Dietary Strategies to Reduce Environmental Impact: A Critical Review of the Evidence Base

Bradley G Ridoutt,[1,2] **Gilly A Hendrie,**[3] **and Manny Noakes**[3]

[1]Commonwealth Scientific and Industrial Research Organisation (CSIRO) Agriculture and Food, Victoria, Australia; [2]University of the Free State, Department of Agricultural Economics, Bloemfontein, South Africa; and [3]CSIRO Biosecurity and Health, Adelaide, South Australia, Australia

ABSTRACT

The food system is a major source of environmental impact, and dietary change has been recommended as an important and necessary strategy to reduce this impact. However, assessing the environmental performance of diets is complex due to the many types of foods eaten and the diversity of agricultural production systems and local environmental settings. To assess the state of science and identify knowledge gaps, an integrative review of the broad topic of environment and diet was undertaken, with particular focus on the completeness of coverage of environmental concerns and the metrics used. Compared with the 14 discrete environmental areas of concern identified in the United Nations Sustainable Development Goals, the located journal literature mainly addressed greenhouse gas (GHG) emissions and, to a lesser extent, land and water use. Some relevant concerns were rarely addressed or not addressed at all. In the case of GHG emissions, changes in land use and soil carbon stocks were seldom considered. This represents a disconnect between the science informing strategic climate action in the agricultural sector and the science informing public health nutrition. In the case of land and water use, few studies used metrics that are appropriate in a life-cycle context. Some metrics produce inherently biased results, which misinform about environmental impact. The limited evidence generally points to recommended diets having lower environmental impacts than typical diets, although not in every case. This is largely explained by the overconsumption of food energy associated with average diets, which is also a major driver of obesity. A shared-knowledge framework is identified as being needed to guide future research on this topic. Until the evidence base becomes more complete, commentators on sustainable diets should not be quick to assume that a dietary strategy to reduce overall environmental impact can be readily defined or recommended. *Adv Nutr* 2017;8:933–46.

Keywords: climate change, dietary guidelines, environmental impact assessment, greenhouse gas emissions, land use, life cycle assessment, sustainable diet, United Nations Sustainable Development Goals, water use

Introduction

Dietary strategies have traditionally sought to promote health and well-being and to reduce the incidence of diet-related disease. However, in recent years, dietary strategies have increasingly been investigated as an approach to reducing environmental impacts from the food system (1–3). The reason for this is that the food system has been recognized as a major source of environmental impact (4, 5), with a close relation to several of the so-called planetary boundaries (6). For example, the food system is currently estimated to contribute between 19% and 29% of global greenhouse gas (GHG) emissions (7) and to account for ~70% of global freshwater use (8). Concerns about the environmental impacts of the food system are compounded by the increasing world population and the shifts to resource-intensive patterns of food consumption that can accompany economic development. Dietary change is not the only way of reducing environmental impacts associated with the food system. Efficiencies in production and reductions in food waste are other important strategies. It has also been suggested that change in the governance of the food system is necessary (9). Nevertheless, commitment to achieving lower environmental impacts through dietary change appears to be strong, as evidenced by the variety of national food-based dietary guidelines that now incorporate sustainability principles (10).

Supported by a grant from Meat & Livestock Australia (Sydney, Australia; project D.NRP.1703). The authors have exercised freedom in interpreting the data and making the decision to publish.

Author disclosures: BGR has undertaken food systems research related to environmental issues for a variety of private sector organizations and Australian government agencies. GAH and MN undertake contract research for several companies and nongovernmental organizations on a fee-for-service basis unrelated to environmental issues.

Address correspondence to BGR (e-mail: brad.ridoutt@csiro.au).

Abbreviations used: GHG, greenhouse gas; GWP, global warming potential; ISO, International Organization for Standardization; LCA, life cycle assessment; SDG, Sustainable Development Goal; WSI, Water Scarcity Index.

Adv Nutr 2017;8:933–46; doi: https://doi.org/10.3945/an.117.016691.

Life cycle assessment (LCA) is the technique usually used to quantify the environmental impacts associated with the production and consumption of individual products or services, including foods (11), and with sufficient data the technique can also be applied to dietary patterns (12). As the name suggests, LCA is distinguished by its life cycle perspective, taking into account the various forms of resource use and emissions to air, soil, and water that occur during the various stages of production, such as in farming, processing, packaging, and distribution. Some studies also include food preparation and waste management. The life cycle perspective is critical because the food system is complex and can involve global supply chains. Through the interconnected nature of modern economies, consumers of food can be linked to environmental impacts far from their local environment. In LCA, complex models are used to evaluate the significance of the various forms of resource use and emissions in relation to environmental issues of concern, known as impact categories. The objective of LCA is to inform decision making to address the processes responsible for the most critical environmental impacts, and to avoid policies and decisions that lead to problem shifting from one life cycle stage to another, from one geography to another, or from one type of environmental burden to another. As such, the international standards that govern the practice of LCA (13, 14) incorporate a principle of comprehensiveness, meaning that there should be consideration given to all relevant environmental impacts.

The research literature that describes and compares the environmental performance of different dietary patterns has expanded greatly in recent years. Already, several reviews of this literature have been published (15, 16), with some framed by the broader context of sustainable diets, which can include social and economic aspects (17–19), and others combining environmental performance and nutritional or health indicators (20–24). The point has been underscored that dietary strategies to reduce environmental impact must be nutritionally complete and support longstanding public health nutrition objectives (25). One factor that complicates the interpretation of the current evidence base is the diversity of metrics used to report environmental performance (19). It is often found that metrics calculated by using different methods are reported with the use of the same name. In other cases, the same metric is reported with the use of different names. In addition, there are metrics being used that do not reliably inform about environmental performance and should not be used in the life cycle context. Another factor that complicates the interpretation of the evidence base is that there is often an a priori decision to study one or a particular selection of environmental impact categories and not others. Admittedly, the assessment of the environmental performance of diets is complex due to the many types of food eaten and the diversity of agricultural production methods and local environmental contexts. However, there is danger if conclusions are drawn without critical evaluation of the reliability of metrics and the completeness of impact categories covered. In this context, we performed a literature review of research studies concerning environment and diet with specific attention to impact categories and metrics. The aim was to present the state of the scientific evidence and to identify important knowledge gaps.

Methods

The use of dietary strategies to reduce environmental impact is a broad and cross-cutting research topic. In the absence of a sufficiently specific clinical research question, it is difficult to apply a formal systematic review method on the basis of a narrowly defined set of keywords and rigid inclusion and exclusion criteria for source identification and selection. The relevant evidence base is also diverse in both quality and experimental design. Randomized controlled trials, which are common in the health care literature, are not typically used in the study of the environmental impact of diets. Few studies concerning environment and diet can be compared without interpretation due to the diversity of modeling choices. As such, an integrative review method was applied to synthesize and critically evaluate the variety of evidence in a structured way (26, 27). A narrative review method was not chosen because the scope of the study was beyond a theoretical or conceptual discussion of the topic.

An original search for research articles published in scientific journals was undertaken in February 2017 by using Web of Science (www.webofknowledge.com). The goal was to locate studies that reported an environmental assessment of diets. This is differentiated from the many studies that report environmental assessments of individual foods or food production systems. A wide range of keyword search combinations were used, including: *diet*, environment*, LCA, life cycle assessment, footprint*, sustainable, ecological, carbon, GHG, greenhouse gas, global warming, climate, energy use, water, land, nitrogen, phosphor*, nutrient, eutrophication,* and *pesticide*. This search strategy was supplemented by purposive sampling of highly cited review articles with forward and backward searching of citations. The intention was to broadly survey the landscape of journal articles on the topic. Due to the cross-cutting nature of the topic, it is possible that not every relevant article was located.

The Sustainable Development Goals (SDGs), developed by the UN and released in 2015, identify a wide range of issues relevant to sustainable development (28). The 17 SDGs, comprising 169 targets, were assessed to identify discrete environmental areas of concern (29). Each of the research articles concerning the environmental assessment of diets was then assessed to identify which of the environmental areas of concern found in the SDGs were addressed. The purpose of this analysis was to determine the completeness of coverage of environmental areas of concern by the existing evidence base.

For environmental areas of concern for which a substantial body of literature existed, a critical review of the metrics used was undertaken. Each class of metric was assessed in relation to environmental relevance (30)—that is, its reliability to inform about environmental impact in a life cycle context, which, as mentioned in the Introduction, is critical because resource use and emissions occur across the food chain. Where possible, external benchmarks were used in this assessment, such as the international water footprint standard in the case of water-use assessment (31). For each environmental area of concern, those studies that used reliable metrics were further assessed to identify any generalizable findings with respect to lower environmental impact dietary strategies.

Results

Completeness of coverage of environmental areas of concern

Analysis of the 169 separate targets making up the 17 SDGs showed a wide range of environmental areas of concern (Table 1). The scope of the environmental pillar of sustainable development therefore extends well beyond climate change and the need to mitigate GHG emissions. Also important is the need to address water scarcity (target 6.4), natural resource depletion (targets 8.4 and 12.2), and urban air quality (target 11.6), among others. In total, 14 discrete environmental

TABLE 1 Alignment of environmental areas of concern identified in the UN SDGs and the research literature concerning lower–environmental impact diets[1]

Area of concern	SDG targets	Diet × environment studies,[2] %
Water scarcity	6.4	27
Natural resource depletion	8.4, 12.2	12
Urban air quality	11.6	4
Ozone depletion	12.4	4
Human and ecotoxicity	3.9, 6.3, 12.4	7
Climate change	13.1, 13.2, 13.3, 14.3	74
Marine debris	14.1	0
Marine eutrophication	14.1	18
Freshwater ecosystem quality	6.6, 15.1	12
Depletion of fish stocks	14.4, 14.6	1
Deforestation	15.1, 15.2, 15b	41[3]
Land degradation and desertification	2.4, 15.3	
Biodiversity loss	15.4, 15.5, 15.9, 15a	
Invasive species	15.8	0

[1] SDG, Sustainable Development Goal.

[2] Total of 93 studies assessed.

[3] The diet × environment literature generally assesses land use as a proxy indicator for deforestation, land degradation, and biodiversity loss.

areas of concern were identified across the SDG targets, expressed by using a variety of terms.

The literature search located 93 journal articles that reported on the environmental assessment of diets (32–124). Overall, there was a weak alignment of the environmental areas of concern covered by this literature and those identified in the SDGs (Table 1). The most commonly addressed area of concern was climate change (74% of studies). Deforestation, land degradation and desertification, and biodiversity loss are all closely related to land use, which was addressed by 41% of studies. Water scarcity is related to water consumption, which was addressed by 27% of studies. Other environmental areas of concern were addressed by fewer studies. None of the studies addressed marine debris or invasive species. Only one study addressed the depletion of fish stocks, which is immediately relevant to the food system and a major international concern (125). Only 7% of studies addressed human and ecotoxicity, which relates to the use and management of chemicals and wastes. The use of pesticides and other chemicals in the food systems is an important concern (126, 127).

It is well known that GHG emissions are not a proxy for the full range of environmental impacts associated with food production. As discussed by Nemecek et al. (12), agricultural production can affect the environment in important ways that are unrelated to fossil energy use or GHG emissions, including through emissions of nutrients that contribute to eutrophication, the emission of pesticides and heavy metals that are toxic to humans and ecosystems, and depletion of water resources, which leads to water scarcity and affects freshwater biodiversity. As previously mentioned, the use of land for food production can contribute to deforestation, land degradation, and terrestrial biodiversity loss. Furthermore, although GHG emissions may be of vital importance in some specific food production systems, in the context of the complete food system they may not be the most important environmental area of concern. Castellani et al. (128) undertook an assessment of a basket of 17 food products representative of European Union consumption, and although the results were highly sensitive to modeling choices, <2% of overall environmental impact was attributed to GHG emissions. The highest contribution to overall environmental impact came from human toxicity (cancer and noncancer effects of chemical emissions; >50%). In 2013, the European Food Sustainable Consumption and Production Roundtable released a protocol for the environmental assessment of food and beverage products (129). This protocol requires 14 different environmental impacts to be assessed, which align broadly with the environmental areas of concern identified in the SDGs. According to this protocol, impact categories can only be excluded from the assessment with justification. Again, this highlights the insufficiency of GHG emissions alone in describing the overall environmental performance of a diet.

Other studies have shown that, in comparing food production systems, the results for different environmental impacts are not necessarily correlated. For example, Ridoutt et al. (130) showed that, for beef production systems in Australia, the system with the highest carbon footprint had the second-lowest water footprint, and the system with the highest water footprint had the lowest land-use footprint. Comparing various fresh-tomato production systems for the Sydney market, Page et al. (131) reported that fruit produced year-round with the use of a high-technology greenhouse system had one of the lowest water footprints but the highest carbon footprint. In summary, considering the 93 located journal articles that reported on the environmental assessment of diets, there was generally an incomplete coverage of relevant environmental areas of concern. Although there was substantial literature found that described GHG emissions and diets, there were many fewer studies that addressed land and water use and their impacts, and fewer studies again that addressed other areas of concern. This imbalance has been noted by other authors as well (17, 19). This has important implications for terminology. We have noted a disturbing tendency for sustainable diets to be described as healthy diets with lower GHG emissions (e.g., 38). This is entirely inappropriate. To begin with, sustainability encompasses a wider range of concerns than just the environment, such as social and economic concerns (18). In addition, there are a wide range of concerns relating to the environment, and not just GHG emissions.

Critical review of metrics

Climate change, water use, and land use were the environmental subjects most commonly addressed in the literature (Table 1). For each of these subjects, the metrics used in the literature were classified and assessed in relation to the ability to inform reliably about environmental impact in a life cycle context. Resource use and emissions to the environment can occur at multiple stages along food value chains and in multiple locations. It is important that environmental metrics take into account the different types of resource use, the different types of emissions, as well as any relevant differences in local environmental context in which resource use and emissions occur. When aggregating data along food value chains (agricultural production, processing, transportation, etc.) and across food categories that make up a diet, having common units is necessary but is not the only requirement. Environmental equivalence is also necessary (30). For example, it would not be environmentally meaningful to aggregate emissions of different GHGs without first taking into account their relative global warming potential (GWP). Similarly, it would not be environmentally meaningful to aggregate the emissions of different pollutants without taking into account their different fate, exposure, and effect characteristics. A small emission of a highly toxic pollutant could be of greater concern than a larger emission of a relatively benign pollutant. When resource use or emissions are aggregated across the food system and there is not an adequate consideration of environmental equivalence, higher and lower values for the metrics may not be reliably informing about greater and lesser environmental impact.

GHG emissions. GHG emissions, also referred to by the term "carbon footprint," relate to the climate change area of concern. All of the studies that reported dietary GHG emissions used the GWP metric, which reports results relative to an emission of carbon dioxide (i.e., carbon dioxide equivalent). However, less than half of the studies clearly stated that GWP was assessed over a 100-y time horizon (i.e., GWP_{100}). Because GWP_{100} is the most widely used GWP metric, it is likely that it was also used in other studies, even when it was not specifically stated. GWP_{100} is considered to be an environmentally meaningful metric for the assessment of relative climate impact, because it is published by the Intergovernmental Panel on Climate Change (132) and used in a wide range of industry standards (133–135). However, it is important to note that GWP can be calculated over other time horizons (e.g., 20 or 500 y) and alternative metrics, such as Global Temperature Change Potential, also exist (136) and the use of metrics other than GWP_{100} can affect results when assessing alternative diets. It has also been noted that GWP_{100} may not be the most informative climate metric in all research and policy contexts (137).

In only a small minority of studies was the calculation of the GWP metric found to include GHG emissions (and removals) associated with changes in land use and with changes in soil carbon stocks (9% and 3% of studies assessing GHG emissions, respectively). In the case of changes in land use, the explanation is possibly the potential for highly variable estimates for different agricultural products depending on the accounting method chosen (138). In the case of soil carbon, the explanation is more likely the lack of available data relating changes in soil carbon stocks to specific foods, because changes in soil carbon vary according to local agricultural practices as well as with local soil and climatic conditions. As such, including changes in soil carbon stocks in studies at the level of complete diets is rather difficult. However, the typical omission of soil carbon change in dietary studies can have important implications. The building up of soil carbon stocks is an important GHG mitigation strategy, especially in countries with large land bases. Studies have shown the potential for carbon sequestration in pastures to partially or even completely offset the GHG emissions of ruminant livestock (139). Studies have also shown the GHG emission benefits of land-use change from annual cropping to pastoral farming (140). Tree planting on farms can also make possible GHG-neutral livestock production (141). The key point here is the disconnect between the science that is informing climate action in the agricultural sector and the science that is informing the public health nutrition community about low-GHG-emission diets. On the one hand, the livestock sector is seen as part of a positive strategy to reduce agricultural GHG emissions, whereas on the other hand, reducing the consumption of animal products is often suggested as a key strategy to reduce dietary GHG emissions (1). These 2 perspectives can only be reconciled if the methods used to assess the GHG emissions associated with dietary patterns become more sophisticated and take into account local and regional differences in the agricultural sector and the uptake of sustainable agricultural practices.

Water use. A substantial minority (27%) of the located journal articles addressed water use in some way. Although a variety of terms were found to be used, 4 main types of metrics were identified (**Table 2**). One of the most commonly used metrics was blue water use, which is the consumption of freshwater from surface-water bodies (e.g., rivers, lakes) and groundwater. The problem with this metric is that it does not differentiate water use in regions of water scarcity from water use in regions of water abundance (142, 143). As such, blue water use is not an indicator of contribution to water scarcity, which is the relevant area of concern (Table 1). It makes no sense to aggregate blue water use in a life cycle context because it involves the simple aggregation of water use from locations of differing water scarcity, and as such, the results become uninterpretable. A food item or dietary pattern with a small blue water use in predominantly high–water stress locations could be of greater environmental concern than would a food item or dietary pattern with a larger blue water use in low-water-stress regions. This is the reason why International Organization for Standardization (ISO) 14046:2014 (31), the international water footprint standard, forbids the summation of water use from different locations with different environmental condition indicators.

Green water use is another, less often used, metric to describe water use (Table 2). Green water refers to soil water derived from natural rainfall, which is a precious resource that supports world food production. It has been estimated that between 60% and 70% of global food production is on rain-fed land that relies entirely on green water (144), and over the remaining areas, irrigation is usually supplemental

TABLE 2 Characterization of metrics relating to water use applied in the research literature concerning lower–environmental impact diets

Metric	Number of studies	Reliability[1]	Description
Blue water use	13	No	Volume of surface and groundwater consumed in the production of the different foods that make up the diet
Green water use	6	No	Volume of soil moisture from natural rainfall consumed in the production of the different foods that make up the diet
Virtual-water footprint	13	No	Sum of blue and green water consumption associated with the production of the different foods that make up the diet; can also include gray water, which is a theoretical volume of water required to dilute the load of pollutants emitted to freshwater to the natural background concentration or a selected water quality standard
Water-scarcity footprint	4	Yes	Each instance of water consumption is multiplied by a local Water Scarcity Index and subsequently summed across the life cycle of the different foods that make up the diet; an International Organization for Standardization (ISO14046:2014)–compliant metric

[1] The ability to describe the relative level of environmental impact when applied in a life cycle context.

to green water. The importance of careful and wise management of green water must be underscored: for example, through conservation tillage and mulching to avoid unproductive soil water evaporation. In arid and semiarid regions, green water is often the yield-limiting factor. However, green water is only accessible through the occupation of land. The rain that falls on one field does not fall on another. The inseparability of green water and land means that green water use is actually a type of proxy land-use indicator. Unless an agricultural production system changes the amount of precipitation that flows, via drainage, to ground and surface water, the availability of water resources in the region is not affected. As such, the green water use metric is also not compliant with ISO14046:2014 (31) because it does not address the water-scarcity area of concern and cannot be used to compare the environmental impact from water use in one location with another, or meaningfully aggregated in the life cycle context.

Another commonly used metric to assess water use is virtual water (Table 2). This is essentially the aggregation of blue and green water use, which effectively compounds the problems identified above and is similarly not compliant with ISO14046:2014 (31). Four studies were found to use a water-scarcity footprint metric. To calculate a water-scarcity footprint, each instance of water use in the life cycle of a food product or a diet is multiplied by the relevant local Water Scarcity Index (WSI). Only after applying the WSI are the local water-scarcity results summed across the life cycle. Several global WSI data sets are available for this purpose, and it is important that results are only compared when the same WSI has been applied (145). Water-scarcity footprints calculated in this way are reliable in quantifying the relative contribution to the problem of water scarcity and are ISO14046:2014 compliant. In summary, a reasonable body of literature exists that describes water use in relation to diets. However, very few studies use a metric that informs about relative level of environmental impact with respect to the area-of-concern water scarcity.

Land use. Slightly more than 40% of the located journal articles addressed land use in some way, with the use of 6 different types of metrics (**Table 3**). The most common metric used was total land use. The problem with this metric is that it aggregates land use of different types (e.g., pasture, cropping) and of different productivity. It leads to the natural conclusion that foods produced on the most productive land and by the most intensive methods of production are preferable, because these foods (and dietary patterns that include them) will have the least total land use. However, agricultural lands differ in their inherent productive capability due to differing climatic, topographic, and soil properties. Well-managed agricultural lands of lower productivity are not less sustainable than well-managed agricultural lands of higher productivity. In addition, excessive intensification of agricultural land can lead to land degradation and is least supportive of biodiversity, which are 2 of the areas of concern identified by the SDGs. This metric is also inherently biased against pasture- and rangeland-based livestock production systems that may utilize large areas, but these areas may be unsuitable for other forms of food production. There is also a bias against agricultural production in developing countries where there may be less access to new agricultural technologies and less adoption of intensive farming practices.

The second, third, and fourth metrics (Table 3) are variants on the total land-use theme. The land use by land-use type, which considers arable and nonarable land separately, is an improvement. However, there is often not a rigid distinction between arable and nonarable land and legume-based pastures grown in sequence with crops can offer benefits such as improved soil fertility and a disease break for cereal root pathogens. In addition, the problem of summing together land of different inherent productivity still remains. Other studies have assessed diets relative to a conceptual land-use limit that would enable national food self-sufficiency. However, food self-sufficiency is an unrealistic goal for many countries and may not even enhance national food security compared with a more distributed food system. In any case, this metric goes beyond the scope of describing environmental impact. The ecological footprint

TABLE 3 Characterization of metrics related to land use applied in the research literature concerning lower–environmental impact diets

Metric	Number of studies	Reliability[1]	Description
Total land use	21	No	Total area of arable and nonarable land used in the production of the different foods that make up the diet
Land use × use class	11	No	Land used in the production of the different foods that make up the diet, separately reported for different land-use classes, such as land used for cropping, land used for grazing
Land use relative to a defined limit	2	No	Total land area used in the production of the different foods that make up the diet is compared with a land-availability constraint, such as national agricultural land availability, and reported as a percentage of this limit
Ecological footprint	4	No	A measure of land use required for the production of the different foods that make up the diet, as well as land required for energy production, land for sequestration of emitted greenhouse gases, and water surface area required to support fisheries; the results are expressed in global hectares—globally comparable, standardized hectares with world average productivity
Soil organic carbon deficit	1	Yes	Soil organic carbon content is considered a proxy for soil quality; the metric, which is based on generic factors for soil carbon loss for different forms of land occupation (146), has been recommended as a default method for use in life cycle assessment studies by the European Commission Joint Research Centre (147)
Biodiversity damage potential	2	Yes	Occupied land areas are classified according to type of use (e.g., annual cropping, pasture) and biome; the biodiversity damage potential is based on differences in species richness between agricultural and natural land

[1] The ability to describe the relative level of environmental impact when applied in a life cycle context.

assesses the use of biologically productive land and water surface required to produce resources and to absorb waste (148). The results are expressed in global hectares, taking into account differences in the productivity of land and water resources. As such, it overcomes one of the major problems associated with other land-use metrics. However, the ecological footprint is much more than a land-use metric because it also incorporates a theoretical quantity of land required to sequester GHG emissions and to provide for energy use. As such, it aims to integrate many types of environmental impacts under a perspective that sees land as the ultimate scarce resource. Interpretation is therefore difficult, and there is no particular relation to the areas of concern: deforestation, land degradation and desertification, or biodiversity loss.

The fifth and sixth land-use metrics (Table 3) are distinctly different from the first 4 in that they attempt to address specific environmental areas of concern, rather than the quantum of land use. The soil organic carbon deficit metric is based on soil organic matter as a foundational soil-quality indicator. Loss of soil organic matter is considered to have an environmental impact on soil quality. Generic factors for soil carbon loss under various land uses have been published (146). These generic factors may not accurately reflect changes in soil carbon in specific situations and it is preferable to use local data, although such data may not be readily available for researchers studying diets. The data-intensive nature of the method is its main limitation. Nevertheless, it is considered a reliable metric and has been recommended for use in LCA studies by the European Commission (147). The biodiversity damage potential metric (149) attempts to quantify biodiversity loss by land use. The method is based on differences in species richness between different land-use classes in different biomes. The development of methods to assess land-use impacts on biodiversity in a life cycle context is an active area of research (150), and several new, but related, models have emerged (151). These models all have limitations. For example, they do not generally express the positive biodiversity effects of well-managed, seminatural pastures, and they are usually applied in a way that is too coarse to capture positive biodiversity benefits of environmental plantings on farms, or the local differences in biodiversity impact between production systems of varying intensity. Nevertheless, having been developed within the field of LCA, these metrics are considered appropriate for use in a life cycle context, provided their current limitations are taken into consideration. In summary, there are a reasonable number of studies addressing land use and diets. However, as was found for water use, very few use a metric that provides any reliable information about the relative level of environmental impact.

Evidence in relation to diets and environmental impact

Climate change. Climate change is the area of concern for which there is the greatest amount of evidence with regard to diets (Table 1). Study designs can generally be classified into 2 main types. First, there are modeling studies in which the GHG emissions of average diets are quantified and compared to an alternative dietary pattern. Rather predictably, when the intake of foods with a higher GHG emission intensity is reduced or excluded, the total dietary GHG emissions are lowered. However, the alternative dietary patterns that have been modeled to show potential GHG emission savings have not always been nutritionally complete, in that they were developed only on the basis of total energy or on the supply of a single macronutrient such as protein (22). This is reflected in the findings of a recent systematic review in which 64% of lower-GHG-emission diets were linked to worse nutritional and health indicators, including higher sugar intake and lower micronutrient intake (24). In one study, an average European diet was compared with a modeled diet with a 50% reduction in contents of beef, dairy, pork, poultry, and eggs, which was substituted with a 50% higher intake of bread (79). Not surprisingly, with a net per capita subtraction of 67.6 kg food from the diet/y, a substantial reduction in GHG emissions was reported (>35%). However, the value of this type of modeling scenario must be questioned from a nutritional perspective, and also in terms of population acceptance. In another study, the alternative dietary scenarios for Organization for Economic Co-operation and Development countries included replacing either ruminant meat, all meat, or all livestock products with an equivalent quantity of plant protein (42). The study did not report nutritional indicators and does not appear to have been informed by guidelines for recommended intakes of micronutrients.

More informative are those studies that have modeled the GHG emissions of average diets relative to nutritionally complete recommended diets. In most cases, these studies also reported GHG emission benefits, even ≤25% (e.g., 35, 46, 58), although exceptions exist in which GHG emissions are reported to increase [e.g., 6% (122)]. Largely, this is explained by the typically lower total energy intake of recommended diets than of average diets and the finding that total energy intake and total GHG emissions are positively correlated (43, 73). However, these savings in GHG emissions can be counterbalanced by the additional GHG emissions associated with an increased average intake of dairy products required to meet nutrient requirements and dietary guidelines. Larger potential GHG emission reductions have been shown with the modeling of well-balanced diets that also limit or exclude high-GHG-emission-intensive foods. This includes vegetarian and vegan diets (e.g., 40, 51). With the use of linear programming, Wilson et al. (49) identified a dietary pattern with a reduction of >80% in GHG emissions but with an extreme narrowing of food choice. As diets become more restrictive, increasing care is needed in planning to ensure intake remains nutritionally complete. In Western diets, critical micronutrients typically include vitamins A and B-12, zinc, calcium, highly bioavailable iron, and omega-3 fats. Furthermore, the likelihood of a substantial proportion of the population adopting such inflexible dietary patterns, which vary greatly from cultural norms, must be questioned.

The second main study design involves quantifying the GHG emissions of individual diets in a population, followed by the identification of subgroups with desirable nutritional and environmental characteristics (e.g., 45, 53, 73). As expected, actual diets vary greatly in terms of having a combination of both higher or lower GHG emissions as well as higher or lower diet quality. Importantly, there is already a wide range of dietary patterns in the community that have the characteristics of lower GHG emissions as well as higher nutritional quality. In an Australian study, which was based on >9000 individual adult daily diets, the differences in GHG emissions between the higher-quality, lower-GHG-emission dietary pattern subgroup and the lower-quality, higher-GHG-emission dietary pattern subgroup were 44% for men and 46% for women (152). Critically, the primary differentiating characteristic was the content of energy-dense and nutrient-poor noncore (or discretionary) foods (including alcoholic beverages, sugar-sweetened beverages, confectionary, baked and salted snacks, desserts, and processed meats). Discretionary foods contribute to excess energy intake, they inflate dietary GHG emissions, and they can displace the consumption of nutrient-dense core foods, leading to inadequate micronutrient intake.

In summary, dietary patterns with lower GHG emissions are relatively easy to prescribe. The greater challenge is how to effect dietary change. As far as we are aware there are no statistically valid published studies that describe the nutritional and GHG emission outcomes of a public health nutrition intervention designed to encourage the adoption of lower-GHG-emission diets. Modeling studies, by their nature, make favorable, and usually simplistic, assumptions about dietary substitutions. However, little is known about the way people will actually respond to dietary guidance designed to lower GHG emissions. There is reason to be sober about the prospects for change, given the eating patterns that are prevalent in many countries, despite an abundance of dietary guidance and the very direct personal consequences of unhealthy eating. This is best described as still an emerging area of science with many unanswered questions.

Water scarcity. Compared with climate change, very few of the located journal articles addressed the water-scarcity area of concern with the use of metrics deemed reliable in a life cycle context (**Table 4**). In relation to the British diet, Hess et al. (95) compared the water-scarcity footprints of 3 starchy-carbohydrate food choices: a typical serving of locally grown potatoes, dried pasta from Italy, and basmati rice from India. A shift in British dietary preferences toward rice was found to increase overall water-scarcity impacts and displace those impacts from the United Kingdom to India where water scarcity is a greater environmental concern. British potatoes are gown with modest amounts of irrigation (10.8 L/kg) and mostly in regions of relatively low water scarcity. In contrast, the cultivation of basmati rice in India not only consumes more irrigation water (2407 L/kg) but the local regions are generally characterized by moderate to high water scarcity (95). Hess et al. (94) also assessed the water-scarcity footprints of the average

TABLE 4 Summary of evidence in relation to dietary patterns and water-scarcity impacts

Study, year (ref)[1]	Study context	Comparison	Key finding
Hess et al., 2016 (95)	United Kingdom	Typical portion of fresh potatoes, Italian-produced dried pasta, and Indian-produced basmati rice	The water scarcity footprint of a serving of basmati rice was 2 orders of magnitude greater than a serving of potatoes or pasta
Hess et al., 2015 (94)	United Kingdom	Average UK diet and 5 healthier diets based on the Eatwell Plate	In all cases, fruit and vegetables made the highest contribution to the water-scarcity footprint; healthier diets led to modest changes in the water-scarcity footprint (−3% to +2%); the potential for large shifts in the geographic location of the water scarcity impacts was noted
Notarnicola et al., 2017 (79)	European Union	Basket of 17 foods representative of European Union consumption—scenario 1: 25% reduction in beef, dairy, pork, poultry, and eggs substituted with a 25% increase in bread; scenario 2: as above but with 50% reductions or increases	Scenarios 1 and 2 reduced the water-scarcity footprint by 11% and 22%, respectively
Goldstein et al., 2016 (124)	Denmark	Average Danish adult diet, lacto-ovovegetarian diet, and vegan diet, all normalized to 2000 kcal/d	Compared with the average Danish diet, the vegetarian and vegan diets had 26% and 31% higher water-scarcity footprints, respectively

[1] ref, reference.

UK diet and 5 healthier dietary scenarios on the basis of the Eatwell Plate associated with their dietary guidelines. In all cases, fruit and vegetables made the highest contribution. Overall, the water-scarcity footprints differed little between the diets (<5% change); however, depending on the patterns of trade, major changes in the geographical distribution of the water-scarcity footprints were possible. Notarnicola et al. (79) studied a basket of 17 foods representative of European Union consumption. Scenarios were also modeled in which 25% or 50% reductions in meat and dairy products were substituted with corresponding 25% or 50% increases in bread. Although these alternative scenarios led to reductions in the water-scarcity footprint, they were not nutritionally complete and did not provide sensible information to inform dietary strategies to reduce environmental impact. Finally, Goldstein et al. (124) compared the average Danish diet with a vegetarian and vegan diet, all normalized to 2000 kcal/d. The vegetarian and vegan diets had 26% and 31% increased water-scarcity footprints, respectively. In summary, the available evidence with regard to dietary patterns and water scarcity is very limited. We identified no generalizable findings. Due to the differences in food systems, trade patterns, and their intersection with regions of high water scarcity, findings may not be transferable from one regional or national context to another.

Land degradation and biodiversity loss. Only 3 of the located journal articles addressed areas of concern related to land use with the use of metrics that are applicable in a life cycle context (**Table 5**). Even then, these studies used generic impact-assessment models that may not accurately reflect local conditions, as described previously. The study by Notarnicola et al. (79) that assessed water-scarcity impacts also assessed soil carbon deficit, an indicator of impact on soil health. However, as mentioned in the discussion about water scarcity, the dietary scenarios applied in this study were not nutritionally complete and do not provide sensible information to inform dietary strategies to reduce environmental impact. The studies by Röös et al. (47) and Baroni et al. (115) assessed biodiversity damage potential. A common finding was that well-balanced diets had lower biodiversity impacts than average diets. Although this finding offers additional support for the adoption of recommended diets, the evidence base is rather limited and could have narrow generalizability due, in particular, to regional differences in livestock production systems. As mentioned, well-managed pasture- and rangeland-based livestock production systems can have positive impacts on biodiversity (e.g., 153–155) compared with industrialized livestock production systems that increase demand for cropland and that are more commonly associated with negative biodiversity impacts.

Conclusions

Although the number of journal articles on the subject of environment and diet has grown enormously in recent years, this remains a relatively new area of research and the evidence base to inform dietary interventions for reduced environmental impact is rather incomplete and scant. Compared with the 14 discrete environmental areas of concern identified in the SDGs, the located journal articles mainly addressed GHG emissions; and although this is undoubtedly an important area of concern, it is not a proxy for the full range of environmental concerns associated with food production and consumption and may not even be

TABLE 5 Summary of evidence in relation to dietary patterns and land-use impacts[1]

Study, year (ref)	Study context	Comparison	Key finding
Röös et al., 2015 (47)	Sweden	Current Swedish diet, recommended Nordic diet, and LCHF diet, all adjusted to same energy content	Compared with the recommended Nordic diet, the biodiversity impacts were ∼25% higher for the current diet and ∼60% higher for the LCHF diet
Baroni et al., 2007 (115)	Italy	Average Italian diet and 3 other well-balanced diets: omnivorous (2105 kcal/d), vegetarian (2158 kcal/d), and vegan (2298 kcal/d), produced by using conventional or organic systems	Biodiversity impacts were much higher for the average Italian diet than for any of the 3 well-balanced diets; also, biodiversity impacts were generally higher for diets based on organic farming; biodiversity impacts were lowest for the vegan diet
Notarnicola et al., 2017 (79)	European Union	Basket of 17 foods representative of European Union consumption—scenario 1: 25% reduction in beef, dairy, pork, poultry, and eggs substituted with a 25% increase in bread; scenario 2: as above but with 50% reductions or increases	Scenarios 1 and 2 reduced the estimated soil carbon loss by ∼18% and 36%, respectively

[1] LCHF, low-carbohydrate, high-fat; ref, reference.

the most important one. The located literature also addressed water and land use, but less frequently than GHG emissions, and mainly with the use of metrics that make little sense in a life cycle context and that fail to reliably inform about the level of environmental impact. Some of the environmental areas of concern identified in the SDGs were rarely addressed in the located literature, or not addressed at all. In summary, a reasonable body of evidence exists with regard to diets and GHG emissions, but this cannot be said about the wider topic of diets and environmental impact.

The environmental assessment of diets presents a very complex analytical challenge. Diets are made up of a wide range of individual foods. Some of these foods are minimally processed (e.g., fresh fruit, vegetables, and meats), whereas others are more highly processed and combine various food ingredients. It is not uncommon for larger grocery stores to stock >30,000 individual products. Each of these products has a unique supply chain that reaches back into agriculture, and the individual agricultural production systems can vary greatly, both within and between regions, as can the local environmental context. For example, some agricultural production systems utilize irrigation, whereas others rely entirely on natural rainfall. Where irrigation is practiced, it can be in a region of water scarcity in which environmental flows are compromised or in a region of water abundance in which impacts of water consumption are of little environmental concern.

One of the first challenges in characterizing the environmental impacts of diets is to access data that are accurate in describing the underpinning production systems. However, very often, high-quality data are difficult to obtain and generalizations are made, such as applying a single environmental parameter to an entire agricultural commodity or food category. In other cases, the scope of the assessment is limited. For example, in the case of GHG emissions, changes in soil carbon stocks were rarely considered in the located literature. Furthermore, in the few cases in which changes in soil carbon stocks were considered, generic factors were applied that may not even be indicative of local farming systems. What this leads to is a disconnect between the science that is informing strategic climate action on the ground in the agricultural sector and the science that is seeking to inform the public health nutrition community. This disconnect can only be resolved by improved environmental modeling of diets.

Another challenge is the use of metrics that reliably inform about environmental impact when applied in a life cycle context. In the case of water and land use, we found that appropriate metrics were rarely chosen. Some of the metrics even have the potential to misinform about environmental impact. For example, the total land use metric is inherently biased against pasture- and rangeland-based production systems, as well as cropping systems that utilize less-intensive production practices or land with lower productive capability. There is no reason to conclude that food production on well-managed land of lower inherent productivity (due to climatic, edaphic, or topographic factors) is less sustainable than food production on well-managed land of higher inherent productivity, simply because the former achieves lower yields and therefore requires greater land use per unit of production.

Taking all of the available evidence, there is little that can be concluded, at this time, about dietary strategies to reduce environmental impact. The limited evidence generally points to recommended diets having lower environmental impacts than average diets, although not in every case. This is broadly explained by the overconsumption of food energy, which is common in most average diets and is also a major driver of obesity. The advantage of this approach is that it is consistent with existing public health nutrition advice and will therefore support improved nutrition, and not only environmental impact reduction. Along the same lines, reducing food waste can also be recommended, although this is not a dietary strategy per se but a commonsense, practical action. The importance of strategies to reduce food waste should not be underestimated because it is estimated that 30–50% of all food produced is wasted (156); and in developed countries, the largest proportion of food waste occurs at the household level (157). Modeling studies have also shown the potential for deeper cuts in GHG emissions through the formulation of nutritionally complete diets with minimal inclusion of higher-GHG-emission-intensive foods. However, it has yet to be shown, through the use of reliable metrics, how such diets perform with respect to other environmental areas of concern. There are also major unanswered questions about the effectiveness of interventions to encourage the intake of such diets that offer less flexibility and vary greatly from cultural norms. There is also the potential for unintended nutritional consequences if the food substitutions that occur in practice differ from those that are prescribed. Herein lies a major knowledge gap. It is one thing to develop dietary scenarios to reduce environmental impact, it will be quite another challenge to achieve the successful adoption of such diets.

Perhaps what is most urgently needed is the development of a shared-knowledge framework to inform the design of future research on the topic of environment and diet. At present, the evidence base is not growing nearly as rapidly as the number of new journal articles. The literature is not balanced in terms of environmental areas of concern, there is not enough care taken in the selection of environmentally meaningful metrics, and diets are not always informed by guidelines for recommended intakes of micronutrients. These are just some of the weaknesses of the existing evidence base. A shared-knowledge framework, if developed, would emphasize the need to assess a balance of environmental areas of concern with the use of reliable metrics. The framework would also emphasize the importance of nutritional adequacy, the diversity of dietary patterns already existing within the community, and the existing public health nutrition challenges in achieving recommended intakes of micronutrients (i.e., a whole-diet approach). Furthermore, it would give much greater importance to local variations in food systems, local environmental contexts, and local food-related behaviors. Until such time as the evidence base becomes more complete and robust, commentators on sustainable diets should not be quick to assume that a dietary pattern with a low overall environmental impact can be readily defined or recommended.

Acknowledgments

All authors read and approved the final manuscript.

References

1. Garnett T. Plating up solutions. Science 2016;353:1202–4.
2. Drewnowski A. Healthy diets for a healthy planet. Am J Clin Nutr 2014;99:1284–5.
3. Stehfest E. Food choices for health and planet. Nature 2014;515:501–2.
4. UN Environment Program. Assessing the environmental impacts of consumption and production: priority products and materials. Paris: UN Environment Program; 2010.
5. Tukker A, Huppes G, Guinée J, Heijungs R, de Koning A, van Oers L, Suh S, Geerken T, Van Holderbeke M, Jansen B, et al. Environmental Impact of Products (EIPRO). Technical report EUR22284EN [Internet]. Seville (Spain): EC Joint Research Centre—IPTS; 2006. [cited 2017 Feb 2]. Available from: http://ipts.jrc.ec.europa.eu/publications/pub.cfm?id=1429.
6. Steffen W, Richardson K, Rockström J, Cornell SE, Fetzer I, Bennett EM, Biggs R, Carpenter SR, de Vries W, de Wit CA, et al. Planetary boundaries: guiding human development on a changing planet. Science 2015;347, DOI: 10.1126/science.1259855.
7. Vermeulen SJ, Campbell BM, Ingram JSI. Climate change and food systems. Annu Rev Environ Resour 2012;37:195–222.
8. Whitmee S, Haines A, Beyrer C, Boltz F, Capon AG, Dias BFDS, Ezeh A, Frumkin H, Gong P, Head P, et al. Safeguarding human health in the Anthropocene epoch: report of The Rockefeller Foundation-Lancet Commission on planetary health. Lancet 2015; 386:1973–2028.
9. Garnett T. Food sustainability: problems, perspectives and solutions. Proc Nutr Soc 2013;72:29–39.
10. Fischer CG, Garnett T. Plates, pyramids and planets, developments in national Healthy and Sustainable Dietary Guidelines: a state of play assessment. Oxford (United Kingdom): FAO, University of Oxford; 2016.
11. Hellweg S, Milà i Canals L. Emerging approaches, challenges and opportunities in life cycle assessment. Science 2014;344:1109–13.
12. Nemecek T, Jungbluth N, Milà i Canals L, Schenck R. Environmental impacts of food consumption and nutrition: where are we and what is next? Int J Life Cycle Assess 2016;21:607–20.
13. International Organization for Standardization. ISO 14040:2006. Environmental management: life cycle assessment—principles and framework. Geneva (Switzerland): International Organization for Standardization; 2006.
14. International Organization for Standardization. ISO 14044:2006. Environmental management: life cycle assessment—requirements and guidelines. Geneva (Switzerland): International Organization for Standardization; 2006.
15. Clune S, Crossin E, Verghese K. Systematic review of greenhouse gas emissions for different fresh food categories. J Clean Prod 2017;140: 766–83.
16. Hallström E, Carlsson-Kanyama A, Börjesson P. Environmental impact of dietary change: a systematic review. J Clean Prod 2015;91:1–11.
17. Auestad N, Fulgoni VL III. What current literature tells us about sustainable diets: emerging research linking dietary patterns, environmental sustainability, and economics. Adv Nutr 2015;6:19–36.
18. Johnston JL, Fanzo JC, Cogill B. Understanding sustainable diets: a descriptive analysis of the determinants and processes that influence diets and their impact on health, food security, and environmental sustainability. Adv Nutr 2014;5:418–29.
19. Jones AD, Hoey L, Blesh J, Miller L, Green A, Shapiro LF. A systematic review of the measurement of sustainable diets. Adv Nutr 2016;7: 641–64.
20. Heller MC, Keoleian GA, Willett WC. Toward a life cycle-based, diet-level framework for food environmental impact and nutritional quality assessment. Environ Sci Technol 2013;47:12632–47.
21. Aleksandrowicz L, Green R, Joy EJM, Smith P, Haines A. The impacts of dietary change on greenhouse gas emissions, land use, water use, and health: a systematic review. PLoS One 2016;11:e0165797.
22. Perignon M, Vieux F, Soler LG, Masset G, Darmon N. Improving diet sustainability through evolution of food choices: review of epidemiological studies on the environmental impact of diets. Nutr Rev 2017; 75:2–17.
23. Nelson ME, Hamm MW, Hu FB, Abrams SA, Griffin TS. Alignment of healthy dietary patterns and environmental sustainability: a systematic review. Adv Nutr 2016;7:1005–25.
24. Payne CLR, Scarborough P, Cobiac L. Do low-carbon-emission diets lead to higher nutritional quality and positive health outcomes? A systematic review of the literature. Public Health Nutr 2016;19:2654–61.
25. Ridoutt B, Hendrie G, Noakes M. Dietary strategies to reduce environmental impact must be nutritionally complete. J Clean Prod 2017; 152:26–7.
26. Whittemore R, Knafl K. The integrative review: updated methodology. J Adv Nurs 2005;52:546–53.
27. Russell CL. An overview of the integrative research review. Prog Transplant 2005;15:8–13.

28. United Nations. Transforming our world: the 2030 agenda for sustainable development [Internet]. New York: UN Division for Sustainable Development; 2015. [cited 2017 May 2]. Available from: https://sustainabledevelopment.un.org/post2015/transformingourworld.
29. Ridoutt B, Pfister S, Manzardo A, Bare J, Boulay AM, Cherubini F, Fantke P, Frischknecht R, Hauschild M, Henderson A, et al. Area of concern: a new paradigm in life cycle assessment for the development of footprint metrics. Int J Life Cycle Assess 2016;21:276–80.
30. Ridoutt B, Fantke P, Pfister S, Bare J, Boulay AM, Cherubini F, Frischknecht R, Hauschild M, Hellweg S, Henderson A, et al. Making sense of the minefield of footprint indicators. Environ Sci Technol 2015;49:2601–3.
31. International Organization for Standardization. ISO 14046:2014. Environmental management: water footprint—principles, requirements and guidelines. Geneva (Switzerland): International Organization for Standardization; 2014.
32. Westhoek H, Lesschen JP, Rood T, Wagner S, De Marco A, Murphy-Bokern D, Leip A, van Grinsven H, Sutton MA, Oenema O. Food choices, health and environment: effects of cutting Europe's meat and dairy intake. Glob Environ Change 2014;26:196–205.
33. Yip CSY, Crane G, Karnon J. Systematic review of reducing population meat consumption to reduce greenhouse gas emissions and obtain health benefits: effectiveness and models assessments. Int J Public Health 2013;58:683–93.
34. Germani A, Vitiello V, Giusti AM, Pinto A, Donini LM, del Balzo V. Environmental and economic sustainability of the Mediterranean diet. Int J Food Sci Nutr 2014;65:1008–12.
35. Meier T, Christen O. Environmental impacts of dietary recommendations and dietary styles: Germany as an example. Environ Sci Technol 2013;47:877–88.
36. Hoolohan C, Berners-Lee M, McKinstry-West J, Hewitt CN. Mitigating the greenhouse gas emissions embodied in food through realistic consumer choices. Energy Policy 2013;63:1065–74.
37. Hallström E, Röös E, Börjesson P. Sustainable meat consumption: a quantitative analysis of nutritional intake, greenhouse gas emissions and land use from a Swedish perspective. Food Policy 2014;47:81–90.
38. Horgan GW, Perrin A, Whybrow S, Macdiarmid JI. Achieving dietary recommendations and reducing greenhouse gas emissions: modelling diets to minimize the change from current intakes. Int J Behav Nutr Phy Act 2016;13:46.
39. Tilman D, Clark M. Global diets link environmental sustainability and human health. Nature 2014;515:518–22.
40. Springmann M, Godfray HCJ, Rayner M, Scarborough P. Analysis and valuation of the health and climate change cobenefits of dietary change. Proc Natl Acad Sci USA 2016;113:4146–51.
41. Carlsson-Kanyama A. Climate change and dietary choices—how can emissions of greenhouse gases from food consumption be reduced? Food Policy 1998;23:277–93.
42. Stehfest E, Bouwman L, van Vuuren DP, den Elzen MGJ, Eickhout B, Kabat P. Climate benefits of changing diet. Clim Change 2009;95:83–102.
43. Vieux F, Darmon N, Touazi D, Soler LG. Greenhouse gas emissions of self-selected individual diets in France: changing the diet structure or consuming less? Ecol Econ 2012;75:91–101.
44. Saxe H, Larsen TM, Mogensen L. The global warming potential of two healthy Nordic diets compared with the average Danish diet. Clim Change 2013;116:249–62.
45. Vieux F, Soler LG, Touazi D, Darmon N. High nutritional quality is not associated with low greenhouse gas emissions in self-selected diets of French adults. Am J Clin Nutr 2013;97:569–83.
46. van Dooren C, Marinussen M, Blonk H, Aiking H, Vellinga P. Exploring dietary guidelines based on ecological and nutritional values: a comparison of six dietary patterns. Food Policy 2014;44:36–46.
47. Röös E, Karlsson H, Witthöft C, Sundberg C. Evaluating the sustainability of diets – combining environmental and nutritional aspects. Environ Sci Policy 2015;47:157–66.
48. Berners-Lee M, Hoolohan C, Cammack H, Hewitt CN. The relative greenhouse gas impacts of realistic dietary choices. Energy Policy 2012;43:184–90.
49. Wilson N, Nghiem N, Mhurchu CN, Eyles H, Baker MG, Blakely T. Foods and dietary patterns that are healthy, low-cost, and environmentally sustainable: a case study of optimization modeling for New Zealand. PLoS One 2013;8:e59648.
50. Soret S, Mejia A, Batech M, Jaceldo-Siegl K, Harwatt H, Sabaté J. Climate change mitigation and health effects of varied dietary patterns in real-life settings throughout North America. Am J Clin Nutr 2014; 100:490S–5S.
51. Aston LM, Smith JN, Powles JW. Impact of a reduced red and processed meat dietary pattern on disease risks and greenhouse gas emissions in the UK: a modelling study. BMJ Open 2012;2:e001072.
52. Macdiarmid JI, Kyle J, Horgan GW, Loe J, Fyfe C, Johnstone A, McNeill G. Sustainable diets for the future: can we contribute to reducing greenhouse gas emissions by eating a healthy diet. Am J Clin Nutr 2012;96:632–9.
53. Masset G, Vieux F, Verger EO, Soler LG, Touazi D, Darmon N. Reducing energy intake and energy density for a sustainable diet: a study based on self-selected diets in French adults. Am J Clin Nutr 2014;99: 1460–9.
54. Masset G, Soler LG, Vieux F, Darmon N. Identifying sustainable foods: the relationship between environmental impact, nutritional quality, and prices of foods representative of the French diet. J Acad Nutr Diet 2014;114:862–9.
55. Temme EHM, Bakker HME, Seves SM, Verkaik-Kloosterman J. How may a shift towards a more sustainable food consumption pattern affect nutrient intakes of Dutch children? Public Health Nutr 2015;18: 2468–78.
56. Tyszler M, Kramer G, Blonk H. Just eating healthier is not enough: studying the environmental impact of different diet scenarios for Dutch women (31-50 years old) by linear programming. Int J Life Cycle Assess 2016;21:701–9.
57. Ribal J. Fenollosa1 ML, García-Segovia P, Clemente G, Escobar N, Sanjuán N. Designing healthy, climate friendly and affordable school lunches. Int J Life Cycle Assess 2016;21:631–45.
58. Hendrie GA, Ridoutt BG, Wiedmann TO, Noakes M. Greenhouse gas emissions and the Australian diet—comparing dietary recommendations with average intakes. Nutrients 2014;6:289–303.
59. Scarborough P, Appleby PN, Mizdrak A, Briggs ADM, Travis RC, Bradbury KE, Key TJ. Dietary greenhouse gas emissions of meat-eaters, fish-eaters, vegetarians and vegans in the UK. Clim Change 2014;125:179–92.
60. Milner J, Green R, Dangour AD, Haines A, Chalabi Z, Spadaro J, Markandya A, Wilkinson P. Health effects of adopting low greenhouse gas emission diets in the UK. BMJ Open 2015;5:e007364.
61. Coelho CRV, Pernollet F, van der Werf HMG. Environmental life cycle assessment of diets with improved omega-3 fatty acid profiles. PLoS One 2016;11:e0160397.
62. Green R, Milner J, Dangour AD, Haines A, Chalabi Z, Markandya A, Spadaro J, Wilkinson P. The potential to reduce greenhouse gas emissions in the UK through healthy and realistic dietary change. Clim Change 2015;129:253–65.
63. Hadjikakou M. Trimming the excess: environmental impacts of discretionary food consumption in Australia. Ecol Econ 2017;131:119–28.
64. Heller MC, Keoleian GA. Greenhouse gas emission estimates of U.S. dietary choices and food loss. J Ind Ecol 2014;19:391–401.
65. Monsivais P, Scarborough P, Lloyd T, Mizdrak A, Luben R, Mulligan AA, Wareham NJ, Woodcock J. Greater accordance with the Dietary Approaches to Stop Hypertension dietary pattern is associated with lower diet-related greenhouse gas production but higher dietary costs in the United Kingdom. Am J Clin Nutr 2015;102:138–45.
66. Temme EHM, Toxopeus IB, Kramer GFH, Brosens MCC, Drijvers JMM, Tyszler M, Ocké MC. Greenhouse gas emission of diets in The Netherlands and associations with food, energy and macronutrient intakes. Public Health Nutr 2015;18:2433–45.
67. Sjörs C, Raposo SE, Sjölander A, Bälter O, Hedenus F, Bälter K. Diet-related greenhouse gas emissions assessed by a food frequency questionnaire and validated using 7-day weighed food records. Environ Health 2016;15:15.

68. Hobbs DA, Lovegrove JA, Givens DI. The role of dairy products in sustainable diets: modelling nutritional adequacy, financial and environmental impacts. Proc Nutr Soc 2015;74:E310.
69. Pradhan P, Reusser DE, Kropp JP. Embodied greenhouse gas emissions in diets. PLoS One 2013;8:e62228.
70. Wickramasinghe KK, Rayner M, Goldacre M, Townsend N, Scarborough P. Contribution of healthy and unhealthy primary school meals to greenhouse gas emissions in England: linking nutritional data and greenhouse gas emission data of diets. Eur J Clin Nutr 2016;70:1162–7.
71. Werner LB, Flysjö A, Tholstrup T. Greenhouse gas emissions of realistic dietary choices in Denmark: the carbon footprint and nutritional value of dairy products. Food Nutr Res 2014;58:20687.
72. Vidal R, Moliner E, Pikula A, Mena-Nieto A, Ortega A. Comparison of the carbon footprint of different patient diets in a Spanish hospital. J Health Serv Res Policy 2015;20:39–44.
73. Hendrie GA, Baird D, Ridoutt B, Hadjikakou M, Noakes M. Overconsumption of energy and excessive discretionary food intake inflates dietary greenhouse gas emissions in Australia. Nutrients 2016;8:690.
74. Benvenuti L, De Santis A, Santesarti F, Tocca L. An optimal plan for food consumption with minimal environmental impact: the cse of school lunch menus. J Clean Prod 2016;129:704–13.
75. Pairotti MB, Cerutti AK, Martini F, Vesce E, Padovan D, Beltramo R. Energy consumption and GHG emission of the Mediterranean diet: a systemic assessment using a hybrid LCA-IO method. J Clean Prod 2015;103:507–16.
76. Ulaszewska MM, Luzzani G, Pignatelli S, Capri E. Assessment of diet-related GHG emissions using the environmental hourglass approach for the Mediterranean and new Nordic diets. Sci Total Environ 2017;574:829–36.
77. Tukker A, Goldbohm RA, de Koning A, Verheijden M, Kleijn R, Wolf O, Pérez-Domínguez I, Rueda-Cantuche JM. Environmental impacts of changes to healthier diets in Europe. Ecol Econ 2011;70:1776–88.
78. de Boer J, de Witt A, Aiking H. Help the climate, change your diet: a cross-sectional study on how to involve consumers in a transition to a low-carbon society. Appetite 2016;98:19–27.
79. Notarnicola B, Tassielli G, Renzulli PA, Castellani V, Sala S. Environmental impacts of food consumption in Europe. J Clean Prod 2017;140:753–65.
80. Jiang L, Seto KC, Bai J. Urban economic development, changes in food consumption patterns and land requirements for food production in China. China Agric Econ Rev 2015;7:240–61.
81. Wirsenius S, Azar C, Berndes G. How much land is needed for global food production under scenarios of dietary changes and livestock productivity increases in 2030? Agric Syst 2010;103:621–38.
82. Eshel G, Martin PA, Bowen EE. Land use and reactive nitrogen discharge: effects of dietary choices. Earth Interact 2010;14:21.
83. Kastner T, Rivas MJI, Koch W, Nonhebel S. Global changes in diets and the consequences for land requirements for food. Natl Acad Sci USA 2012;109:6868–72.
84. de Ruiter H, Kastner T, Nonhebel S. European dietary patterns and their associated land use: variation between and within countries. Food Policy 2014;44:158–66.
85. Meier T, Christen O, Semler E, Jahreis G, Voget-Kleschin L, Schrode A, Artmann M. Balancing virtual land imports by a shift in the diet: using a land balance approach to assess the sustainability of food consumption—Germany as an example. Appetite 2014;74:20–34.
86. Springer NP, Duchin F. Feeding nine billion people sustainably: conserving land and water through shifting diets and changes in technologies. Environ Sci Technol 2014;48:4444–51.
87. Thaler S, Zessner M, Weigl M, Rechberger H, Schilling K, Kroiss H. Possible implications of dietary changes on nutrient fluxes, environment and land use in Austria. Agric Syst 2015;136:14–29.
88. Alexander P, Rounsevell MDA, Dislich C, Dodson JR, Engström K, Moran D. Drivers of global agricultural land use change: the nexus of diet, population, yield and bioenergy. Glob Environ Change 2015;35:138–47.
89. Alexander P, Brown C, Arneth A, Finnigan J, Rounsevell MDA. Human appropriation of land for food: the role of diet. Glob Environ Change 2016;41:88–98.
90. Briggs ADM, Kehlbacher A, Tiffin R, Garnett T, Rayner M, Scarborough P. Assessing the impact on chronic disease of incorporating the societal cost of greenhouse gases into the price of food: an econometric and comparative risk assessment modelling study. BMJ Open 2013;3:e003543.
91. Jalava M, Kummu M, Porkka M, Siebert S, Varis O. Diet change—a solution to reduce water use? Environ Res Lett 2014;9:074016.
92. Jalava M, Guillaume JHA, Kummu M, Porkka M, Siebert S, Varis O. Diet change and food loss reduction: what is their combined impact on global water use and scarcity. Earths Futur 2016;4:62–78.
93. Vanham D, del Pozo S, Pekcan AG, Keinan-Boker L, Trichopoulou A, Gawlik BM. Water consumption related to different diets in Mediterranean cities. Sci Total Environ 2016;573:96–105.
94. Hess T, Andersson U, Mena C, Williams A. The impact of healthier dietary scenarios on the global blue water scarcity footprint of food consumption in the UK. Food Policy 2015;50:1–10.
95. Hess T, Chatterton J, Daccache A, Williams A. The impact of changing food choices on the blue water scarcity footprint and greenhouse gas emissions of the British diet: the example of potato, pasta and rice. J Clean Prod 2016;112:4558–68.
96. Blas A, Garrido A, Willaarts BA. Evaluating the water footprint of the Mediterranean and American diets. Water 2016;8:448.
97. Metson GS, Cordell D, Ridoutt B. Potential impact of dietary choices on phosphorus recycling and global phosphorus footprints: the case of the average Australian city. Front Nutr 2016;3:35.
98. Metson GS, Bennett EM, Elser JJ. The role of diet in phosphorus demand. Environ Res Lett 2012;7:044043.
99. Gephart JA, Davis KF, Emery KA, Leach AM, Galloway JN, Pace ML. The environmental cost of subsistence: optimizing diets to minimize footprints. Sci Total Environ 2016;553:120–7.
100. Vintilă I. Ecological footprint evaluation of improved student's menus using fishery products. AACL Bioflux 2010;3:247–53.
101. Vanham D. The water footprint of Austria for different diets. Water Sci Technol 2013;67:824–30.
102. Vanham D, Mekonnen MM, Hoekstra AY. The water footprint of the EU for different diets. Ecol Indic 2013;32:1–8.
103. Sáez-Almendros S, Obrador B, Bach-Faig A, Serra-Majem L. Environmental footprints of Mediterranean versus Western dietary patterns: beyond the health benefits of the Mediterranean diet. Environ Health 2013;12:118.
104. Biesbroek S, Bueno-de-Mesquita HB, Peeters PHM, Verschuren WMM, van der Schouw YT, Kramer GFH, Tyszler M, Temme EHM. Reducing our environmental footprint and improving our health: greenhouse gas emission and land use of usual diet and mortality in EPIC-NL: a prospective cohort study. Environ Health 2014;13:27.
105. Tessari P, Lante A, Mosca G. Essential amino acids: master regulators of nutrition and environmental footprint? Sci Rep 2016;6:26074.
106. Pernollet F, Coelho CRV, van der Werf HMG. Methods to simplify diet and food life cycle inventories: accuracy versus data-collection resources. J Clean Prod 2017;140:410–20.
107. Lukas M, Scheiper ML, Ansorge J, Rohn H, Liedtke C, Teitscheid P. The nutritional footprint—an assessment tool for health and environmental effects of nutrition. Ernahr-Umsch 2014;61:164–70.
108. Lukas M, Rohn H, Lettenmeier M, Liedtke C, Wiesen K. The nutritional footprint—integrated methodology using environmental and health indicators to indicate potential for absolute reduction of natural resource use in the field of food and nutrition. J Clean Prod 2016; 132:161–70.
109. Chen DM, Tucker B, Badami MG, Ramankutty N, Rhemtulla JM. A multi-dimensional metric for facilitating sustainable food choices in campus cafeterias. J Clean Prod 2016;135:1351–62.
110. Marlow HJ, Harwatt H, Soret S, Sabaté J. Comparing the water, energy, pesticide and fertilizer usage for the production of foods consumed by different dietary types in California. Public Health Nutr 2015;18:2425–32.
111. Billen G, Lassaletta L, Garnier J. A vast range of opportunities for feeding the world in 2050: trade-off between diet, N contamination and international trade. Environ Res Lett 2015;10:025001.

112. Lassaletta L, Billen G, Romero E, Garnier J, Aguilera E. How changes in diet and trade patterns have shaped the N cycle at the national scale: Spain (1961-2009). Reg Environ Change 2014;14:785–97.
113. Liu C, Zou C, Wang Q, Hayashi Y, Yasunari T. Impact assessment of human diet changes with rapid urbanization on regional nitrogen and phosphorus flows—a case study of the megacity Shanghai. Environ Sci Pollut Res Int 2014;21:1905–14.
114. Van Kernebeek HRJ, Oosting SJ, Feskens EJM, Gerber PJ, De Boer IJM. The effect of nutritional quality on comparing environmental impacts of human diets. J Clean Prod 2014;73:88–99.
115. Baroni L, Cenci L, Tettamanti M, Berati M. Evaluating the environmental impact of various dietary patterns combined with different food production systems. Eur J Clin Nutr 2007;61:279–86.
116. Marlow HJ, Hayes WK, Soret S, Carter RL, Schwab ER, Sabaté J. Diet and the environment: does what you eat matter? Am J Clin Nutr 2009; 89(Suppl):1699S–703S.
117. Muñoz I, Milà i Canals L, Fernández-Alba AR. Life cycle assessment of the average Spanish diet including human excretion. Int J Life Cycle Assess 2010;15:794–805.
118. Bertoluci G, Masset G, Gomy C, Mottet J, Darmon N. How to build a standardized country-specific environmental food database for nutritional epidemiology studies. PLoS One 2016;11:e0150617.
119. Donati M, Menozzi D, Zighetti C, Rosi A, Zinetti A, Scazzina F. Towards a sustainable diet combining economic, environmental and nutritional objectives. Appetite 2016;106:48–57.
120. Perignon M, Masset G, Ferrari G, Barré T, Vieux F, Maillot M, Amiot MJ, Darmon N. How low can dietary greenhouse gas emissions be reduced without impairing nutritional adequacy, affordability and acceptability of the diet? A modelling study to guide sustainable food choices. Public Health Nutr 2016;19:2662–74.
121. Röös E, Patel M, Spángberg J, Carlsson G, Rydhmer L. Limiting livestock production to pasture and by-products in a search for sustainable diets. Food Policy 2016;58:1–13.
122. Tom MS, Fischbeck PS, Hendrickson CT. Energy use, blue water footprint, and greenhouse gas emissions for current food consumption patterns and dietary recommendations in the US. Environ Syst Decis 2016;36:92–103.
123. Eshel G, Shepon A, Makov T, Milo R. Land, irrigation water, greenhouse gas, and reactive nitrogen burdens of meat, eggs, and dairy production in the United States. Proc Natl Acad Sci USA 2014;111:11996–2001.
124. Goldstein B, Hansen SF, Gjerris M, Laurent A, Birkved M. Ethical aspects of life cycle assessments of diets. Food Policy 2016;59:139–51.
125. FAO. The State of World Fisheries and Aquaculture 2016: contributing to food security and nutrition for all. Rome (Italy): FAO; 2016.
126. Margni M, Rossier D, Crettaz P, Jolliet O. Life cycle impact assessment of pesticides on human health and ecosystems. Agric Ecosyst Environ 2002;93:379–92.
127. Fantke P, Jolliet O. Life cycle human health impacts of 875 pesticides. Int J Life Cycle Assess 2016;21:722–33.
128. Castellani V, Sala S, Benini L. Hotspots analysis and critical interpretation of food life cycle assessment studies for selecting eco-innovation options and for policy support. J Clean Prod 2017;140:556–68.
129. European Food Sustainable Consumption and Production Round Table Working Group 1. ENVIFOOD protocol, environmental assessment of food and drink protocol. Brussels (Belgium): European Food Sustainable Consumption and Production Round Table; 2013.
130. Ridoutt BG, Page G, Opie K, Huang J, Bellotti W. Carbon, water and land use footprints of beef cattle production systems in southern Australia. J Clean Prod 2014;73:24–30.
131. Page G, Ridoutt B, Bellotti B. Carbon and water footprint tradeoffs in fresh tomato production. J Clean Prod 2012;32:219–26.
132. Forster P, Ramaswamy V. Changes in atmospheric constituents and in radiative forcing. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL, editors. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge (United Kingdom): Cambridge University Press; 2007. p. 129–234.
133. International Organization for Standardization. ISO/TS 14067:2013. Greenhouse gases: carbon footprint of products—requirements and guidelines for quantification and communication. Geneva (Switzerland): International Organization for Standardization; 2013.
134. British Standards Institution. PAS2050:2008: specification for the assessment of the life cycle greenhouse gas emissions of goods and services. London: British Standards Institution; 2008.
135. World Resources Institute and World Business Council for Sustainable Development. Greenhouse Gas Protocol: product life cycle accounting and reporting standard [Internet]. 2011. [cited 2017 May 9]. Available from: http://www.ghgprotocol.org/product-standard.
136. Levasseur A, Cavalett O, Fuglestvedt JS, Gasserd T, Johansson DJA, Jørgensen SV, Raugei M, Reisinger A, Schivley G, Strømman A, et al. Enhancing life cycle impact assessment from climate science: review of recent findings and recommendations for application to LCA. Ecol Indic 2016;71:163–74.
137. Cherubini F, Fuglestvedt J, Gasser T, Reisinger A, Cavalett O, Huijbregts MAJ, Johansson DJA, Jørgensen SV, Raugei M, Schivley G, et al. Bridging the gap between impact assessment methods and climate science. Environ Sci Policy 2016;64:129–40.
138. Leinonen I, Williams AG, Kyriazakis I. Evaluating methods to account for the greenhouse gas emissions from land use changes in agricultural LCA. In: Schenck R, Huizenga D, editors. Proceedings of the 9th International Conference on Life Cycle Assessment in the Agri-Food Sector (LCA Food 2014). Vashon (WA): American Center for Life Cycle Assessment; 2014. p. 711–17.
139. Meyer R, Cullen BR, Eckard RJ. Modelling the influence of soil carbon on net greenhouse gas emissions from grazed pastures. Anim Prod Sci 2016;56:585–93.
140. Page G, Simmons A, Ridoutt B, Badgery W, Bellotti B. Using life cycle approach to evaluate trade-offs associated with payment for ecosystem services schemes. In: Schenck R, Huizenga D, editors. Proceedings of the 9th International Conference on Life Cycle Assessment in the Agri-Food Sector (LCA Food 2014). Vashon (WA): American Center for Life Cycle Assessment; 2014. p. 941–47.
141. Doran-Browne NA, Ive J, Graham P, Eckard RJ. Carbon-neutral wool farming in south-eastern Australia. Anim Prod Sci 2016;56: 417–22.
142. Ridoutt BG, Pfister S. A revised approach to water footprinting to make transparent the impacts of consumption and production on global freshwater scarcity. Glob Environ Change 2010;20:113–20.
143. Pfister S, Boulay AM, Berger M, Hadjikakou M, Motoshita M, Hess T, Ridoutt B, Weinzettel J, Scherer L, Döll P, et al. Understanding the LCA and ISO water footprint: a response to Hoekstra (2016) "A critique on the water-scarcity weighted water footprint in LCA". Ecol Indic 2017;72:352–9.
144. Rost S, Gerten D, Bondeau A, Lucht W, Rohwer J, Schaphoff S. Agricultural green and blue water consumption and its influence on the global water system. Water Resour Res 2008;44:W09405.
145. Ridoutt B, Hodges D. From ISO14046 to water footprint labeling: a case study of indicators applied to milk production in south-eastern Australia. Sci Total Environ 2017;599–600:14–9.
146. Milà i Canals L, Muñoz I, McLaren SJ. LCA methodology and modelling considerations for vegetable production and consumption. CES Working Paper 02/07 [Internet]. Guildford (United Kingdom): University of Surrey; 2007. [cited 2017 May 5]. Available from: https://www.surrey.ac.uk/ces/files/pdf/0207_LCA_Methodol_and_LCI_Model_RELU.pdf.
147. European Commission Joint Research Centre. ILCD handbook: recommendations for life cycle impact assessment in the European context based on existing environmental impact assessment models and factors. Vol. 24571. Luxembourg: Publication Office of the European Union; 2011.
148. Ewing B, Moore D, Goldfinger S, Oursler A, Reed A, Wackernagel M. The ecological footprint atlas 2010. Oakland (CA): Global Footprint Network; 2010.

149. de Baan L, Alkemade R, Koellner T. Land use impacts on biodiversity in LCA: a global approach. Int J Life Cycle Assess 2013;18:1216–30.
150. Jolliet O, Frischknecht R, Bare J, Boulay AM, Bulle C, Fantke P, Gheewala S, Hauschild M, Itsubo N, Margni M, et al. Global guidance on environmental life cycle impact assessment indicators: findings of the scoping phase. Int J Life Cycle Assess 2014;19:962–7.
151. Frischknecht R, Fantke P, Tschümperlin L, Niero M, Antón A, Bare J, Boulay AM, Cherubini F, Hauschild MZ, Henderson A, et al. Global guidance on environmental life cycle impact assessment: progress and case study. Int J Life Cycle Assess 2016;21:429–42.
152. Ridoutt B, Hendrie G, Baird D, Hadjikakou M, Noakes M. The balance of core and noncore foods: a critical intervention point to concurrently address both health eating and dietary GHG emissions reduction objectives. In: Proceedings of the 10th International Conference on Life Cycle Assessment of Food 2016. Belfield (Ireland): University College Dublin; 2016. p. A1127–34.
153. Arcoverde GB, Andersen AN, Setterfield SA. Is livestock grazing compatible with biodiversity conservation? Impacts on savanna ant communities in the Australian seasonal tropics. Biodivers Conserv 2017;26:883–97.
154. Fraser MD, Moorby JM, Vale JE, Evans DM. Mixed grazing systems benefit both upland biodiversity and livestock production. PLoS One 2014;9:e89054.
155. van Klink R, Nolte S, Mandema FS, Lagendijk DDG, Wallis DeVries MF, Bakker JP, Esselink P, Smit C. Effects of grazing management on biodiversity across trophic levels—the importance of livestock species and stocking density in salt marshes. Agric Ecosyst Environ 2016;235:329–39.
156. Institution of Mechanical Engineers. Global food: waste not, want not. Westminster (London): Institution of Mechanical Engineers; 2013.
157. Waste and Resources Action Programme. The food we waste: food waste, report v2. Banbury (United Kingdom): Waste and Resources Action Programme; 2008.