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Carbon and Environmental Footprinting of Global Biofuel Production

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ABSTRACT

The carbon and environmental footprints associated with the global production of biofuels have been computed from a baseline of 2007-2009 out until 2019. Estimates of future global biofuel production were adopted from OECD-FAO and related projections. In order to determine the footprints associated with these (essentially ‘*first generation*’) biofuel resources, the overall environmental footprint was disaggregated into bioproductive land, built land, carbon, embodied energy, materials and waste, transport, and water components. The global carbon footprint of biofuels was estimated to be 0.248 billion (bn) global hectares (gha) in 2010; arising to 0.449 bn gha by 2019. The total environmental footprint for the global production of biofuels was estimated to be 0.720 billion gha for 2010; rising to 1.242 bn gha by 2019. Bioproductive land use proved to give rise to the highest element of the footprint, with the ‘carbon footprint’ as the next highest, followed by the water footprint, and then the transport component. The waste, built land, and embodied energy components contributed an insignificant amount to the total environmental footprint.

KEYWORDS: biofuels, carbon footprints, environmental footprints, global biofuel production, sustainability

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1. INTRODUCTION

1.1 Background

Humans were almost wholly dependent on finite fossil and nuclear fuels for energy resources at the turn of the Millennium; amounting to about 77% and 7% of global primary energy needs respectively [1]. ‘Traditional’ renewable energy sources, such as burning fuelwood and dung or using water and windmills, accounted for 11% of these worldwide requirements. Large-scale hydroelectric power contributed 3%, and other renewables (including modern wind turbines and liquid biofuels) contributed just 2%. Sustainable development in a strict sense requires a reversal of these roles, but it is unlikely that renewable energy technologies could meet a high proportion of industrial countries’ energy demand before at least the middle of the 21st Century. This is partly due to the conflict between the needs of environmental sustainability and the downward economic pressures on energy prices arising from moves towards energy market liberalisation in the industrialised world; even in the European Union (EU) that has had a long-term policy of encouraging modern renewables. But the EU target of 20% renewables use by the year 2020 (with 10% of ‘green fuels’, principally biofuels, for transport) is seen by many analysts as being over ambitious. Although renewable energy technologies are growing across much of Europe, they have not played a dominant role in achieving the ‘greenhouse gas’ (GHG) mitigation target of 8% reduction against a base year of 1990 by 2008-2012 agreed under the Kyoto Protocol. This is an international agreement linked to the United Nations Framework Convention on Climate Change (UNFCCC) and adopted at the third UNFCCC Conference of the Parties (COP) in Kyoto (Japan) on 11 December 1997. The major feature of the Kyoto Protocol is that it sets binding targets for 37 industrialized countries and the EU (of originally 15 countries, i.e., the EU-15) for reducing GHG emissions. These targets cover emissions of the six main GHGs, namely: carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs); and sulphur hexafluoride (SF₆). Here the quantity of GHG emissions is measured in terms of the CO₂ equivalent (CO_{2e}). They amounted to an average of around 5% compared to 1990 (the base line) levels by 2008-2012.

Human activities have led to quite dramatic increases since 1950 in the ‘basket’ of GHGs incorporated in the Kyoto Protocol; concentrations have risen from 330 ppm to about 430 ppm currently [2]. Prior to the first industrial revolution in the 18th Century the atmospheric concentration of ‘Kyoto gases’ was only some 270 ppm. The cause of the observed rise in

global average near-surface temperatures over the second half of the 20th Century has been a matter of dispute and controversy. But the most recent (2007) scientific assessment by the Intergovernmental Panel on Climate Change (IPCC) [2] states with ‘very high confidence’ that humans are having a significant impact on the global warming. They argue that GHG emissions from human activities trap long-wave thermal radiation from the Earth’s surface in the atmosphere (not strictly ‘greenhouse’ phenomena), and that these are the main cause of rises in climatic temperatures.

The major distinction between the Kyoto Protocol and the UNFCCC is that, while the Convention encouraged industrialised countries to stabilise GHG emissions, the Protocol commits them to do so. The United States of America (USA) signed, but did not ratify, the Protocol and Canada withdrew from it in 2011. Since the USA has not ratified the treaty, the collective emissions reduction of the so-called Kyoto Annex I (industrialised) countries fell from 5.2% to 4.2% below base year, excluding international aviation and shipping. The Kyoto Protocol is generally seen as an important first step towards a truly global emission reduction regime that will stabilize GHG emissions, and provides the essential architecture for any future international agreement on climate change. However, the progress made under the Kyoto Protocol (including imports and excluding exports) appears weak. Europe's savings reduced to just 1% from 1990 to 2008, whilst the developed world as a whole saw its emissions rise by 7% over the same period.

A new international framework needs to have been negotiated and ratified by the end of the first commitment period of the Kyoto Protocol in 2012 that can deliver the sort of stringent GHG emission reductions which the IPCC has clearly indicated are required to mitigate large-scale, anthropogenic climate change [2]. At the 2012 Doha COP18 climate change negotiations hosted by Qatar, the parties to the Kyoto Protocol agreed to a second commitment period of emissions reductions from 1 January 2013 to 31 December 2020. This will take the form of an amendment to the Protocol with 37 countries being allocated binding GHG targets in the second commitment period: Australia, all members of the European Union (the present EU-27), Belarus, Croatia, Iceland, Kazakhstan, Norway, Switzerland, and Ukraine. However, a last minute objection at COP18 by the Russian Federation, Ukraine, Belarus and Kazakhstan suggests that they may withdraw from the Protocol or not ratify the Protocol amendment. The emission targets specified in second commitment period will apply to about 15% of the world's greenhouse gas emissions. Several Annex I countries who

participated in Kyoto Protocol's first-round have not taken on new targets in the second commitment period, including Japan, New Zealand, and (as noted above) the Russian Federation. Other Annex I countries without second-round GHG targets are the USA and Canada. The original EU-15 signatory countries [3] are on track to meet their initial GHG target, but mainly because of the post-2008 economic recession in the industrialised countries and via improvements in energy and end-use efficiency rather than the take-up of renewables, except for biofuels in the transport sector.

Transport underpins the mobility of people around the world, but presently accounts for around 20% of global anthropogenic carbon dioxide (CO₂) emissions [4,5]: an unwanted side-effect. The adoption of liquid biofuels in the transport sector [6] has therefore been seen, particularly by the EU, as a means for meeting climate change mitigation targets, enhancing regional energy or fuel security, and contributing to rural development (through the provision of an alternative source of income in otherwise depressed agricultural communities). Biomass can be converted into premium-quality liquid biofuels and biochemicals [7]. Bioethanol and biodiesel also hold out the prospect of retaining the existing transport infrastructure (e.g., refuelling or 'petrol' stations), in contrast to other low carbon options such as hydrogen-fuelled or electric vehicles. This has significant benefits in terms of limiting capital expenditure and the potential speed of take-up. But the deployment of biofuels has been linked to significant impacts in terms of direct and indirect land use change (LUC and iLUC), loss of biodiversity and eco-system services [6,8], and competition with food production. *First generation biofuels* (FGB), for example, are produced primarily from food crops [5], and are limited by their inability to achieve targets for oil-product substitution (without threatening food supplies and biodiversity) and for GHG reductions. In contrast, more advanced or *second generation biofuels* (SGB) are generally produced from agricultural or crop 'wastes' (such as straw) and from non-food energy crops, which significantly reduces these negative impacts [5]. Potential feedstocks and conversion routes [6] therefore need to be assessed against the full range of sustainability considerations and over the full life-cycle of the biofuel supply chain [4,5,8,9]: from 'field-to-(*gas* or petrol station) forecourt' or 'seed-to-wheel'. Only in this way will the true consequences of a given biofuel – environmental, economic and social - be determined [9].

1.2 The Issues Considered

Environmental or ‘ecological’ footprints (*ef*) have been widely used in recent years as indicators of resource consumption and waste absorption transformed on the basis of biologically productive land area [in global hectares (gha)] required *per capita* with prevailing technology [10-14]. They represent a partial measure of the extent to which an activity [that might be associated with communities, technologies, or systems] is ‘sustainable’ [12,13]. In contrast, ‘carbon footprints’ (*cf*) are the amount of carbon [or CO_{2e}] emissions associated with such activities [14,15]. But, unlike environmental footprints, they are generally presented in terms of units of mass or weight (kilograms per functional unit), rather than in spatial units (such as gha). These carbon footprints have become the ‘currency’ of debate in a climate-constrained world [13]. They are increasingly popular ecological indicators, adopted by individuals, businesses, governments, and the media alike.

Methods for calculating the environmental and carbon footprints of the global biofuel production have been employed based on historic data and projections out to 2019. This footprint analysis is consistent with that developed by the *Global Footprint Network* (GFN) [<http://www.footprintnetwork.org/>] and related bodies. The environmental footprint (*ef*) was broken down respectively into carbon (effectively *cf*), embodied energy, transport, built land, water, and waste components. *ef* was then calculated on an annual basis from 2010-2019. The effect of the uncertainties in the constituent data related on these footprints were estimated using an established procedure for uncertainty analysis [12,14,16] (see the Appendix and Table 2 below), although that for the total environmental footprint was found to be only about $\pm 3\%$. However, the global biofuel projections employed here were deterministic in nature, rather than stochastic. Scatter in the footprint calculations are therefore principally dependent on the variation in the estimates of year-on-year global biofuel projection into the future.

2. GLOBAL BIOFUEL PRODUCTION

2.1 Biofuels, Feedstocks, and Upstream Impacts

Biofuels are fuels which have been produced from renewable resources, such as plant biomass, vegetable oils, and treated municipal and industrial wastes [7]. They are considered potentially ‘carbon neutral’, due to the fact that the plants absorb the carbon dioxide which is released when they are burnt. The extent to which carbon emissions are actually reduced, depends on (direct and indirect) land use changes associated with their production. Thus, the life-cycle GHG savings associated with various types of biofuel range from about + 85% to -

30%, depending on the feedstock involved and their production methods [18]. The use of biofuels as an additive to petroleum-based fuels (with low or high blends) can also result in cleaner burning with smaller releases of carbon monoxide and particulates [7]. In addition to climate change mitigation, biofuels help to diversify and improve security of energy supplies, as well as aiding rural development [7].

Bioethanol is currently produced using first generation technology (i.e., FGB) to ferment and then distil sugar (e.g., from sugarcane, sugar beet, and sweet sorghum) or starchy crops (e.g., corn, wheat, and cassava). It is therefore typically produced by fermentation of crops high in sugar, or by a series of hydrolysis/fermentation steps for starchy materials [6]. Bioethanol has long been produced from sugarcane in Brazil, and from corn (maize) and soybeans in the USA [8]. It is viewed as a cleaner-burning replacement for petroleum-based oil. However, the energy requirements for starch-based bioethanol are significantly greater than that for sugar-based bioethanol, due to the process of first converting starches into sugar. Bioethanol production from sugar crops is consequently preferred on performance grounds over starchy crops as their energy and GHG balances are preferable [6]. In contrast, biodiesel is a liquid fuel made up of fatty acid alkyl esters, fatty acid methyl esters (FAME), or long-chain mono alkyl esters [6]. It is produced from either oil extracted from seeds or oil-rich nuts, or recovered waste vegetable oils and animal fats [6]. Biodiesel is obtained by transesterification of these feedstocks to produce methyl ether [6]. Such biodiesel can be used in compression-ignition diesel engines, normally as a 5% blend, although it can be employed at 100% in specially-modified engines [6].

The next (second and third) generation biofuel technologies are considered to offer a potential solution for some of the sustainability issues associated with FGB [5,9]. SGB use cellulosic biomass which include herbaceous lignocellulosic species [such as miscanthus, switchgrass and reed canary grass (perennial crops) and trees such as poplar, willow and eucalyptus (short rotation crops)], as well as forestry and agricultural residue [5,6]. Biodiesel is derived from various agricultural products depending on their availability in different regions. In India, *Jatropha* and *Pongamia* (a genus of legume in the *Fabaceae* family) are presently used to produce biodiesel. Palm oil is in widespread production in South East Asia to generate a high yield biofuel, which is an edible (albeit relatively expensive) advanced feedstock option for the longer term (and it is therefore often referred to as a ‘third generation’ biofuel). Algae are also being evaluated and demonstrated as a diesel fuel and related co-products.

SGB can reduce life-cycle GHG emissions, because of their higher energy yields per hectare and the potential of remaining plant material (mostly lignin) that can be employed as process energy. The greatest sources of emissions are in the upstream stage of the biofuel life-cycle [18]. These include land-use changes and cultivation, fuel production, feedstock recovery, fertilizer manufacture, and ‘displaced’ emissions (sometimes referred to, perhaps inappropriately, as ‘co-product credits’ [18]). However, the conversion technologies are at a relatively early stage of development [6]. Substantial technological and economic barriers impede their commercial deployment [5,19], including high production costs, logistics, and supply chain challenges. Another important barrier is the set of agricultural/forestry sector practices needed to regularly supply the lignocellulosic feedstock. These depend on changes in agricultural management, as well as policy changes, both of which will take time to implement [19].

2.2 Global Projections of Biofuel Production

The estimates of biofuel production and their projection out to 2019 employed here were taken from those produced on a regular basis by the OECD-FAO [20]. These are viewed as being ‘low band estimates’ by Slade *et al.* [21] from a comprehensive global bioenergy resource assessment. The OECD-FAO bioethanol projections [20] suggest that the major feedstock is likely to remain coarse grains. They argue that this bioethanol production will grow relatively slowly after 2015. Almost 40% of the increase in first generation bioethanol worldwide production will be due to the increase in production from sugarcane, mainly from Brazil, in order to meet both domestic and US demands [20]. Second generation bioethanol is only expected to develop in the latter years of the forecast period (2010-2019); representing about 7% of total bioethanol production [20]. Roots, tubers and molasses are expected to be used as feedstocks for bioethanol production in developing countries. Edible vegetable oil is thought likely to be the main feedstock used to produce biodiesel [20]. However, its share in total biodiesel production is likely to decrease from almost 90% over the baseline (2007-2009) to about 75% by 2019. This is due to the development of the production of biodiesel from *Jatropha* mainly in India, to the increasing use of animal fats to produce biodiesel in the US, and to the availability of second generation biodiesel in the latter years of the forecast period. The OECD-FAO estimate that biodiesel will amount to almost 6.5% of total diesel production by 2019 [20]. The overall estimates of global biofuel production made by the OECD-FAO [20] are close to those produced by *Office of Policy Analysis* at the US

Department of Energy [22]. The latter are about 8.5% higher in the baseline period, but less than 0.5% by 2019.

Worldwide biofuel use represents an important share of global cereal, sugar and vegetable oil production. According to the OECD-FAO [20], about 13% of the global production of coarse grains will be used to produce bioethanol by 2019, compared to 9% over the baseline period (2007-2009). 16% of the global production of vegetable oil will be used to produce biodiesel compared to 9% over this baseline. The share of sugarcane to be used for bioethanol production at the global level is expected to reach almost 35% in 2019 [20]. The OECD-FAO [20] recognises that biofuel markets depend heavily on government incentives and regulation or mandates {as did Adams *et al.* [19] in the United Kingdom (UK) context}. They note that the prospects remain uncertain in the light of variations in crude oil prices, changes in policy interventions, and developments in SGB technologies [20].

3. CARBON AND ENVIRONMENTAL FOOTPRINTING

3.1 The Environmental Footprint Methodology

The use of 'ecological' or environmental footprint analysis has grown in popularity over recent years, both in Europe and North America. They provide a simple, but often graphic, measure of the environmental impact of human activity: whether or not in the foreseeable future humanity will be able to "tread softly on the Earth" [23]. William Rees used footprint analysis in its basic form to teach planning students for some 20 years (see Wackernagel and Rees [24]). He decided to adopt the term 'ecological footprint' in the early 1990s, rather than 'appropriated carrying capacity' that he had previously used, after buying a new television set [14]. It had a smaller footprint (that is, took up less space) than his old model. The terms 'environmental' and 'ecological' footprints are used interchangeably here (as they were previously by Hammond [11], Eaton *et al.* [12], Cranston and Hammond [13], and Alderson *et al.* [14]), although the former expression is preferred. Ecology is that branch of biology dealing with the interaction of organisms and their surroundings. 'Human ecology', sometimes used for the study of humans and their environment, is closer to the usage implied by footprint analysis.

Footprint calculations involve several steps. Initially the land area per functional unit (e.g., *per capita* or, in the present case, per kg or tonne of biofuel) appropriated for each major category of consumption (aa_i) is determined:

$$aa_i = \frac{c_i}{p_i} \sim \frac{\text{annual consumption of an item}}{\text{average annual yield}}$$

In the original version of environmental footprint analysis (EFA) employed by Wackernagel and Rees [24], four consumption categories were identified: energy use, the built environment (the land area covered by a settlement and its connection infrastructure), food, and forestry products. This is a restricted subset of all goods and services consumed which was determined by the practical requirements of data gathering and influenced by the development of the technique in a Canadian setting. Five land types are typically been employed: Chambers *et al.* [10], for example, adopted bioproductive land, bioproductive sea, energy land, built land, and the land needed to secure biodiversity as their categories (see also Eaton *et al.* [12] and Fig. 1). Here the components analysed, in addition to the carbon footprint, were ‘built land’, ‘embodied energy’, ‘materials and wastes’, ‘transport’, and ‘water’. In order to calculate the footprint per functional unit (ef) in global hectares (gha), the appropriated land area for each consumption category is then summed to yield, after Wackernagel and Rees [24]:

$$ef = \sum_{i=1}^{i=n} aa_i$$

Approximate location of Figure 1

One global hectare represents a hectare (ha) of biologically productive land at the average global productivity. The different footprint components (see Fig. 2) need to be normalised, so that global hectares account for disparities in land productivities. This computation then leads to a matrix of consumption categories and land use requirements, which is ideally suited to a spreadsheet implementation. In order to determine the total footprint for a given activity [e.g., community, product, or resource (EF)], the functional unit figure (ef) is simply multiplied by the relevant population size (N), thus {following Wackernagel and Rees [24]}:

$$EF = ef(N)$$

Approximate location of Figure 2

3.2 The Carbon Footprint Component

The concept of the ‘carbon footprint’ (*cf*) is rooted within the framework used to determine the eco-footprint. However, Hammond [26] noted that a ‘footprint’ would normally be measured in spatial units [such as global hectares (gha)], but that the carbon footprint is typically presented in mass (or weight) units, i.e., kilograms (kg) or tonnes (t). He therefore argued that it should perhaps be termed a ‘carbon weight’ (C_w) or something similar. Wiedmann and Minx [27] reviewed various suggestions, including that of Hammond [26], and then proposed a definition for the ‘carbon footprint’ as including the “total amount of CO₂ emissions that is directly and indirectly caused by an activity”. Unfortunately, no definition has been formally adopted in a ‘standard’ with the agreement of the communities involved. Indeed, many organisations have adopted the use of the term carbon footprint when assessing the carbon dioxide emissions released during various processes or activities, although these are again measured in tonnes of carbon dioxide [26,27].

3.3 Other Components of the Environmental Footprint

The initial phase of footprint analysis involves the collection of consumption data covering the various components [10,12]. This yields the flow of resources into and out of the global biofuel production sector. Proxy (or secondary) data adapted from international statistics was employed in the absence of sector-specific obtained (or primary) data [12,14]. This collation and analysis of data is highly disaggregated with very many individual items of information. In addition to the consumption data needed for footprint analysis, yield and conversion (or ‘equivalence’) factors were required. The EFA resource components had to be identified and categorised to reflect broad and identifiable policy making categories, which match the consumption of ‘natural capital’ [12,13]. In the present study, these components were [12,25]:

- Bioproductive and Built Land: Land appropriated for biofuels development.
- Embodied Energy: The quantity of energy required for the processing equipment or to process fuels for the sector [28].
- Materials and Waste: Consumption of products and materials for biofuels development.
- Transport: ‘Full fuel cycle’ transportation requirements.
- Water: The use of water for biofuels development.

‘Double accounting’ can arise when the embodied energy component [28] includes the ‘process energy’ used in production; fuels for fertiliser production here. Thus, in the present study, the embodied energy incorporates only the ‘upstream’ use of energy, whilst the carbon footprint represents the direct fuel inputs for biofuels development. This practice was first adopted by Alderson *et al.* [14].

4. DETERMINATION OF THE BIOFUEL FOOTPRINT COMPONENTS

4.1 Bioproductive Land

‘Bioproductive land’ consists of arable land, forests, and pasture, as well as (where appropriate) bioproductive sea [10]. The productivity each land type will vary, but they will normally yield significant animal and plant output [10]. Consequently, the bioproductive land component of the environmental footprint, calculated for the current study, included the land required for the cultivation of the different feedstocks that produce biofuels. This bioproductive land footprint component per litre for the OECD-FAO estimates of global biofuel production [20] was therefore computed as follows [14]:

$$\begin{aligned} &\textbf{Bioproductive Land Footprint Component (gha/litre of biofuel)} \\ &= \textbf{Area of Developed Land (ha/litre of biofuel) * Conversion Factor (gha/ha)} \end{aligned}$$

$$\begin{aligned} &\textbf{Conversion Factor (gha/ha)} \\ &= \textbf{UK Average Crop Yield Factor * Equivalence Factor (gha/ha)} \end{aligned}$$

An estimation of the amount of bioproductive land required/litre of biofuel was computed using a global crop ‘yield factor’ suggested by Alderson *et al.* [14] of 2.44 and the related equivalence factor of 2.1 gha/ha [14]. This yield factor is the factor by which different land types are more biologically productive than the world average [10]. Thus, a conversion factor of 5.124 gha/ha was obtained [14]. {Simmons *et al.* [25] adopted an equivalence factor of 2.82 gha/ha for what they termed ‘arable land’ (in contrast to 0.54 gha/ha for ‘pasture’ and 1.14 gha/ha for ‘forest’). Very similar values were also employed by Chambers *et al.* [10].} The bioproductive land footprints for the different feedstock of bioethanol and biodiesel were subsequently computed separately, and then summed together.

4.2 Built Land

Built land is land whose productive capacity has been largely utilised (or ‘lost’) for development purposes [10], i.e., for buildings, roads, and the like. In the present case, this represents land used for the construction of biorefineries and the associated infrastructure, and consequently this make up the built land footprint component. The footprint component per litre of biofuel for the OECD-FAO global biofuel projections [20] was computed as follows [14]:

$$\begin{aligned} &\textbf{Built Land Footprint Component (gha/litre of biofuel)} \\ &= \textbf{Area of Developed Land (ha/litre of biofuel) * Conversion Factor (gha/ha)} \end{aligned}$$

$$\begin{aligned} &\textbf{Conversion Factor (gha/ha)} \\ &= \textbf{UK Average Crop Yield Factor * Equivalence Factor (gha/ha)} \end{aligned}$$

The estimation of the amount of built land required/litre of biofuel produced was computed on the presumption that the biorefineries and associated infrastructure were located on crop land, and so the area of potential crop land that has been replaced will be represented by the built land footprint component. The global crop yield factor of again 2.44 [14] was employed, and hence an equivalence factor of 2.1 gha/ha [14] was used in order to adjust the built land for its relative productivity. The resulting built land footprint conversion factor was once more taken as 5.124 gha/ha of crop land [14]. This figure is then multiplied by the OECD-FAO estimates of global biofuel production [20] in order to attain values for the built land component. {Simmons *et al.* [25] adopted an equivalence factor of 2.82 gha/ha for what they termed ‘built-up area’, which was subsequently employed by Chambers *et al.* [10].} The built land footprints for the different feedstock of bioethanol and biodiesel were computed here separately, and then summed together to yield footprints for all biofuels.

4.3 Carbon Emissions

The carbon component of the footprint was calculated using ‘carbon weight’ (C_w) values and the amount of land required to sequester carbon. The carbon weight is the amount of carbon released in tonnes per tonne of biofuel produced by each global biofuel plant. Therefore the global carbon footprint per litre of biofuel from each type was calculated as follows [14]:

$$\begin{aligned} &\textbf{Carbon Footprint (gha/litre of biofuel)} \\ &= \textbf{Carbon Weight (tC/litre of biofuel) * Conversion Factor (gha/tC)} \end{aligned}$$

$$\begin{aligned} &\text{Conversion Factor (gha/tC)} \\ &= \frac{\text{Carbon Responsibility} * \text{Equivalence Factor (gha/ha)}}{\text{World Carbon Absorption Factor (tC/ha)}} \end{aligned}$$

Carbon absorbed by the oceans is not explicitly included in this footprinting study, although it was represented by the ‘Carbon Responsibility’ factor. The latter factor accounts for the fact that carbon is absorbed by the oceans, and therefore only 69% of carbon emitted needs to be absorbed by forest [14]. The equivalence factor adopted was for forests, which was taken (after Alderson *et al.* [14]) as 1.4 gha/ha, and the annual ‘World Carbon Absorption Factor’ as 0.95 tC/ha [14]. Hence, the conversion factor for the carbon footprint component is 1.017 gha/tC [14]. These figures were then be multiplied by OECD-FAO global biofuel production for bioethanol and biodiesel [20] in order to determine the aggregate global carbon footprint associated with worldwide biofuel production year-on-year. {The equivalence factor for forests adopted by Simmons *et al.* [25] was 1.14 gha/ha, with a closely similar value subsequently employed by Chambers *et al.* [10].} The estimation of the amount of CO₂/litre of biofuel produced here was compared and contrasted with several biofuel studies (including those of Delucchi [18]) for various feedstocks for bioethanol and biodiesel.

4.4 Embodied Energy

The energy embodied in the structural materials of, and energy used in, the construction of each biofuel production plant (or biorefinery) is termed as ‘embodied energy’ [28]. The footprint for embodied energy footprint per litre of biofuel was then calculated via [14]:

$$\begin{aligned} &\text{Embodied Energy Footprint Component (gha/litre of biofuel)} \\ &= \text{Embodied Energy (GJ/litre of biofuel)} * \text{Conversion Factor (gha/GJ)} \end{aligned}$$

It was presumed here that the origin of embodied energy was associated with fossil fuels. The conversion factor was hence computed from primary energy sources and the conversion factors adopted by Alderson *et al.* [14] (see Table 1). These conversion factors had already taken account of equivalence factors for different land types, which were presented in terms of global hectares. Consequently, they do not require any further manipulation [14]. The embodied energy footprint component was then multiplied by the OECD-FAO estimates of global production for bioethanol and biodiesel [20] in order to obtain the total embodied energy footprint associated for the future use of each biofuel. These values were then summed together to obtain the overall global embodied energy footprint.

Approximate location of Table 1

4.5 Transport

The transport component includes the transport of fuel for input into the biorefinery process to the plant and, in principle, the removal of waste products to disposal sites. Thus, the transport footprint per litre of biofuel is estimated as follows [14]:

$$\begin{aligned} \text{Transport Footprint (gha/litre of biofuel)} \\ = \text{Fuel Input (t/litre of biofuel)} * \text{Conversion Factor (gha/t)} \end{aligned}$$

Here the conversion factor was calculated for each mode of transport (based on carbon emissions) and summed as follows [14]:

$$\begin{aligned} \text{Conversion Factor (gha/tC)} \\ = \sum [\text{Average Distance (km)} * \text{Carbon Emissions (tC/t-km)} * \text{Factor (gha/tC)}] \end{aligned}$$

$$\begin{aligned} \text{Factor (gha/tC)} \\ = \frac{\text{Carbon Responsibility} * \text{Uplift Factor} * \text{Equivalence Factor (gha/ha)}}{\text{World Carbon Absorption Factor (tC/ha)}} \end{aligned}$$

Values for the carbon responsibility, equivalence factor and world carbon absorption factor of 0.69, 1.4 gha/ha and 0.95 tC/ha respectively were adopted as in the carbon footprint calculation above (as suggested by Alderson *et al.* [14]). The ‘uplift factor’ accounts for the energy required to manufacture and maintain vehicles, and the necessary road infrastructure. It was assumed that vehicle manufacture and maintenance increases carbon emissions by 15% and the development of necessary infrastructure increases carbon emissions by a further 30% [14]. Therefore an uplift factor of 1.45 was allocated to road, rail and waterborne transport. The resulting factor used in the conversion factor is 14.744 gha/tC [14]. {The equivalence factor for ‘fossil energy’ adopted by Simmons *et al.* [25] was 1.14 gha/ha, with a similar value of 1.17 gha/ha for ‘petrol consumption’ subsequently employed by Chambers *et al.* [10]. The latter tabulate ‘uplift factors’ as having values of 1.11, 1.45 and 1.93 for their low, medium and high estimates respectively.} The average distance travelled and the associated emissions vary for road, rail and waterborne transport [10,12,25] so the conversion factor was calculated separately for each transport mode, and then summed to give the overall

conversion factor. It was then used to calculate the transport footprint per litre of bioethanol and biodiesel respectively, which in turn was multiplied by the amount of biofuels produced globally (litres) [20] to give the corresponding overall transport footprint.

4.6 Waste Arisings

The waste footprint component includes all wastes produced as a result of releases from each biorefinery process, and its footprint is calculated as follows [14]:

$$\text{Waste Footprint (gha/litre of biofuel)} = \frac{\text{Waste Arisings (t/ litre of biofuel)} * \text{Equivalence Factor (gha/ha)}}{\text{World Average Yield (t/ha)}}$$

This equation was used to calculate the waste footprint per litre of biofuel produced globally. It was then multiplied by the future worldwide biofuel production estimated by the OECD-FAO [20] in order to obtain the global waste footprint from bioethanol and biodiesel. Since it is assumed that waste disposal takes up fertile land, which could be otherwise used for agricultural purposes, an equivalence factor is the crop land factor of 2.1 gha/ha (following the practice recently adopted by Alderson *et al.* [14]). The world yield factor, however, varies for the different types of wastes (see, for example, Eaton *et al.* [12]) that would be produced during the global biofuel production. These were extracted from the environmental life-cycle assessment (LCA) study by of biofuels Delucchi [18].

4.7 Water Usage

A water footprint consists of three components: the so-called ‘blue’, ‘green’ and ‘grey’ water footprint. The ‘blue’ water footprint is associated with the volume of freshwater that evaporated from the global blue water resources (surface water and ground water) to produce the goods and services consumed by the individual or community. In contrast, the ‘green’ water footprint is the volume of water evaporated from the global green water resources (rainwater stored in the soil as soil moisture). Finally, the ‘grey’ water footprint is the volume of polluted water that associates with the production of all goods and services for the individual or community. This can be estimated as the volume of water that is required to dilute pollutants to such an extent that the quality of the water remains at or above agreed water quality standards.

The water footprint component per litre of biofuel from each type of biofuel was calculated via the following expression [14]:

$$\begin{aligned} \text{Water Footprint (gha/litre of biofuel)} \\ = \text{Consumption of Water (litre of water/litre of biofuel)} \\ * \text{Conversion Factor (gha/litres of water)} \end{aligned}$$

An estimation of the amount of water required/litre of biofuel produced was computed with the help of data from the biofuel LCA study by Delucchi [18] for different feedstocks that are used to produce bioethanol and biodiesel. The conversion factor for the water component was adopted from the estimate of 0.102 gha/M litres provided by Alderson *et al.* [14]. This conversion factor was then used to calculate the water footprint per litre of biofuel produced globally using the equation above. The total water footprint component was obtained by multiplying the water footprint per litre of biofuel by the overall global biofuel production determined by the OECD-FAO [20] over the period 2010-2019.

5. RESULTS AND DISCUSSION

5.1 Environmental Footprint Analysis (EFA) Versus Environmental Life-Cycle Assessment (LCA)

It is now widely recognised that in order to evaluate the environmental consequences of a product or activity the impact resulting from each stage of its life cycle must be considered [6,29]. This has led to the development of a range of analytical techniques that now come under the 'umbrella' of LCA. In a full LCA study, the energy and materials used, and pollutants or wastes released into the environment as a consequence of a product or activity are quantified over the whole life-cycle; again 'from cradle-to-grave' [30,31]. This requires the determination of a balance or budget for the raw materials and pollutant emissions (outputs) emanating from the system. Energy is treated concurrently, thereby obviating the need for a separate inventory of embodied energy. LCA is a product or system-based form of environmental auditing which is often geographically diverse; that is, the material inputs to a product may be drawn from any continent or geo-political region of the world. Due to an early lack of consensus regarding methodology, LCA was codified under the auspices of the *Society of Environmental Toxicology and Chemistry* (SETAC) at a series of workshops in the early 1990s [29,31]. These largely defined the standard framework for LCA, which subsequently formed the basis of the ISO 14040 series of LCA standards. These were

modified, and reduced from four to two standards, in 2006 [32,33]. There are four main stages of an LCA (see ISO [32] and [33]) which are shown to follow a logical sequence of goal definition and scoping (outlining aims, methodology and boundary conditions), inventory analysis (data collection - determining inputs and outputs of materials, fuels, and process emissions), impact assessment (determination of the life-cycle environmental impacts for the pre-determined inventory), and recommendations for improvement. Gathering data for the life-cycle inventory (LCI) can be a time-consuming task, but it is aided by the provision of various proprietary databases and software tools [28,29,31]. The impact assessment and interpretation stages are still undergoing refinement; although they have been codified in the ISO 14040-14044 standards (launched in 2000, but revised in 2006).

There has been an increasing interest amongst researchers and practitioners in the relationship and interaction between EFA and LCA [34,35]. A particularly useful comparison between the two methods has recently been reported by Castellani and Sala [34] in the context of sustainability assessment of tourism activities in Italy. They drew out the main strengths and weaknesses of the EFA and LCA approaches. The former does not capture the full range of environmental impact categories [34] embracing, for example, damage to resources (resulting from the consumption of fossil fuels and other minerals), damage to ecosystem quality (caused by acidification, eutrophication, ecotoxicity, etc.), and damage to human health (due to human toxicity). On the other hand, EFA provides a useful means of environmental monitoring against a specific physical threshold: the amount of land available. Unlike Life Cycle Impact Assessment (LCIA), EFA also takes account of limited natural resources or the carrying capacity of the planet. However, the EFA approach doesn't allow for the multi-purpose use of ecosystems, e.g., to sustain biodiversity, for timber production, and for carbon sequestration. Castellani and Sala [34] explore the interactions between footprint components, like the seven different components used in the present work, and typical LCA impact categories and associated inventory data. They note that collecting primary data from specific LCA studies of each consumption category will enhance the robustness of EFA. Another recent study by Huijbregts *et al.* [35] again examined the interrelation between EFA and LCA, but for a range of some 1550 product/process groups consumed in the industrialised global economy. They used the Eco-indicator 99 (EI) LCIA method [35], and found that the EF/EI ratio was constant to within a variation of about $\pm 17\%$. Considerations of this type have led leading EFA practitioners to place the acquisition of better data sources (including those from process and input-output LCA studies) high on their research agenda [36].

5.2 Life-Cycle Environmental Impacts of Biofuels

In order to determine the carbon and environmental footprints associated with global biofuel production, the present study has drawn on the LCA study of Delucchi [18] in order to estimate the life-cycle CO_{2e} emissions from various biomass feedstocks. Separate calculations were then performed in order to ascertain the values for each of the footprint components (see Fig. 2) for bioethanol and biodiesel respectively; each from different feedstock varieties. These were then aggregated to determine the overall (or total) footprint of global biofuel production based on the OECD-FAO [20] biofuel projections. It is only the latter that are reported here.

The LCA study undertaken by Delucchi [18] found that, in contrast to many other studies, corn (or maize) bioethanol does not have significantly lower GHG emissions in comparison to petrol (or 'gasoline'). Indeed cellulosic bioethanol was found to have only about 50% lower CO_{2e} emissions. The main reason for this is that Delucchi [18] estimated relatively high CO_{2e} emissions from feedstock and fertilizer production, from land use and cultivation, and from emissions of non-CO₂ GHGs from vehicles. Therefore the largest sources for CO_{2e} emissions arose at the upstream end of the biofuels life-cycle, i.e., those associated with fuel production, feedstock recovery, fertilizer manufacture, and 'displaced' emissions. Delucchi [18] observed that the emissions related to feedstock transmission, fuel distribution, and liquid-fuel dispensing was relatively small. Nevertheless, he argued that emissions related to dispensing gaseous fuels can be substantial, because of the energy requirement for compressing gaseous fuels.

5.3 Carbon Footprint of Biofuels

The overall carbon footprint due to the production of global biofuels was estimated in the present study to be 0.248 billion (bn) gha for 2010; rising to 0.449 bn gha by 2019 (see Fig. 3 below). Jatropha and vegetable oil contributed around 11000 kg of CO_{2e} /litre of biodiesel which, according to the life-cycle assessment by Delucchi [18], is the highest value as compared to other feedstocks used to produce biofuels. In contrast, molasses produced only 416 kg of CO_{2e} during its life-cycle per tonne of bioethanol produced, and was one of the lowest GHG emitters amongst the various feedstocks. Vegetable oil was found to produce the

highest carbon footprint as compared to other feedstocks. This was simply due to the fact that biodiesel from vegetable oil produces the greatest amount of life-cycle CO_{2e} per unit of output as compared to other feedstocks.

Approximate location of Figure 3

The above overall carbon footprint values arising from the world biofuel production represents the concatenated results for the individual footprints for bioethanol and biodiesel respectively. The carbon footprint emanating from global bioethanol production over the period from 2007-2019 is depicted in Fig. 4 below for the different feedstocks. In 2010 the total carbon footprint was 0.0494 bn gha, and is likely to grow in line with OECD-FAO projections to 0.0816 bn gha by 2019. This growth was primarily caused by increases in bioethanol production from sugarcane; reaching 27.143 bn litres by 2019. Sugarcane yields some 0.759 kg CO_{2e} per litre of bioethanol produced [18], whilst coarse grains and wheat are likely to produce 0.404 and 0.514 kg CO_{2e} per litre respectively. Consequently, sugarcane accounted for 48% of the bioethanol footprint in 2007, which is projected to rise to just 54% in 2019. Over the corresponding period, coarse grains will contribute between 36-32% of the footprint, with all the remaining feedstocks (see again Fig. 4) making up the difference of ~15% in roughly similar proportions.

Approximate location of Figure 4

Life cycle CO_{2e} emissions for the production of 1 tonne biodiesel from vegetable oil and Jatropha oil suggest combined values of 11,000 kg CO_{2e} /tonne biodiesel [18]. Almost 60% of these emissions come from the crop plantation stage, which includes activities such as fertilization, irrigation on peatland and non-peatland, as well as the use of diesel for plantation based vehicles (like tractors). On the other hand, the milling (or oil extraction) and biodiesel production stages contribute approximately 17% and 24% respectively. The carbon footprint emanating from world bioethanol production over the period from 2007-2019 is shown in Fig. 5 below for various feedstocks. The total carbon footprint was found to be about 0.198 bn gha for 2010; rising to 0.367 bn gha by 2019. Vegetable oil yields around between 93% and 80% of biodiesel over the corresponding period. The difference in 2019 is likely to be made up, according to OECD-FAO production estimates, by roughly equal shares of Jatropha oil and non-agricultural waste products.

Approximate location of Figure 5

5.4 Environmental Footprint of Biofuels

Once all the individual environmental footprint components associated with worldwide biofuel production had been calculated on an annual basis (see Section 4 above), the overall footprint (EF) for the OECD-FAO global biofuel projections [20] can be expressed in terms of the different components, viz:

$$\begin{aligned} \text{Total Environmental Footprint (EF)} = & \text{Bioproductive Land Footprint} \\ & + \text{Built Land Footprint} + \text{Carbon Footprint} + \text{Embodied Energy Footprint} \\ & + \text{Transport Footprint} + \text{Waste Footprint} + \text{Water Footprint} \end{aligned}$$

The entire process is then repeated for each year of the study period, and hence calculations are best carried out through spreadsheet implementation.

The overall environmental footprint associated with the production of global biofuels was estimated to be 0.720 bn gha for 2010, and rises to 1.242 bn gha by 2019 (see Fig. 4 and 5 below). Bioproductive land (denoted by ‘Land’ in Fig. 4 and 5) is seen to vary from 0.403 bn gha in 2010 to 0.669 bn gha in 2019. This proved to be largest footprint component, followed by CO₂ (from 0.247 bn gha in 2010 to 0.448 bn gha in 2019), water (from 0.0381 bn gha in 2010 to 0.070 bn gha in 2019), and finally transport (from 0.031 bn gha in 2010 to 0.054 bn gha in 2019). The waste, built land and embodied energy was found to contribute an insignificant amount to the total environmental footprint (EF) of worldwide biofuel production.

Approximate location of Figure 6

The impact of bioproductive land (about 55% to the total environmental footprint; see Fig. 5) on global biofuel production clearly provides a restriction on biofuel developments going forward. The biofuel production yields a non-food cash crop rather than a food crop, and may well be a preferred income source for farmers. This might induce shortages of essential food crops, such as wheat, in the future. The carbon footprint is the next largest component at around 35% of the total environmental footprint of worldwide biofuel production.

Approximate location of Figure 7

5.5 General Findings and Discussion

Environmental life-cycle assessment (LCA) [6,18,29,30-33] constitutes a very useful environmental appraisal technique, but it has many limitations at its present state of development [29,38-40]. It is recommended as a comparative technique [32,33], but the results are often reported in absolute terms. There are many technical issues that need to be addressed during the conduct of LCA (and about which Ayres [39] and Rajagopal and Zilberman [40] have been critical). These include the definition of system boundaries, the quality of data available, and the way the results are normalized [29,30-33]. Many organizations (especially corporations) regard data as either confidential or simply do not have the sort of detailed records needed for a credible whole-life study [29,36]. Both Ayres [38] and Rajagopal and Zilberman [40] have argued for the need for monetarisation of life-cycle emissions, although Hammond and Winnett [29] have noted the resulting very large (orders-of-magnitude) uncertainty band depending on the monetary valuation method adopted. Rajagopal and Zilberman [40] also suggested that account needs to be taken of changes in technology and policy over time within biofuel LCA studies. Delucchi [38] recently reviewed the climate change, water and land use impacts of biofuels, including emerging issues concerning the application of LCA. He drew on his earlier biofuel LCA work [18], and argued that the determination of life-cycle ('field-to-forecourt') CO_{2e} emissions was dependent on four factors [38]: fossil fuel use for upstream activities; nitrogen fertiliser application; co-product allocation (such as animal feed); and carbon emissions due to direct land use change (LUC). Börjesson [41] observed that for *first generation biofuels* (FGB) these four factors can alter the GHG benefits or disbenefits of, for example, bioethanol very significantly – from positive to negative. They are also likely [38] to increase stresses on land use and water supplies (including water quality). Delucchi [38] consequently argued that it was not possible to employ LCA to quantitatively evaluate the life-cycle CO_{2e} emissions of biofuels with confidence. Nevertheless, he believes that it can yield useful qualitative insights, including about the relative advantages of *first and second generation biofuels*.

Bioenergy and biofuel footprints and land-take reflect relatively large environmental burdens when compared to other fuels. This can be illustrated via the recent study of the carbon and environmental footprints of UK power generation reported by Alderson *et al.* [14]. In that work, the environmental footprints per unit electricity (*ef*) associated with various power generators in their 'baseline' year (taken as 2005) are depicted in Fig. 8. Here the functional unit employed was the GWh, and thus the footprints are presented in terms of gha/GWh.

Carbon emissions or footprints are largely associated with fossil-fuelled power plants. The environmental footprints of these plants were coal - 158 gha/GWh, oil - 122 gha/GWh, and natural gas - 80 gha/GWh [14]. Nuclear power and renewables (other than bioenergy) are near zero carbon emitters. Their *ef* values are consequently 57 gha/GWh and <25 gha/GWh respectively. Solid, ‘first generation’ biofuels are shown to give rise to potentially significant emissions, and exhibit the highest land-take of any of the technologies shown in Fig. 8. They therefore lead to the largest *ef* value of 214 gha/GWh. For a similar reason, bioproductive land use proved to give rise to the highest component of the liquid biofuel footprint in the present study. The power plants categorised as ‘Other’ in Fig. 8 [14] represent other thermal sources that include those from various coke oven gas, blast furnace gas, waste products from chemical processes, and refuse derived fuels. It gives rise to the second largest footprint per unit electricity at 194 gha/GWh. Nevertheless, the overall environmental footprint (EF) of such plants is relatively insignificant, because their total power capacity in the UK is small.

Approximate location of Figure 8

6. Concluding Remarks

The environmental and carbon footprints of the global biofuel production have been determined on both a historic timescale and in accordance with international projections. Methodologies employed were consistent with those developed by the *Global Footprint Network* and related bodies. Annual environmental footprints have been computed from a baseline of 2007-2009 and projected forward to 2019. Estimates of future global biofuel production were adopted from OECD-FAO (and effectively US DOE) projections. In order to determine the footprints associated with these biofuel resources, the overall environmental footprint was disaggregated into bioproductive land, carbon (effectively *cf*), embodied energy, materials and waste, transport, and water components. These mainly reflect the impact of *first generation biofuels* (FGB) as second generation technologies will have a relatively low output up to 2020.

Sugarcane gives rise to around 0.76 kg of life-cycle CO_{2e} per litre of bioethanol [18], which is the highest amount of CO₂ produced from the principal feedstocks. In contrast, biodiesel produced from vegetable oil and *Jatropha* are estimated on a life-cycle basis to produce around 11000 kg CO_{2e} per tonne [18]. *Jatropha* appears to yield a relatively large amount of biodiesel. It uses 2-3 times more land at 1870 litres of biodiesel/hectare (ha) as compared to

vegetable oil and non-agricultural products (which produced 452 and 798 litres of biodiesel/ha respectively). But *Jatropha* requires double the water as compared to the other feedstocks, and is mainly grown in restricted areas of India, Myanmar (or Burma) and Nepal.

The global carbon footprint of biofuels was estimated here to be 0.248 bn gha in 2010; arising to 0.449 bn gha by 2019. These are essentially FGB produced primarily from food crops [5]. They are limited by their inability to achieve targets for oil-product substitution, without threatening food supplies and biodiversity, and for GHG reductions. Biodiesel produced from vegetable oil was found to have the highest carbon footprint in comparison to other feedstocks. The total environmental footprint (EF) for the global production of biofuels was estimated to be 0.720 billion gha for 2010; rising to 1.242 bn gha by 2019. Bioproductive land proved to give rise to the highest component of the overall footprint; rising from 0.403 bn gha in 2010 to 0.669 bn gha in 2019. This distinguishes the footprint results for biofuels from those with other energy sources, such as electricity generation [14], where the land component is relatively small. The carbon footprint of global biofuel production was the next highest (0.247 billion gha in 2010 to 0.45 bn gha in 2019), followed by the water footprint (0.0038 bn gha in 2010 to 0.07 billion gha in 2019) and then transport component (0.031 bn gha in 2010 to 0.054 bn gha in 2019). The waste, built land, and embodied energy components contributed an insignificant amount to the total environmental footprint.

In order to significantly reduce the above impacts, it will be necessary to move towards more advanced or *second generation biofuels* (SGB) produced from agricultural or crop ‘wastes’ (such as straw) and from non-food energy crops, which reduce these negative environmental burdens [5,42]. Cellulosic SGB feedstocks grown, for example, on degraded land with little management and low inputs [38] can result in life-cycle CO_{2e} emissions lower than that for petroleum (or ‘gasoline’). The recently published IEA ‘technology roadmap’ on transport biofuels [43] suggests that, although FGB will dominate the market up to 2020 (in line with the OECD-FAO projections employed here), SGB might constitute some 75% of biofuels production by 2050. They argue [43] that the amount of global biofuels for transport could rise nearly sevenfold over the period 2020-2050 (to just over 30 EJ equivalent primary energy demand). That would represent some 27% of global transport fuel supply by the middle of the 21st Century in contrast to only about 2% today [42]. Such biofuel demands again fall within the ‘low band estimates’ according to the classification of Slade *et al.* [21] in their comprehensive global bioenergy resource assessment.

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NOMENCLATURE

Abbreviations

CO ₂	carbon dioxide
CO _{2e}	carbon dioxide equivalent
DOE	US Department of Energy
EFA	environmental (or ecological) footprint analysis
EU	European Union
FAO	Food and Agricultural Organisation of the United Nations
FGB	first generation biofuels
GHG	‘greenhouse’ gas
IEA	International Energy Agency
LCA	environmental life-cycle assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
OECD	Organisation of Economic Co-operation and Development
SGB	second generation biofuels

Symbols

aa _i	each major category of consumption
<i>cf</i>	carbon footprint <i>per litre of biofuel</i> [gha or tC]
c _i	annual consumption of an item
C _w	carbon weight <i>per litre of biofuel</i> [tC]
<i>ef</i>	environmental footprint <i>per capita</i> [gha]

EF	total environmental footprint [gha]
EI	Eco-indicator 99 score [ecopoints]
N	population size
p_i	average annual yield of an item
R	result of an experiment or study
W_i	uncertainties in the individual variables
x_i	variable in the uncertainty analysis

Subscript

i	i -th category of consumption
-----	---------------------------------

APPENDIX: Uncertainty Analysis of Environmental Footprints

The uncertainties in EFA are dependent on the accuracy of the data collected. Some of the data employed for the present EFA represents a proxy adopted from international resource consumption statistics, and hence errors are inevitably present in footprint calculations. It is therefore desirable to estimate these errors or *uncertainties*. Footprint uncertainties were calculated here using a ‘standard’ method developed originally by Kline and McClintock [16] for single-sample experiments in engineering research. A more accessible description of the technique is given by Holman [44]. Here estimates of uncertainties were based on a careful assessment of errors in the various primary and secondary (or proxy) sources (see also Alderson *et al.* [14] and Eaton *et al.* [12]). The result of an experiment or study can be expressed using a function of the variables:

$$R = R(x_1, x_2, x_3, \dots, x_n)$$

If W_r is the uncertainty in the final result (footprint or biocapacity), and $W_1, W_2, W_3, \dots, W_n$ are the uncertainties in the individual variables, then the uncertainty in the result is given by [19,30]:

$$W_r = \left[\left(\frac{\partial R}{\partial x_1} W_1 \right)^2 + \left(\frac{\partial R}{\partial x_2} W_2 \right)^2 + \dots + \left(\frac{\partial R}{\partial x_n} W_n \right)^2 \right]^{1/2}$$

In the present footprint study, the primary data consisted of resource consumption estimates, via material flow accounting, used to determine each component of the footprint. The function employed to calculate the overall footprint (EF) of the OECD-FAO global biofuel projections can be expressed in terms of the different components, viz:

$$\begin{aligned} \text{Total Environmental Footprint (EF)} = & \text{Bioproductive Land Footprint} + \text{Built Land Footprint} \\ & + \text{Carbon Footprint} + \text{Embodied Energy Footprint} + \text{Transport Footprint} \end{aligned}$$

+ Waste Footprint + Water Footprint

To simplify the calculations, the uncertainty for each component was initially estimated by considering them separately. These uncertainties were then used to determine the total uncertainty in the footprint. In addition, these uncertainties were converted into percentage values for each component. The total uncertainty for each study area was obtained by summing the uncertainties for each component. Here the calculated uncertainty associated with each of the individual components was found to be in the range ± 4 -11% (see Table 2), although that for the total environmental footprint was about ± 3 %. This is in line with previous footprint studies associated with the energy sector by the first author and his co-workers [12,14]. However, the OECD-FAO global biofuel projections [20] employed here are deterministic in nature, rather than stochastic. Scatter in the footprint calculations in each year over the period 2010-2019 are therefore principally dependent on the estimates on global biofuel production.

Approximate location of Table 2

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- Fig. 2. Schematic representation of the component-based approach to environmental footprint analysis (*Source: Eaton et al. [12]; adapted from Simmons et al. [25]*).
- Fig. 3. Carbon footprint associated with world biofuel production (2010-2019).
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- Table 2: Total Environmental Footprint (EF) Uncertainty for the Base Year [2010]

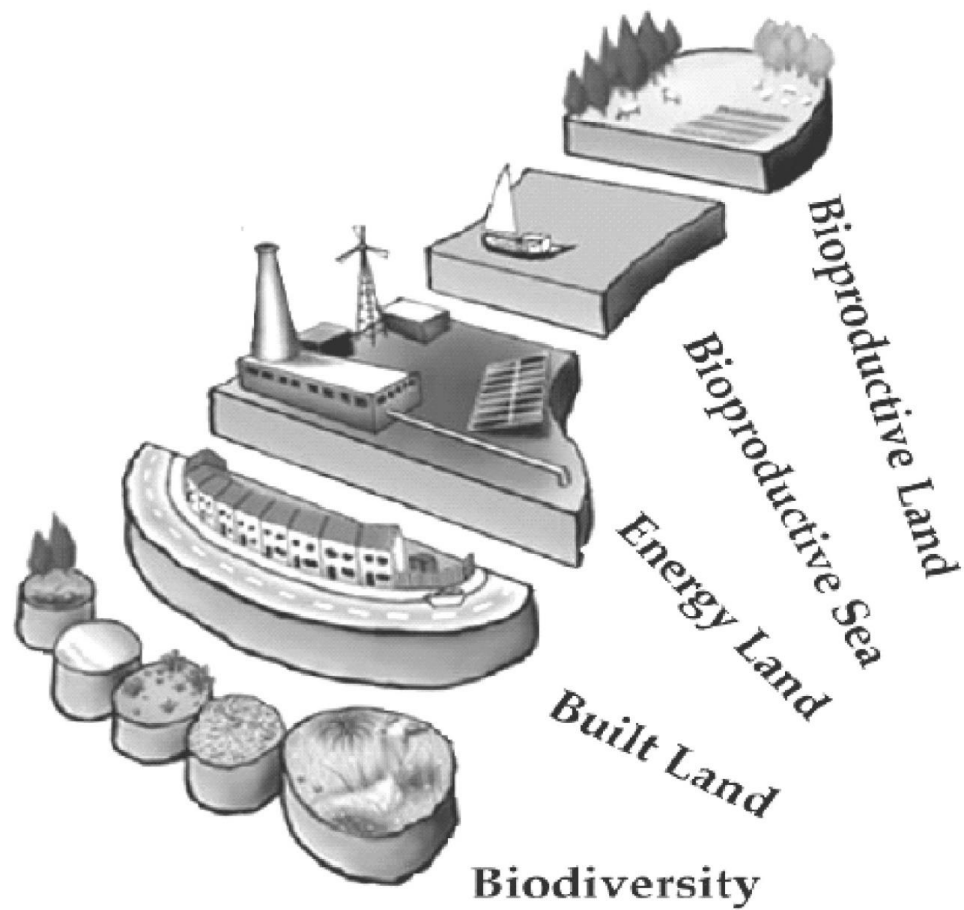


Fig. 1. Schematic representation of the environmental footprint, and its land types (*Source: Eaton et al. [12]; adapted from Chambers et al. [10]*).

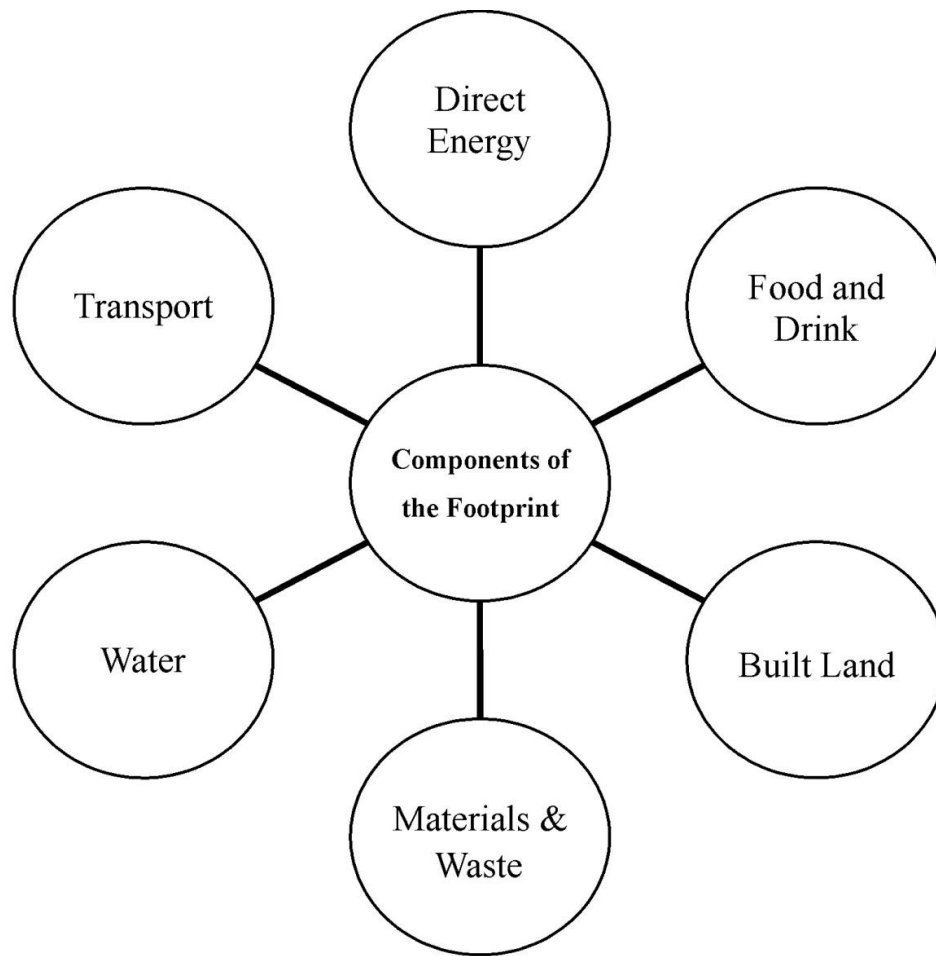


Fig. 2. Schematic representation of the component-based approach to environmental footprint analysis (*Source: Eaton et al. [12]; adapted from Simmons et al. [25]*).

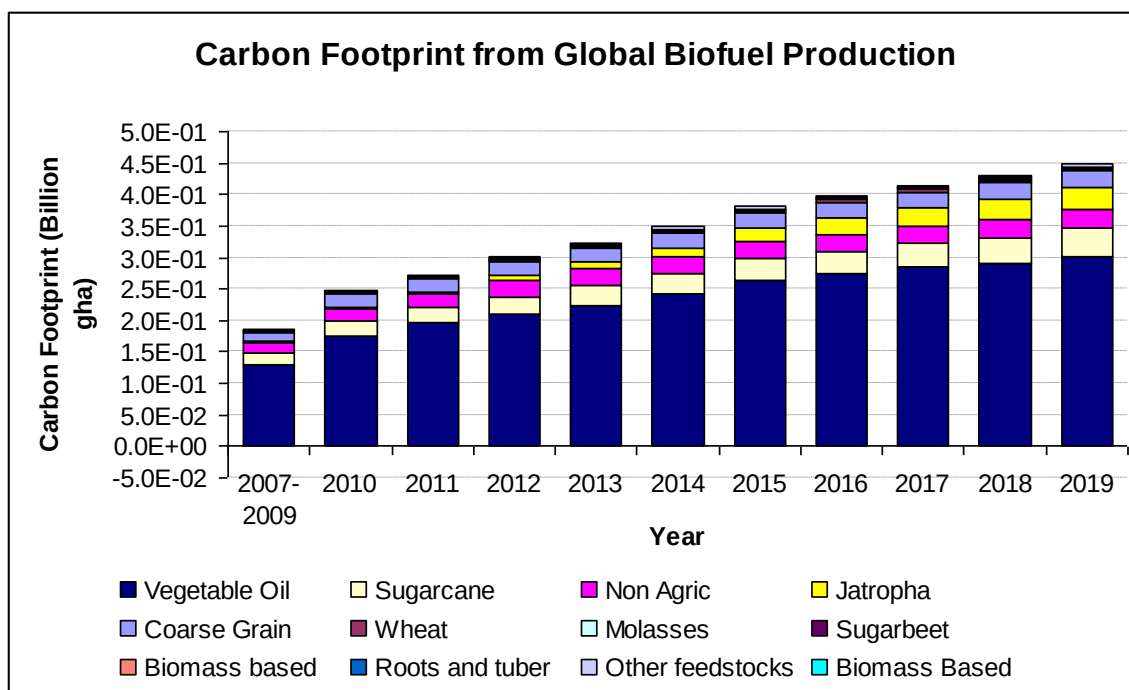


Fig. 3. Carbon footprint associated with world biofuel production (2010-2019).

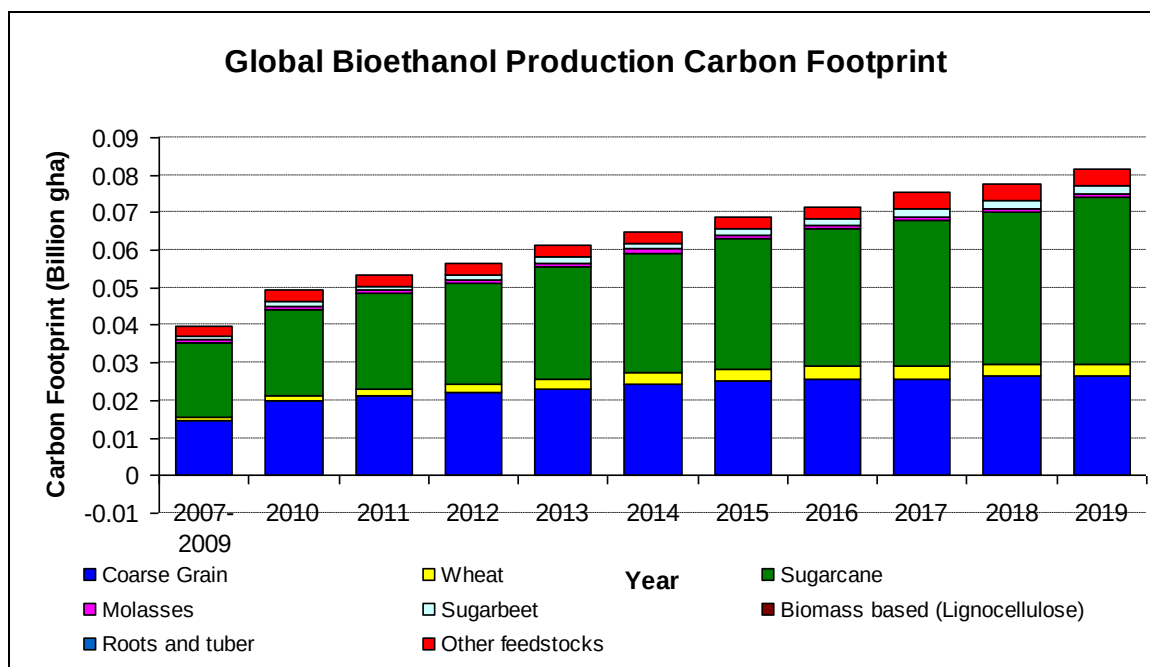


Fig. 4. Carbon footprint associated with world bioethanol production (2010-2019).

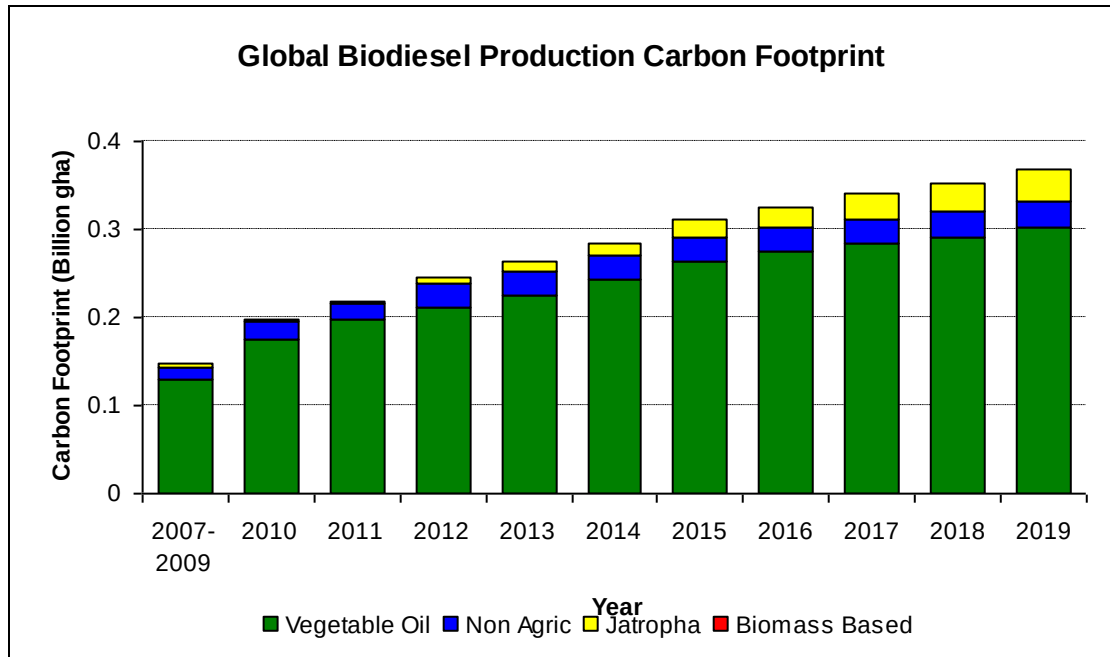


Fig. 5. Carbon footprint associated with world biodiesel production (2010-2019).

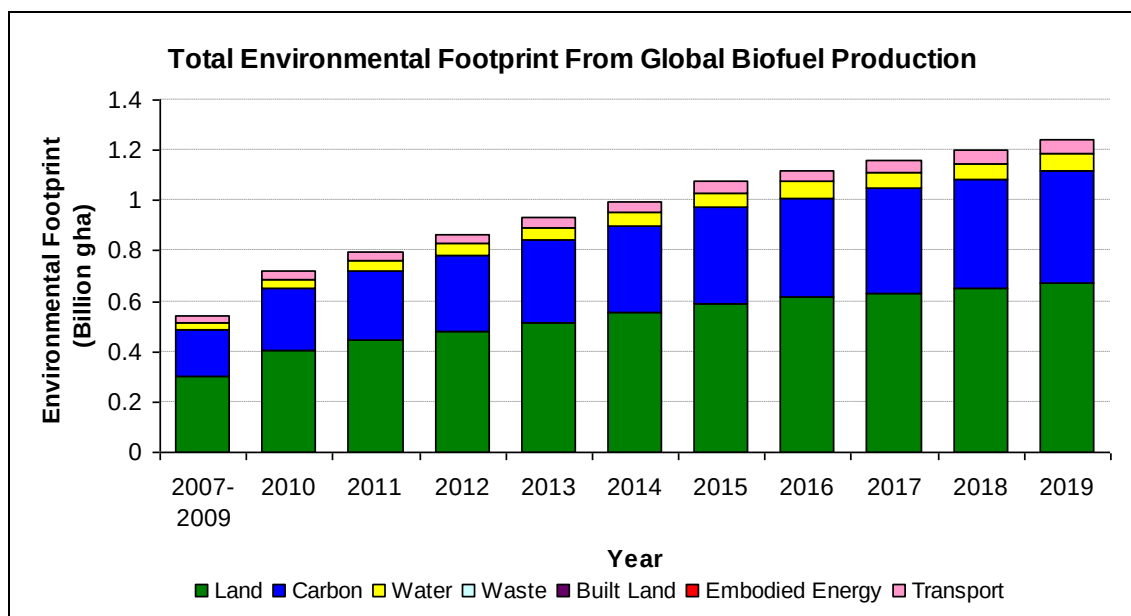


Fig. 6. Environmental footprint associated with world biofuel production (2010-2019).

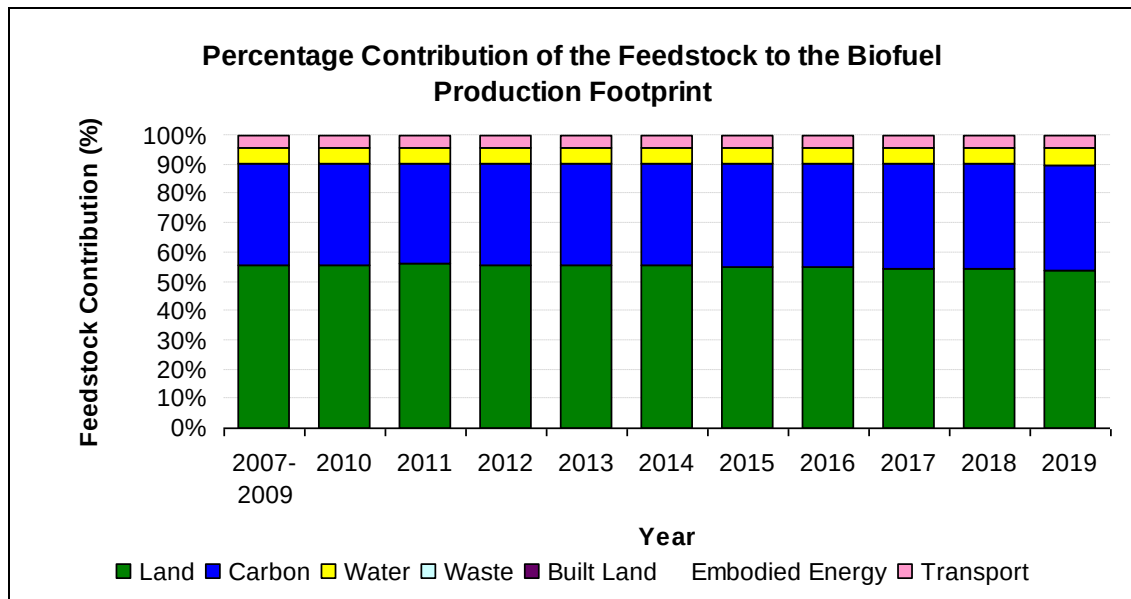


Fig. 7. Environmental footprint component breakdown associated with world biofuel production (2010-2019).

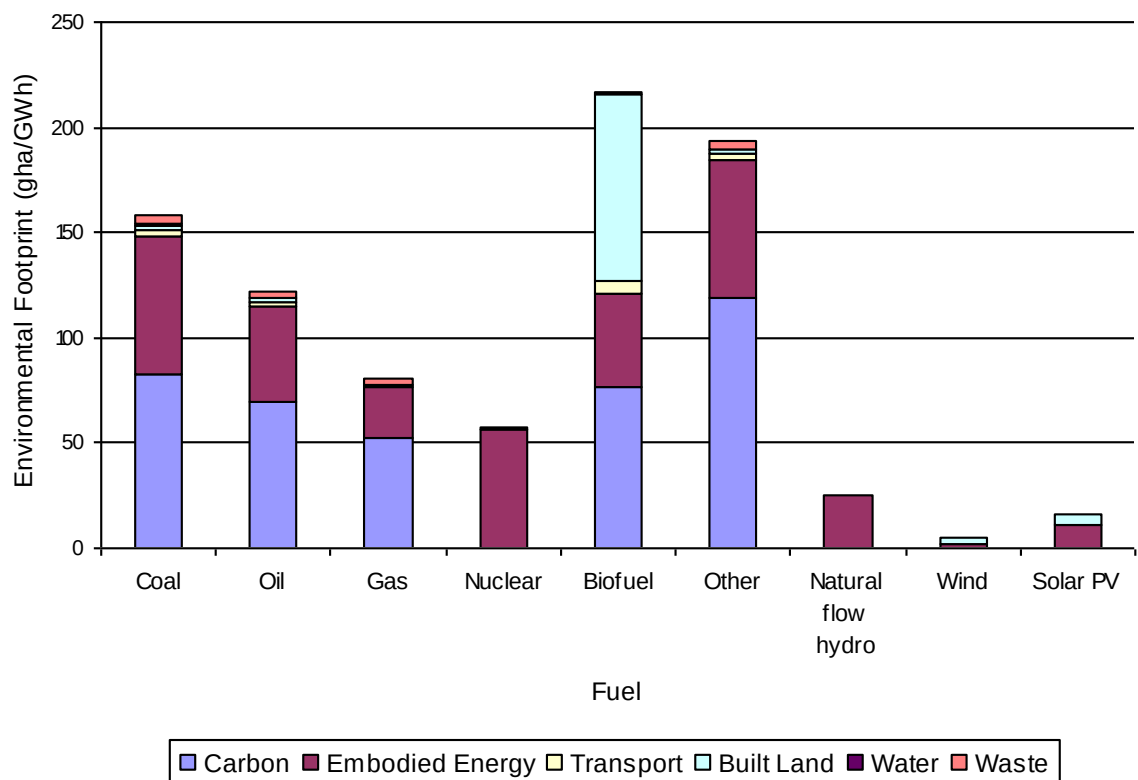


Fig. 8. The environmental footprints per GWh (*ef*) associated with the baseline UK power generators (Source: adapted from Alderson *et al.* [14]).

Table 1: Embodied Energy Footprint Conversion Factors Associated with Primary and Secondary Carriers

Energy Source	Factors (gha/GJ)
Grid Electricity	0.038
Solid Fuel	0.023
Petroleum	0.019
Total	0.080
Conversion Factor (gha/GJ)	0.027

Data Source: Alderson et al. [14].

Table 2: Uncertainty Analysis for the Total Environmental Footprint (EF) of Global Biofuel Production [*circa* 2010]

Footprint Components	Footprint (gha)	Uncertainty	$\left(\frac{\partial R}{\partial x} w\right)^2$
Bioproductive land	4.03E+08	4.20%	2.87E+14
Built land	1.13E+05	4.40%	2.47E+07
Carbon	2.48E+08	5.10%	1.61E+14
Embodied energy	2.38E+03	6.50%	2.40E+04
Transport	3.10E+07	3.80%	1.41E+12
Waste	3.09E+04	5.70%	5.24E+06
Water	7.73E+07	4.03%	2.37E+12
Total	7.59E+08		4.67E+14
Uncertainty-factor (gha)			2.16E+07
Uncertainty			2.95%

NB: The data sources employed here would suggest that these estimates are only valid up to an accuracy of not more than three significant figures.