during the 1990s Starbucks joined forces with Conservation International to find a reliable and ethical source of coffee (Perez-Aleman and Sandilands 2008). Since then, Starbucks and the organization have codeveloped the Coffee and Farmer Equity Practices as a verification program to expand ethical and sustainable sourcing throughout Starbucks' supply chain (Vander Velde 2018).

- **Call on state and national governments and businesses and financiers to conserve, restore, and better manage tropical forests.** This could include advocating for the adoption of policies and commitments at both national (i.e., within the same country) and regional (i.e., between regions across one forest system) levels to restore forests and expand forest cover. For example, the Brazilian National Front of Mayors[48]—a network of mayors from Brazil's 400 largest cities—has raised the importance of forest conservation and restoration with the Brazilian government by effectively aggregating the voices of multiple mayors through one platform. In September 2021, more than 50 city mayors issued the Cities4Forests Call to Action on Forests and Climate,[49] urging national and subnational governments, companies, and financial institutions to urgently ramp up policies and investments to support forest conservation, restoration, and sustainable forest management (Anderson et al. 2021).
- **Incentivize the use of responsibly sourced products from forest-risk commodities** (produced or sold within the city) by working with local food producers and suppliers. For example, the UK city of Chester, led by the Chester Zoo and the local member of Parliament, worked to encourage local businesses to use and sell palm oil products certified by the Roundtable on Sustainable Palm Oil. This recently led to Chester being certified as the world's first sustainable palm oil city[50] (Chester Zoo 2019).

Finance: Faraway forests

- **Compensate for urban emissions by funding tropical forest conservation.** Cities will have difficulty reaching carbon neutrality by cutting emissions alone. Financing tropical forest conservation and restoration offer ways to compensate for remaining emissions (Case Study 8). A "climate co-op" could be created where cities purchase high-quality forest carbon credits via the voluntary carbon market to finance long-term forest conservation with associated carbon benefits. Communicating the carbon benefits of the co-op can incentivize local business participation (Box 16).
- **Match conservation and restoration efforts in the city with conservation in faraway forests.** Creating tangible connections between either inner or nearby and faraway forest conservation can build local awareness of how important it is to support faraway forests. For example, for every tree planted within the city, support parallel restoration efforts in a tropical forest by dedicating a percentage of funds to a suitable tropical forest conservation or restoration project. Use monitoring of this restoration as a way to maintain resident engagement and follow up (through social media, etc.). For example, the London Enfield Council woodland restoration in the United Kingdom partnered with urban reforestation in Port Moresby, the capital city of Papua New Guinea, where 50,000 trees are being planted. The idea was to diversify and expand the impact of local tree planting by linking it to tropical restoration, with associated awareness-raising opportunities in the United Kingdom.

Markets: Faraway forests

- **Establish ecotourism ventures** to conserve and sustainably manage forests threatened by competing land-use pressures. Cities can support the implementation of community owned and operated sustainable tourism programs (Fitzgerald n.d.) by promoting these among their residents to develop a steady clientele pipeline, thereby bolstering the efforts of regional governments and conservation organizations to boost local economies through job creation and increased investment while also preserving faraway forests for endangered species and important landscapes.

BOX 16 | A Climate Co-op for Cities to Fund a Partner Forest for Carbon Capture

Cities4Forests' experience with implementing partner forest programs shows that scope exists for cities to create voluntary forest carbon cooperative funds through which local businesses and residents can contribute to a well-established partner tropical forest conservation program.[a] Contributors could take advantage of positive brand messaging and publicity, and cities could increase their status as climate and conservation leaders. Existing corporate social responsibility budgets would be the first source of funds. The advantages of such programs include the economy of scale to attain higher quality carbon impact per dollar, compared to one-off tree planting programs, better oversight and long-term relationship-building between city and partner forest, and investment in programs that are both scalable and long term, providing many other benefits to cities. Such programs would provide business participants with simple carbon audit tools for self-assessment of their emissions and a framework for voluntary contribution based on levels.

Source: a. Cities4Forests n.d.c.

- **Initiate tropical forest-positive procurement policies and campaigns.** Cities can implement policies that discourage the purchase of commodities implicated in deforestation and provide incentives for purchasing better-sourced commodities or alternatives with lower tropical forest impacts. Tropical timber, coffee, and chocolate are commodities that are especially amenable to this approach (Hylander and Nemomissa 2009; De Beenhouwer et al. 2013; Böhnert et al. 2016). Palm oil, beef, and soy are also good candidates for campaigns (Case Study 8). Promoting awareness of deforestation and changing urban consumption behavior and culture is a first step that cities can take towards these goals. The World Wide Fund for Nature's Earth Hour City Challenge, in which cities can report actions, data, and "wins" to reduce carbon emissions via a carbon reporting platform for cities, is one example of the impact that cities working together can have even through small reductions to city footprints (WWF 2016).
- These are a few specific ideas for procurement innovation:
    - *Make municipal procurement policies forest friendly.* When the city government purchases supplies for its own use—construction, office supplies, food, and so forth—it can source sustainably and track the deforestation impact as a way to showcase impact and engage residents. High impact, visible commodities to start with include wood and coffee (Case Study 10).
    - *Commit to deforestation-free products.* Increased demand by cities for sustainably sourced forest products can support the sustainable use of forest lands and drive increased transparency in public and private sector supply chains. For instance, McDonald's has committed to eliminating deforestation within its supply chains by 2030 using its power of procurement to increase sustainable practices on the ground and avoid purchasing fiber from deforestation areas (McDonald's 2022).
    - *Boost "creative class" innovation on supply chain reform.* Incentivize and support local businesses and entrepreneurs to innovate on forest-positive sourcing/supply chains. Support could come as grants, tax breaks, and in-kind support such as incubator hubs or consulting services from local NGOs.
        - Tap into or create municipal innovation funds to support novel business ideas for pressing challenges, such as New York City's Social Innovation Fund.[51]
        - Apply for innovation funds from national-level grants. For example, the Carbon Neutral Cities Alliance Innovation Fund has provided $2.4 million to 27 city-led early-stage innovation projects since 2015. The fund focuses on decarbonization and has supported recent projects in Rio de Janeiro, Sydney, and Yokohama (CNCA n.d.).

CASE STUDY 10 | Partner Forest Design Concept: Brooklyn Bridge Forest

In 2020, the New York City Council and the Van Allen Institute hosted the Reimagining Brooklyn Bridge competition to foster design ideas that rethink the iconic bridge. The winning design, "Brooklyn Bridge Forest," incorporated elements linking both inner and faraway forests.

The much-loved wooden pedestrian boardwalk of the historic Brooklyn Bridge Promenade in New York City needs to be upgraded and is approaching its next replacement cycle. Wood is an integral part of the Brooklyn Bridge experience, and tropical hardwood has historically been used for its strength and durability.

Tropical hardwood is often obtained in ways that damage rain forests and local cultures. Extracting timber can degrade forests and often precedes further clearing for agriculture. On the other hand, carefully managed timber harvesting can be a force for conservation, providing an economic incentive to keep the forest standing instead of converting it to cropland or cattle pasture. When tropical forest communities can make a living from the forest without removing it, they become forest protectors who often outperform national parks.[a]

The Brooklyn Bridge Forest design would place New York City as a leader in protecting forests by using timber sourced from a Forest Stewardship Council–certified "partner forest" in the tropics. Choosing sustainably sourced timber would help to address the root causes of deforestation by supporting local communities that have chosen to safeguard tropical forests. Specifically, the design proposes that the 11,000 new planks for the Brooklyn Bridge be provided through a partnership with the Guatemalan community of Uaxactun, who protect approximately 80,937 hectares of rain forest. Their low-intensity harvest model—(one tree per 0.4 hectares every 40 years)—has provided income to the community while keeping the rate of deforestation nearly at zero for over 25 years—a unique success in a region where deforestation is rampant.

A dedicated Brooklyn Bridge Forest would be endowed by sponsors for each of the 11,000 planks. The dedicated forest would ensure that the promenade boardwalk has the wood it needs for centuries to come, support the partner community economically, and provide the global environment with a new and powerful ally: the people of New York and the friends of the Brooklyn Bridge.

Note: To learn more about the Brooklyn Bridge Forest, see https://www.brooklynbridgeforest.com.

Source: a. Bray and Velazquez 2009.

CONCLUDING THOUGHTS

The recommendations above represent an investment in forests with returns for cities and their residents that are compounded as trees and forests grow. Engaging with all three levels of forest is key to the sustainable future of cities—each provides unique and essential services to city residents. Some forest benefits are more tangible and immediate—and can be increased directly through action within city boundaries. But cities also depend on forests everywhere, and some of the biggest gains for cities can be had by conserving forests outside their boundaries. Tropical forests are both highly threatened and provide benefits that are essential to all city residents, especially those in marginalized communities. These include maintaining rainfall in many cities and the agricultural regions that feed cities, mitigating climate change, and potentially even helping to prevent future pandemics. Global actions to conserve tropical forests have been insufficient. It is clear that additional action is required, and cities are well poised to quickly rally support and influence consumption patterns.

There is no time to waste. As the well-known proverb says, "The best time to plant a tree was 20 years ago. The second-best time is now." City actions towards improving the livability of cities, helping to mitigate climate change, and improving and sustaining water resources are pressing, and traditional gray infrastructure approaches are falling short. With proper attention and care, the services forests provide can increase over time. Because of this, they can provide a cost-effective way to address many city needs. Unlike traditional infrastructure, forests provide multiple services at once, and they accrue more value over time as trees mature and ecosystem services return. To make the most of the many benefits that forests can offer, the time to act is now.

Appendices

APPENDIX A: RESEARCH METHODOLOGY

The *Better Forests, Better Cities* publication reviewed the latest research on the effects of forests at three levels (inner, nearby, and faraway) on cities and their residents. The report summarizes the findings of research gathered through a series of systematic "reviews of reviews" (surveys of published review papers; e.g., van den Bosch and Sang [2017]) and scoping literature reviews complemented by "snowballing" (reviewing reference lists and/or expert recommendation), reviews of the primary literature, and literature recommended by topical experts, conducted for each of the four main sections: health and well-being, water, climate, and biodiversity.

The body of relevant work in each of these section topics spans multiple decades and encompasses an array of disciplines. Many topics were thus well suited to using the "review of reviews" method, which we found by developing a list of key search terms and performing a series of searches in scholarly databases (see individual sections for details). Throughout the publication, the formal review process was supplemented with primary literature, reports and gray literature, consultations with and recommendations from topical experts (see details of people consulted for each section below), and from the amassed experience of WRI and Pilot Projects in implementing various city-related projects (including Cities4Forests; UrbanShift;[52] Wood at Work;[53] Urban Water Resilience Initiative;[54] the Global Commission on Adaptation,[55] specifically the cities and NBS tracks; Brooklyn Bridge Forest;[56] and various other projects through WRI's Ross Center for Sustainable Cities,[57] Water Program,[58] and Forests Program[59]) and their discussions and engagements with city representatives over the years. These findings have been used in the report as brief in-text illustrations and in-depth case studies to exemplify forest-related ecosystem services and their nuances, highlight success stories, portray other important ideas, and fill gaps in knowledge where insufficient reviews were available. Drafts of each section were also reviewed by experts in the respective fields prior to the formal review process.

Health and Well-Being

To equip urban leaders with an overview of the immense array of information connecting forests to human health and well-being, we conducted a systematic review of reviews—including peer-reviewed syntheses, meta-analyses, and summary reports in gray literature—identified using multiple databases. We supplemented our findings with empirical research from individual cities to provide additional context and geographic representation. Because human health and well-being research that focuses specifically on forests remains limited, we broadened our scope from urban forests and trees to include urban green space, green infrastructure, and urban nature in some portions of this section to provide a more comprehensive overview where forest-specific science was lacking; this shift in emphasis is indicated in the corresponding report text when applicable.

We began by conducting a systematic literature review of existing review papers, including other literature reviews, meta-analyses, and gray literature, later supplemented with additional information from primary sources.

We began a systematic literature review by identifying relevant search terms and seminal works in consultation with topic experts, including Dr. Kathleen Wolf[60] and Dr. Dexter Locke.[61]

After the initial list was created, exploration of existing reviews and reviews of reviews led to the addition of many terms. The search terms were designed to identify review papers that explored forests, urban areas, and at least one issue of social, physical, mental, or economic health and well-being simultaneously (Box A1).

BOX A1 | Search Terms For Health and Well-Being

((agroforest* OR "ecosystem services" OR forest* OR greenspace* OR "nature-based solution*" OR "natural infrastructure" OR tree* OR woodland*) AND ("meta analysis" OR review* OR meta-analysis OR meta-synthesis OR synthesis OR synopsis) AND (city OR cities OR metropolitan OR metro OR urban OR peri-urban OR sprawl) AND (adiposity OR allerg* OR anxiety OR asthma OR "attention restoration" OR attention-deficit OR birth weight OR "blood pressure" OR BMI OR cancer OR cardiovascular OR Child* OR cognitive OR cortisol OR diabetes OR depression OR disease OR disorder OR elderly OR epidemiology OR exercise OR health OR healing OR immune OR immunolog* OR inflammat* OR infant OR mental OR Microbiome OR mindfulness OR Morbidity OR Mortality OR noise OR nutrition OR obesity OR perception OR "physical activity" OR physiological OR prescription OR psycholog* OR public OR PTSD OR "quality of life" OR recreation OR respiratory OR restor* OR risk OR sedentary OR sleep OR sound OR Stress OR "UV radiation" OR vector OR well-being OR wellbeing OR wellness OR youth OR academic OR access OR activity OR aggression OR cohesion OR community OR creativity OR crime OR cultur* OR disparit* OR ethnicity OR equity OR "food security" OR forag* OR fuelwood OR gentrification OR "green streets" OR inequalit* OR "land tenure" OR neighborhood OR race OR recreation OR "soil remediation" OR residential OR resilienc* OR safety OR school* OR social OR societ* OR stewardship OR vacant OR value OR visibility OR walkability OR cooling OR "heat island*" OR heat* OR irradiation OR microclimate OR refuge OR shade OR temperature OR thermal OR UV OR wind OR air OR allergen* OR BVOC OR "carbon monoxide" OR contamin* OR CO OR "Nitrogen Oxide" OR NOx OR ozone OR O3 OR particulate* OR pollen OR pollut* OR smog OR SO2 OR "sulfur dioxide" OR VOC* OR "Volatile Organic Compound*"))

Using a systematic review of three databases (Scopus, Web of Science, and PubMed), as well as Google Scholar, we identified peer-reviewed literature and other publications (e.g., book chapters and summary reports). The first phase of the systematic search returned 1,953 results, supplemented by the first 200 results from two Google Scholar searches (for a total of 2,353). During the first phase, we scanned titles and abstracts to determine relevance. During the second phase, following removal of duplicates, 384 full texts were reviewed. A small number of publications could not be accessed and were thus excluded. A total of 146 peer-reviewed articles, book chapters, and reports met inclusion criteria (i.e., written in English; needed to be a systematic review, meta-analysis, or narrative review; addressed one of the main research questions). In addition to the results of the systematic review, 36 publications identified by snowballing were included. Thus, in total, 182 texts were initially reviewed in full for inclusion in this publication. The returned documents represented a broad variety of disciplines, including urban forestry, landscape planning, environmental health, epidemiology, psychology, and political ecology.

In areas of interest where few or no review articles exist, we consulted relevant empirical studies in the primary literature (nonreview papers), identified via scholarly databases, review of reference lists, and additional recommendations from internal and external experts, including Elleni Ashebir,[62] Dr. Beatriz Cardenas,[63] Dr. Jessica Seddon,[64] Dr. Theodore Eisenman,[65] Dr. Viniece Jennings,[66] Dr. Nick Hewitt,[67] and Dr. David Rojas-Rueda.[68]

As a relatively young field, few studies on the specific health benefits of urban forests exist. Many of the reviews we identified referenced the same seminal studies (e.g., Ulrich 1984 or Kuo 2003). Similarly, many narrowly focused review articles (e.g., reviews of forest bathing) survey and dissect the same small body of literature. Aware of this potential for bias, we consciously sought to minimize repetition of these findings in our report.

To understand potential biases in the research of the 182 texts identified in the original systematic review, we recorded the location of the organization with which the first author of a publication was affiliated. Most of the first authors on the publications originated from North America, Europe, and Australia (Figure A1), which reflects the general pattern of urban ecosystem service research originating primarily in the global North (Haase et al. 2014).

Water

To understand the connections between forests, cities, and their water supplies, we first conducted a scoping review of reviews, later supplemented with findings from empirical studies and reports. A comprehensive discussion of the vast literature on the relationship between forests and hydrological cycles (e.g., Guswa et al. 2020) at local and global scales is beyond the scope of this publication. Instead, we provide an overview of key points of interest for cities, including the effects of urban forests on stormwater and flooding, the importance of forests in maintaining healthy watersheds, and the emerging research on the global interconnections between large, intact forests and water.

As with the health and well-being section, to identify relevant search terms for our scoping review, we consulted experts at WRI (Suzanne Ozment,[69] Todd Gartner,[70] Paige Langer,[71] and Sara Walker[72]) and Conservation International (Aarin Gross[73] and Robin Abell[74]). The initial list was created by combining forest terms, review terms, city terms, and water terms (such as stormwater, drought, flood, and water quality; Box A2). The results from the initial searches using forest terms, review terms, and city terms were complemented by relevant papers that had been identified to inform the broader literature search and from the suggestions of topical experts from WRI and other organizations. As with the health and well-being section, review of primary literature was used as necessary to supplement and illustrate trends, generalizations, and caveats and considerations.

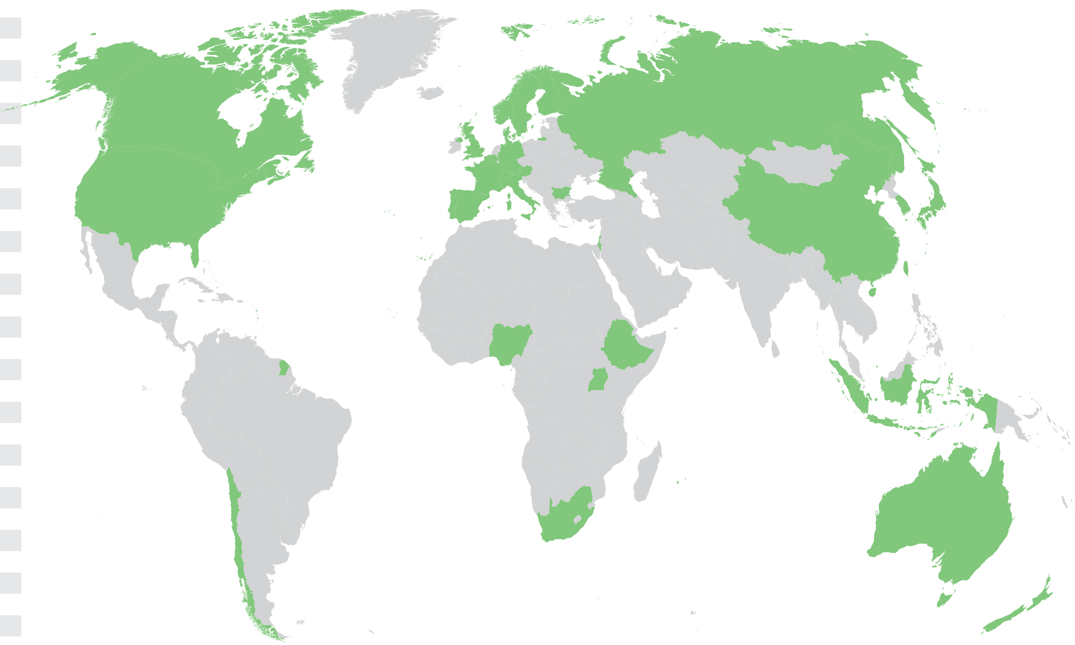
Climate

To explore the connection between climate change mitigation and forests, we conducted two reviews for the climate section: a systematic review of reviews on forests outside cities and a review of reviews and empirical studies on forests inside cities, as the latter is an emerging field with few reviews available.

To identify relevant search terms, we consulted experts within WRI (Frances Seymour,[75] David Gibbs,[76] Nancy Harris,[77] Alexander Rudee[78]) and externally (David Nowak[79]). The initial list combined forest terms, review terms, and carbon and climate terms (Box A3). A secondary search using forest terms, review terms, and city terms yielded few results and encouraged researchers to pursue a different methodology to assess the role of forests inside cities on climate mitigation.

FIGURE A1 | Geographic Locations of Primary Authors of Publications Reviewed During the Original Systematic Review (according to Institutional Affiliation)

Australia	12
Austria	1
Belgium	2
Bulgaria	2
Canada	6
Chile	1
China	5
Denmark	2
Ethiopia	1
Finland	4
France	2
Germany	7
Germany	6
Hong Kong	2
Indonesia	1
Israel	1
Italy	9
Japan	2
New Zealand	1
Nigeria	1
Norway	1
Portugal	1
Russia	1
Singapore	1
South Africa	4
South Korea	2
Spain	12
Sweden	7
Switzerland	1
The Netherlands	4
Uganda	1
United Kingdom	26
United States of America	53
Total	**182**



Source: Authors. Adapted from Haase et al. (2014).

BOX A2 | Search Terms for Water

(Forest* Plantation* "ecosystem service*" "urban forest*" "Street tree*" agroforest* reforest* "tree plant*" mangrove* bamboo silvicult* "natural regenerat*" Bioswale* "green infrastructure" "natural infrastructure" Arboriculture "green space" "Riparian Vegetat*" Afforest* woodland* "filter strip*" "forest buffer*" "green roo*" "rain garden*" "natural capital" "nature based solutions" "nature-based solutions" "ecosystem-based adaptation" "ecosystem based adaptation" **AND** "flying river*" *hydrolog* *transpiration evapo* hydroclimat* Precipit* moisture "cloud forest*" vapor* rain* Stormwater Flood* *filtrat* filter* Regulat* Recharge Erosion Pollut* Flow* Runoff Sewage Drainage Rainwater Throughfall "Surface water" "ground water" "groundwater" Interflow Intercept* Catchment* Canopy Mitigat* Permeab* stemflow uptake "coastal flood*" Drought River* Lake* Streamflow Discharge "water yield*" "water quantity*" Wetland* stream* Watershed* "water scarce*" "water suppl*" provis* "blue water" "green water" "water resource" "water security" "water availability" "water storage" "water balance" "water table" "water production" aquifer "aquifer recharge" hydroelectric* hydropower "water quality" Nutrient* Freshwater Sediment* Nonpoint purifi* nitr* phosph* eutrophic* leach* siltation "water temperature" "stream temperature" "bioindicators" spawn* "fish habitat" "indicator species" "invertebrate*" "EPT index" flyfish* **AND** "meta analysis" Review* Meta-analys* Meta-synthes* Review Synthesis Synopsis "systematic review*" "weight of evidence" "evidence map" **AND** Cit* Urban Metropolitan Peri-urban Sprawl)

We tested the initial list of search terms for forests outside cities on Scopus and Web of Science. Similar to the health and well-being search, we simplified the forest terms, removing references to "ecosystem services" and "nature-based solutions" that greatly increased the number of reviews and were not as directly focused on trees or forests.

For forests outside cities, we conducted a systematic review of reviews on the Web of Science and Scopus databases as well as Google Scholar to identify peer-reviewed literature and other publications relevant to our research topic. The search returned 1,123 results from Web of Science and 854 from Scopus, in addition to the first 100 results from two Google Scholar searches (for a total of 2,177). During the first phase, we scanned titles and abstracts to determine relevance. During the second phase, following removal of duplicates and inclusion of snowballed articles, 410 full texts were flagged for review. A total of 27 peer-reviewed articles, book chapters, and reports met inclusion criteria (i.e., written in English; needed to be a systematic review, meta-analysis, or narrative review; addressed one of the main research questions). We then supplemented our review of these findings with additional recommendations from other colleagues and experts.

For forests inside cities, we conducted a scoping literature review of studies related to forest carbon storage and cooling benefits. Because carbon storage, carbon sequestration, and cooling/avoided emissions are typically classified as ecosystem services, many studies relevant to this section had already been identified in the systematic review conducted for the health and well-being section. We drew from these works and supplemented with additional exploration of the primary literature and of existing reviews.

To provide a comparison of urban forest carbon density per hectare with that of forests outside cities, we used data from seven peer-reviewed publications that were identified in our reviews on carbon storage inside cities that cover a range of climates and geographies. Six of the peer-reviewed studies provided citywide averages (Intasen et al. 2016; Moussa et al. 2019; Speak et al. 2020), and one study provided a national average for the United States (Nowak et al. 2013). (The researchers did not include data from Kumasi, Ghana, where the citywide average was 228 tC per ha, as this data point was considered to be an outlier; see Nero et al. [2018]). These data points for forests inside cities were compared to averages of carbon density in temperate, tropical, and boreal forests outside of cities, using ranges estimated from Pan et al. (2011) and Goldstein et al. (2020).

BOX A3 | Search Terms for Carbon Storage in Forests outside Cities

((forest* OR "tree plantation" OR "timber plantation" OR "monoculture forest*" OR "urban forest*" OR "street tree*" OR agroforest* OR reforest* OR "tree plant*" OR afforest* OR woodland*) AND ("meta analysis" OR meta-analys* OR "evidence synthesis" OR "synthesis of evidence" OR "literature synthesis" OR "synthesis of literature" OR synopsis OR "evidence review" OR "literature review" OR "review of literature" OR "systematic review*" OR "evidence map" OR "review of evidence") AND (carbon OR CO_2 OR biomass OR "greenhouse gas*" OR GHG* OR sequester* OR sequestr* OR REDD*))

Google Scholar search for top 100 articles for both:

- "review tree forest carbon"
- "meta-analysis tree forest carbon"

Biodiversity

To understand the connections between forests, cities, and city water supplies, we conducted a review of the ways that forests at all levels may support biodiversity using an initial list of search terms (Box A4). Each subtopic covered an extensive body of literature, and so by necessity a more general literature review approach was employed rather than a more systematic review of reviews.

Biodiversity often appeared in the searches for the preceding three sections (for example, 56 articles returned for the health and well-being search address some aspect of biodiversity). These papers were reviewed and summarized in the biodiversity section. Additional subtopics of interest identified by the authors through previous experience working with cities and research from preceding sections were covered via a scoping "review of reviews" search, and cases and empirical work were included to fill gaps or to develop fields of research where few or no review papers had been published. Several important sources were found through references from other papers or reviews and experts (Robin Chazdon[80] and Patricia Balvanera[81]) were consulted regarding seminal works on many of the topics.

BOX A4 | General Search Terms for Biodiversity

("Biodiversity", "global biodiversity", "review", "meta analysis", "forests", (urban OR city), (species OR species richness OR diversity) combined with specific terms including: measuring, resilience, function, ecosystem services, carbon, carbon storage, carbon sequestration, invasive species, endemic species, generalist species, health, benefits, well-being, mental health, medicin*, pharmaceutical, pollination, pollinator*, global food production, urban agriculture, peri-urban agriculture, zoonotic disease, pandemic, urban forests)

Case studies on urban forest biodiversity were chosen based on preexisting knowledge of world-renowned urban forests and availability of information. To compare biodiversity in urban areas with areas outside cities, areas outside of the urban bounds were chosen based upon availability of data, proximity to the urban area (to maintain similarity of biome), and size (as close to urban forest area as possible). Specific searches were conducted to provide comparable species richness information for forested areas inside and outside of cities, and sources included peer-reviewed journal articles, gray literature, species lists reported by government or park web resources, and publicly available databases.

Recommendations for Policy and Action

Our recommendations in this section are derived in equal part from direct and indirect suggestions made by authors of the articles reviewed for the four main sections, and from engagements with city representatives (through project implementation, at conferences and during workshops, and through formal and informal discussions) and the experience that the Cities4Forests team has accumulated over the years from implementing forest-related projects with cities, including through the development of our Cities4Forests Toolbox[82] and two learning guides focused on decision-makers, "Urban Forests for Healthier Cities: Policy, Planning, Regulations, and Institutional Arrangements" (Juno and Virsilas 2019) and "Social Equity Considerations for Cities' Decision Making Related to Inner, Nearby, and Faraway Forests" (Trivedi et al. 2020), which represent the culmination of additional research on existing urban forest policy environments and consultation with experts and practitioners. We also relied on the experience of a team of colleagues who work on issues related to forests in cities, namely Todd Gartner, Terra Virsilas,[83] Lisa Beyer,[84] James Anderson,[85] Lizzie Marsters,[86] Suzanne Ozment, Ayushi Trivedi,[87] Natalie Elwell,[88] and Frances Seymour, to develop recommendations and general guidance based on best practices and lessons learned.

Recommendations were developed for several areas of policy and action, including measuring and monitoring, planning, partnerships, finance, and markets. For each forest level, we developed recommendations under each type of recommendation (for example, we outlined specific actions that cities could take to identify financing opportunities for inner forest initiatives). Communication was included as a cross-cutting theme for all forest levels.

Gaps and Limitations of the Methodology

The body of evidence exploring the roles that forests inside and outside of cities play in supporting our four topic areas of focus is expansive and rapidly growing. As a result, our reviews may not reflect some of the most recent developments in these areas. Language barriers and publishing biases may have also presented geographical bias in the reviews. To attempt to remedy this issue, we specifically sought to include findings from primary literature and highlight case studies from under-represented areas in the supplemental stages of our reviews.

Despite these limitations, we believe these reviews provide policymakers; city leaders; practitioners from civil society, community-based, and nonprofit organizations that work hand in hand with cities; and researchers with a broad, interdisciplinary overview of current research connecting forests and trees to the health and well-being of city residents and to cities' goals related to water, climate change mitigation, and biodiversity preservation.

ABBREVIATIONS

AFR100	African Forest Landscape Restoration Initiative
bVOC	biogenic volatile organic compound
C	carbon
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
FONAG	Fondos de Agua (Fund for the Protection of Water)
FRB	Forest Resilience Bond
GGA	Green-Gray Assessment
GHG	greenhouse gas
Gt	metric gigaton
InVEST	Integrated Valuation of Ecosystem Services and Tradeoffs
IPCC	Intergovernmental Panel on Climate Change
Mt	million metric tons
NBS	nature-based solutions
NGO	nongovernmental organization
NYC	New York City
PES	payment for ecosystem services
PM	particulate matter
PWD	Philadelphia Water Department
REDD+	reducing emissions through deforestation and degradation, plus the sustainable management of forests and the conservation and enhancement of forest carbon stocks
t	metric ton

ENDNOTES

1. Nature-based solutions are defined as actions to protect, sustainably manage, and restore natural and modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits (IUCN n.d.)

2. Flooding data are from Aqueduct Floods (database), World Resources Institute, https://www.wri.org/applications/aqueduct/floods/.

3. For more information, see i-Tree Eco, https://www.itreetools.org/tools/i-tree-eco.

4. See the Natural Areas Conservancy, https://naturalareasnyc.org/.

5. See WRI (n.d.b).

6. See the Forests to Faucets initiative, https://cfri.colostate.edu/projects/forests-to-faucets/.

7. The Green-Gray Assessment (GGA) method of World Resources Institute (WRI) allows stakeholders to value the costs and benefits of integrating green or natural infrastructure into water supply systems to improve performance. It has been applied by WRI in multiple watershed systems in the United States, Mexico, Brazil, and Colombia (see Gray et al. 2019).

8. See the Forest Carbon Program, https://kingcounty.gov/services/environment/water-and-land/forestry/forest-carbon.aspx.

9. Read more about the Cities4Forests Forest Footprint tool here: https://cities4forests.com/forest-footprint/.

10. Read more about the Cities4Forests Partner Forest Program here: https://www.partnerforests.org/.

11. Nature-based solutions are defined as actions to protect, sustainably manage, and restore natural and modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits (IUCN n.d.).

12. These four benefits were chosen because they reflect key issues on the agendas of many cities and can be directly improved by supporting forest health, conservation, and restoration.

13. For more information about Cities4Forests, see https://www.wri.org/our-work/project/cities4forests.

14. Note that deforestation and forest loss are distinct. Deforestation implies a conversion from forest to nonforest use, such as when forest is cleared for agriculture. Forest loss could be deforestation, but it could also be followed by regrowth—for example, when a forest regrows after a wildfire (Curtis et al. 2018; FAO 2020). See Pearce (2018) for more information on conflicting forest loss data.

15. Based on unpublished data by S. Francisco.

16. These challenges were noted as being on the agendas of many cities based on interviews with cities in the Cities4Forests network as well as multiple conversations with city representatives at various conferences, including the ICLEI World Congress (Montreal, 2018) and the Urban Future Global Conference (Oslo, 2018).

17. For more information about the Tree Equity Score, see https://treeequityscore.org/.

18. Most research has examined the effects of planting non-native species and reports data on only 10 years or fewer of the effects on hydrology—and over longer periods of time, initial decreases in water yield tend to become smaller (Filoso et al. 2017). Few studies have been conducted on the effects of afforestation and reforestation in large watersheds, and those that have reported conflicting results (Zhang et al. 2017). Furthermore, hydrological cycles are complex, influenced by a variety of factors including local geology, scale of restoration, local climate, and more (Filoso et al. 2017). More research is needed to understand the effects of afforestation and reforestation in various climates, in highly degraded lands, with various introduced and native forest species, and over multidecadal time scales and various spatial scales (van Dijk and Keenan 2007; Ellison et al. 2017; Jones et al. 2020).

19. For more information about the Bonn Challenge, see https://www.bonnchallenge.org/.

20. For more information about Initiative 20x20, see https://initiative20x20.org/.

21. To learn more about AFR100, see https://afr100.org/.

22. To learn more about ECCA30, see https://infoflr.org/bonn-challenge/regional-initiatives/ecca30.

23. For more information about Trillion Trees, see https://trilliontrees.org/.

24. For more information about MillionTreesNYC, see https://www.milliontreesnyc.org/.

25. Calculated with a social cost of carbon valued at $129.80/tC in 2011$.

26. Boreal forests are also extremely important carbon stocks, perhaps storing between 370 and 1,700 GtC, with large portions of this carbon locked in their soil (Bradshaw and Warkentin 2015). In this report, however, we primarily focus on tropical forests because they are currently experiencing greater deforestation pressure related to commodity production. However, we note that boreal forests are also in danger of transitioning from carbon sink to carbon source (Bradshaw and Warkentin 2015). Wildfires and forestry are the key drivers of boreal forest loss (Curtis et al. 2018).

27. Data in this section are from Climate Watch (database), https://www.climatewatchdata.org.

28. Estimates vary widely in part due to the uncertainty of how many species are on Earth, ranging from 3 million to 100 million; most recent estimates are around 8 million (May 2010; Mora et al. 2011; IPBES 2019; FAO 2020).

29. We conducted a scan of published and gray literature as well as city policy documents and webpages to find municipal policies that support forest conservation via sustainable procurement of forest or "deforestation" commodities (soy, beef, palm oil, and so on) or otherwise.

30. It is estimated that this could be increased to about 5 percent if all available urban land were used with intensive production practices.

31. Urban croplands were determined using a spatial overlay analysis and were defined as areas that were both part of an urban extent (areas with a population greater than 50,000 people) and under crop cultivation.

32. This result was developed using "dependence ratios towards pollinators given by a recent review (Klein et al. 2007) and the production value of the most important crops directly used for human food. It measures the part of the gross value of the world food production attributable to insect pollination and can therefore be considered as a conservative assessment of the gross value of the insect pollination service" (Gallai et al. 2009, 816).

33. Cities with populations greater than 300,000 people.

34. Note that the wide range in this estimate is due to the fact that global species estimates are uncertain, but all estimates fall well above 50 percent.

35. Each hot spot has at least 1,500 endemic plant species and has lost at least 70 percent of its original habitat.

36. Read more about Skopje's Green Cadastre here: https://www.undp.org/north-macedonia/projects/resilient-skopje-scaling-sustainability-innovation-and-climate-change.

37. For more information, see i-Tree Eco, https://www.itreetools.org/tools/i-tree-eco.

38. The Cities4Forests Toolbox is a collection of practical tools from around the world to help cities include forests, trees, and green infrastructure in their decision-making, planning, and investments. The tools cover a range of topics, from valuing trees and forests to maximizing key benefits—such as biodiversity, health, water, and carbon—and planning and managing forest-related projects inside and outside their boundaries. To learn more, see https://www.wri.org/our-work/project/cities4forests/cities4forests-toolbox.

39. To learn more about Trees for Life: Master Plan for Barcelona's Trees, see https://ajuntament.barcelona.cat/ecologiaurbana/sites/default/files/Pla-director-arbrat-barcelona-ENG.pdf.

40. For more information about Vancouver's Greenest City 2020 Action Plan, see https://vancouver.ca/files/cov/Greenest-city-action-plan.pdf.

41. To learn more about Sydney's Turn Down the Heat: Strategy and Action Plan, see https://ghhin.org/wp-content/uploads/Western-Sydney-Turn-Down-the-Heat-Strategy-and-Action-Plan-2018-1.pdf.

42. For more information about the Natural Areas Conservancy, see https://naturalareasnyc.org/.

43. See WRI (n.d.b).

44. For more information on Global Forest Watch, see https://www.globalforestwatch.org/.

45. For more about Forests to Faucets, see https://cfri.colostate.edu/projects/forests-to-faucets/.

46. To learn more about the Forest Footprint, see https://forest-footprint.org/.

47. To learn more about the Seattle Zoo's El Yunque National Forest partnership, see https://www.zoo.org/tkcp.

48. For more information about the National Front of Mayors, see https://fnp.org.br/.

49. To learn more about the Cities4Forests Call to Action on Forests and Climate, see https://www.wri.org/our-work/project/cities4forests/call-action.

50. For more information about the Chester Zoo, see https://www.chesterzoo.org/news/chester-named-worlds-first-sustainable-palm-oil-city-2/.

51. To learn more about the Social Innovation Fund, see https://www1.nyc.gov/site/opportunity/portfolio/social-innovation-fund-sif.page.

52. To learn more about UrbanShift, see https://www.shiftcities.org/.

53. For more information about Wood at Work, see https://www.woodatwork.ca/.

54. For more information about the Urban Water Resilience Initiative, see https://www.wri.org/initiatives/urban-water-resilience-africa.

55. To learn more about the Global Commission on Adaptation, see https://www.wri.org/initiatives/global-commission-adaptation.

56. To learn more about the Brooklyn Bridge Forest, see https://www.brooklynbridgeforest.com/.

57. For more information about WRI's Ross Center for Sustainable Cities, see https://wrirosscities.org/.

58. To learn more about WRI's Water Program, see https://www.wri.org/water.

59. To learn more about WRI's Forests Program, see https://www.wri.org/forests.

60. Dr. Kathleen Wolf is a Research Social Scientist in the School of Environmental and Forest Sciences at the University of Washington.

61. Dr. Dexter Locke is a Research Social Scientist with the U.S. Forest Service, Northern Research Station, Baltimore Field Station.

62. Elleni Ashebir was formerly the Program Manager for Cities and Urban Mobility at WRI Ross Center for Sustainable Cities, WRI Africa.

63. Dr. Beatriz Cardenas is the Air Quality Director at WRI Mexico.

64. Dr. Jessica Seddon is the Global Lead for Air Quality at WRI Ross Center for Sustainable Cities.

65. Dr. Theodore Eisenman is an Assistant Professor of Landscape Architecture at the University of Massachusetts, Amherst.

66. Dr. Viniece Jennings is an Assistant Professor at Agnes Scott College and a former Research Scientist with the U.S. Forest Service.

67. Dr. Nick Hewitt is a Distinguished Professor at the Lancaster Environment Centre at Lancaster University.

68. Dr. David Rojas-Rueda is an Assistant Professor at Colorado State University and a Researcher at the Barcelona Institute for Global Health.

69. Suzanne Ozment is a Senior Associate for Natural Infrastructure in WRI's Water Program.

70. Todd Gartner is the Director of Cities4Forests and Natural Infrastructure in WRI's Water Program.

71. Paige Langer is an Associate in WRI's Forests Program.

72. Sara Walker is the Director of Corporate Water Engagement in WRI's Water Program.

73. Aarin Gross is a Senior Program Manager for Conservation Policy & Incentives at Conservation International.

74. Robin Abell is the Freshwater Lead for the Global Strategy Group in the Moore Center for Science at Conservation International.

75. Frances Seymour is a Senior Fellow in WRI's Forests Program.

76. David Gibbs is a Geographic Information System Research Associate for Global Forest Watch in WRI's Forests Program.

77. Nancy Harris is the Research Director for Global Forest Watch in WRI's Forests Program.

78. Alexander Rudee was formerly the Manager of U.S. Natural Climate Solutions in WRI's Climate Program and is now the Senior Program Manager for Nature-based Solutions at Amazon.

79. David Nowak is a Senior Scientist and i-Tree Team Leader with the U.S. Forest Service.

80. Robin Chazdon is the Founder and Director of Forestoration International and Professor Emerita with the Department of Ecology and Evolution at the University of Connecticut.

81. Patricia Balvanera is a Professor at the Institute for Ecosystem and Sustainability Research at the Universidad Nacional Autónoma de México.

82. To learn more about the Cities4Forests Toolkit, see https://cities4forests.com/toolbox/.

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Natural resources are at the foundation of economic opportunity and human well-being. But today, we are depleting Earth's resources at rates that are not sustainable, endangering economies and people's lives. People depend on clean water, fertile land, healthy forests, and a stable climate. Livable cities and clean energy are essential for a sustainable planet. We must address these urgent, global challenges this decade.

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We envision an equitable and prosperous planet driven by the wise management of natural resources. We aspire to create a world where the actions of government, business, and communities combine to eliminate poverty and sustain the natural environment for all people.

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