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Plant-Based Diets for Mitigating Climate Change

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1. What Is the Diet–Climate Connection?

The large human impact on the biophysical environment has been acknowledged by the proposal for defining a new geological epoch, the Anthropocene, and the term is already widely used informally (Ruddiman et al., 2015). This impact is unsustainable (Hoekstra and Wiedmann, 2014; Steffen et al., 2015), and a large part of it is from the food system (Foley et al., 2011; Garnett, 2011). This means that the supply-side solutions to increasing demand due to growing population and increasing consumption that have defined the history of agriculture are no longer an option, and the focus needs to be on demand-side solutions (Cleveland, 2014).

Many environmental impacts of diets via resource consumption and waste emissions have been documented, including on water quality, water supply, air quality, soil quality, land use, and biodiversity. Along with animal welfare and human health, environmental benefits have long been one of the major advantages of plant-based diets (PBDs, comprising vegan and ovolactovegetarian) promoted by proponents, such as Thomas Tryon in 17th-century England (Stuart, 2008, pp. 72–73). For example, water is a critical resource, and agriculture production alone (not including the rest of the food system) uses the great majority of fresh water globally: 92% of our water footprint (Hoekstra and Mekonnen, 2012), but with large variations within and between crops (Mekonnen and Hoekstra, 2014). Animal production consumes 12% of groundwater and surface water for irrigation, and the total water footprint of animal production is 29% of the total for agricultural production (Mekonnen and Hoekstra, 2012, p. 408). Changing diets by reducing animal foods in countries worldwide could reduce global water consumption, with vegan diets having the greatest reduction: 14.4% of blue (irrigation) and 20.8% of green (precipitation held in soil) water (Jalava et al., 2014).

In this chapter, we focus on the diet–climate connection, that is, on the relative contribution of PBDs to anthropogenic climate change (hereafter simply “climate change”) and its mitigation, since climate change is the major environmental threat to our species and our planet. Increasing concentration of greenhouse gases (GHG) in the atmosphere, which drives global climate change, is a prominent part of human impact in the Anthropocene, and current growth in concentration must be stabilized or even

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reversed to avoid a greater than 2°C or less increase in average global temperature, which would be catastrophic (Hansen and Sato, 2016; Pfister and Stocker, 2016). While estimates vary depending on methods, data, and assumptions, it is clear that the food system is responsible for a major portion of all anthropogenic GHG emissions (GHGE) into the atmosphere. Vermeulen et al. (2012, p. 198) estimated that global food systems contribute 19%–29% of total GHGE, including land use change and food waste, with production accounting for 80%–86% of this. However, Bellarby et al. (2008, p. 5) estimated that agricultural production alone accounted for 17%–32% of the global total. For the United Kingdom, Garnett (2011, p. 524) estimated that agricultural production was only 40% of the total food system GHGE, while Gerber et al. (2013, p. 15) estimated that livestock alone accounted for 14.5% of the global total, including land use change. Taken together, these and other estimates suggest that the food system contributes at least one-third or more of global GHGE.

Fortunately, there is a high correlation between foods that are good for our health and foods that are good for the climate and the environment in general, as popularized by the Barilla double pyramid (BCFN, 2015). This correlation is slowly beginning to find its way into official dietary recommendations, with one (Sweden) of four nations that have included environmental sustainability in their guidelines mentioning climate change mitigation as a reason (Gonzalez Fischer and Garnett, 2016). However, such recommendations can be very controversial, as in the United States, where the recommendation of the Dietary Guidelines Advisory Committee (DGAC) (USDA and HHS, 2015b) to make this link in the new edition of the Dietary Guidelines for Americans (DGA) (USDA and HHS, 2015a) was not taken by the government, most likely because of the pressure from the food industry, especially the meat industry (Goldman, 2015; Gonzalez Fischer and Garnett, 2016, pp. 37–38).

Research on the diet–climate connection is growing rapidly (Heller et al., 2013), and since 2005, the Food Climate Research Network at the University of Oxford has become a major source of information and discussion (http://www.fcrn.org.uk). Because the scientific study of the diet–climate relationship is in its infancy and methods and data sources are actively being developed and debated, our goal in this chapter is to provide a guide to the key issues that need to be addressed for an informed discussion of the climate impact of PBDs, and to the general conclusions that are supported, and not to comprehensively review the existing data. To do this we address three main questions: *How can diets be measured to assess their climate impact? How can climate impact be measured and attributed to diet? What do we know about the relative climate impact of different PBDs?*

2. How Can Diets Be Measured to Assess Their Climate Impact?

Climate impact is commonly measured by using the metric global warming potential (GWP) of GHGs, in units of the equivalent mass of carbon dioxide (CO_2e), with the GWP of $CO_2 = 1$ (Section 3). There are two basic methods of estimating this impact. A bottom-up, process-based life cycle assessment (LCA) assembles GHGE data from the processes comprising the life cycle of foods in a diet. A top-down, economic input–output LCA (EIO-LCA) begins with data at an aggregate system level, like a national food system, and partitions impacts to the components of the system (e.g., http://www.eiolca.net/). Hybrid approaches attempt to combine the best of these two (Matthews et al., 2016, pp. 257–264), and have been proposed and tested for assessing the GHGE of foods comprising diets. A study of the French diet found general agreement between process-based LCA and hybrid LCA results, but it found hybrid data to be more reliable (Bertoluci et al., 2016).

LCAs of foods and diets in terms of their climate impact require many decisions, which are inevitably influenced by values (Goldstein et al., 2016), much of the data required is subject to varying levels of uncertainty, and methods are not fully standardized (Hallström et al., 2015; Heller et al., 2013; Röös et al., 2014). For example, defining system boundaries, structurally, temporally, and spatially, is a key aspect of LCA, requires some subjective judgments, and is subject to debate. Another important choice in LCA is the unit of the food to be measured and allocated an environmental impact, referred to in LCA as the functional unit. Functional units based on mass (e.g., kg), energy (e.g., kcal), serving, single nutrient, or nutritional index can have very different results (Section 4.1). Therefore, we need to keep asking questions about how all of these decisions are made, what an LCA does and does not include, how impacts are defined and measured, and quality of the data used, but also about their effect on moving toward greater human and environmental health (Cleveland et al., 2015).

The impact of a diet on climate is the product of individual foods' impacts, their quantities in the diet, and the number of people following the diet. The actual diets of different segments of a population, or different populations, can be compared (Section 4.2), model diets can be constructed to highlight different impacts, or interactions and tradeoffs between them, and compared with each other or with actual diets (Section 4.3). A third way is to focus on the individual foods that differentiate diets (Section 4.4). As Katz and Meller (2014, p. 94) note, because "food selection is a discrete choice that can be made at a given time," there is also a practical advantage in making information on the climate impact of foods available as a guide to food choice. However, foods and diets can also be conflated in ways that lead to misleading results (Section 4.1).

The climate effects of foods can be evaluated in two basic ways. *First*, we can compare the emissions of different life cycles of the same food, e.g., broccoli that is grown at a nearby farm that you purchase, cook, and eat within 24 h, and is never refrigerated, versus broccoli grown at a distant farm, frozen, packaged, transported in a refrigerated truck, stored in a retail store's freezer, then in your home freezer, before cooking 6 months after it is harvested. *Second*, we can compare the emissions of different foods that serve the same or similar roles in the diet, e.g., in terms of the nutrients they supply. An example of this is the comparison of two types of milk, cow versus plant-based, which can serve the role of "milk" in diets in the Global North both in terms of their place in foods and meals and in terms of the nutrients supplied (Röös et al., 2016). Major challenges for both of these approaches are idiosyncratic differences, the need to balance the huge resource demands of determining the impact of each specific food choice, and the resulting necessity of making decisions based on incomplete information.

Finally, there are two different pathways by which foods and diets affect the environment, the food system on which most research to date has been done, and the healthcare system, which is receiving increasing attention. The *first* is the process of getting food to the eater, from the production and transport of inputs (e.g., irrigation water, fertilizers), through in-field production (e.g., fertilizer application, machinery, labor use), transportation, processing, storage, and retailing, to preparation of food in the household or institution (Sections 4.2–4.4). To this is added the impact of waste throughout the life cycle, including postconsumer plate waste and human and animal waste. The *second* is the impact of food on the environment after it is eaten, which includes its effect on the health of eaters, which drives the GHGE of the healthcare system, and the productivity of eaters, which affects the efficiency of resource use (Section 4.5).

Having considered how the diet component of the diet–climate relationship can be measured, in the next section, we discuss how the climate component can be measured.

3. How Can Climate Impact Be Measured and Attributed to Diet?

We focus in this section on GHGs because they are the most important drivers of climate change and the most commonly measured climate impact of diet. GHGs in the Earth's atmosphere absorb infrared radiation that would otherwise radiate directly into space, resulting in the greenhouse effect. While the greenhouse effect has been recognized for centuries as a beneficial factor for making the Earth much warmer on average than it would otherwise be (Weart, 2008), the additional GHG in the atmosphere due to human activity during the Anthropocene has changed the radiation balance of the Earth's climate system and increased the amount of heat retained, increasing global average temperatures and precipitation extremes (Stocker et al., 2013). The heat-retention effect of a GHG is commonly measured in terms of its net radiative forcing (RF), with a positive RF leading to an increase in heat energy gain in the Earth system, which contributes to global warming. Current rates of increasing RF are predicted to have major and even devastating consequences for humans and the Earth's climate system (Hansen and Sato, 2016; IPCC, 2014; Pfister and Stocker, 2016; Stocker, 2013; Pfister and Stocker 2016; Stocker 2013). Different GHGs have different values of RF based on their heat radiation absorption properties, their concentration in the atmosphere, and their lifetime in the atmosphere. We begin this section with the question of how the climate impact of dietary GHG can be measured.

3.1 How Can We Measure the Climate Impact of GHGs from Diets?

The GWP, the most commonly used metric for measuring the climate impact of GHG, is "An index, based on radiative properties of greenhouse gases, measuring the radiative forcing following a pulse emission of a unit mass of a given greenhouse gas in the present-day atmosphere integrated over a chosen time horizon, relative to that of carbon dioxide" (IPCC, 2013a). For example, releasing 1 kg of methane, which has a 100-year GWP of 34, has the same RF effect of 34 kg of CO_2 on the climate system over 100 years.

Because of the various properties of different GHGs, it can be quite challenging to estimate the climate impact of individual foods or diets, including PBDs. For example, methane is a powerful greenhouse gas, but it has a relatively short lifetime in the atmosphere of only 12.4 years, producing water, CO_2, and ozone (O_3) as feedbacks (Section 3.2). CO_2 is a weaker greenhouse gas, but it lasts much longer in the atmosphere. So, choosing the time periods to use as the basis for the GWP of the different GHGs is arbitrary (Section 3.2). The major world climate science and policy body has stated that there is "no scientific argument" for the 100-year versus other time periods and that it is therefore "a value judgment" (IPCC, 2013b, pp. 711–712).

There are other metrics for comparing GHGs, but they each have problems. For instance, global temperature potential (GTP) is a metric that considers the net change in temperature at a given time in the future, from a pulse of a GHG, and compares it to the temperature change from CO_2. As with the GWP, the assigned time in the future is a highly subjective decision. In the very near term, GTP can be very high for gases such as methane, but less so for times far into the future (Persson et al., 2015), so that using the very low 100-year GTP may lead to claims that do not accurately capture the climate impact of continual release of methane, or the important potential of rapid emissions reduction.

3.2 Why is Methane So Important for Understanding the Climate Impact of Diets?

Methane from the food system comes primarily from enteric fermentation of ruminant animals and anaerobic decomposition of organic waste including manure and food waste. Production of most plant foods has relatively low CH_4 emissions, with the exception of rice, which has relatively high emissions compared with other crops due to anaerobic conditions in flooded paddies. About 31% of methane in the United States comes from enteric fermentation (primarily cows) and manure management (EPA, 2016), with the largest source from ruminant production, dominated by beef, and globally, about 44% of total methane emissions are from livestock (Gerber et al., 2013, p. 15). For example, incorporating beef carcass GHGE (Pelletier et al., 2010), carcass-to-bone-free weight (Hallström and Börjesson, 2013), and a 100-year GWP of 34 for methane, yields a total GHGE impact of 43 kg CO_2e per kg of beef, with methane comprising at least half (22 kg CO_2e).

However, even though the data currently show a large contribution of methane from animal foods, top-down methods often used in national assessments may underestimate this. For example, EPA estimates of the contribution of beef and dairy production to US emissions may underestimate methane emissions by almost 50% (Turner et al., 2015), yet livestock is the only major economic sector not required to report GHGE (Halverson, 2015).

Because methane's lifetime in the atmosphere is only 12.4 years, using a shorter time frame leads to a higher GWP: the 20-year GWP for methane is 86 (including climate-carbon feedbacks), while it is 34 for a 100-year time frame (Myhre et al., 2013, p. 714, Table 8.7). The effects are less pronounced for other food system GHGs with longer lifetimes, such as N_2O with a 121-year lifetime. Most LCAs that include the climate impact of methane from the diet use the 100-year GWP, and many used outdated estimates as low as 21. The 100-year GWP detracts attention from the potential of reductions in short-lived GHGs like methane to mitigate climate change in the short-term (Scovronick et al., 2015), and because of the large proportion of methane emissions are from animal foods, a realistic estimate of the potential of PBDs to mitigate climate change may require using the 20-year GWP.

While experts may debate the relative merits of GWP versus GTP, the overall implication of either metric is clear: reducing methane, including a move to more PBDs, has the potential to contribute to rapid climate change mitigation. Immediate or rapid reductions in methane release will have a substantial impact in the critical short-term, although sustaining these reductions would mean that the benefits would bottom out in the long run as methane concentrations in the atmosphere drop. Thus, methane reductions cannot eliminate the need for CO_2 emission reductions, but they can make important contributions in the near term for rapid reductions in RF.

3.3 Is CO_2 from Respiration a Greenhouse Gas?

Biogenic CO_2 from animal respiration is usually considered climate neutral, i.e., not a GHG (Herrero et al., 2011), because the CO_2 that animals exhale is from the oxidation of the carbon compounds in the plants they eat, which were only recently created by photosynthesis by incorporating carbon in CO_2 removed from the atmosphere. However, Goodland and Anhang's (2009, 2012) much cited research asserted that 51% of the global anthropogenic GHGE is attributable to animal agriculture, including a large proportion due to respiration. Their estimate of 51% has also been widely cited and featured in the recent popular documentary *Cowspiracy* (http://www.cowspiracy.com/). As a result of criticisms of their work (Herrero et al., 2011), Goodland and Anhang (2012) proposed respiration as a "proxy" for past land use change that has resulted in less carbon uptake via photosynthesis than would have otherwise happened. But their methods are not clear, and the result could be double counting CO_2 from respiration and land use change. The impact of land use change for animal food production may be better analyzed on its own, without respiration CO_2 being included.

However, it is important to recognize that there can be longer term imbalances in the amount of CO_2 going into the atmosphere via oxidation from respiration (or burning) of organic matter and the amount of CO_2 leaving the atmosphere via photosynthesis. For example, release of CO_2 via oxidation of carbon compounds in aboveground biomass and soil organic matter as a result of changes in land use, such as clearing native vegetation for pasture or crop production, may exceed the CO_2 removed by photosynthesis during reforestation or crop growth. Omnivorous diets contribute a large proportion of these CO_2 emissions since animal agriculture occupies 80% of land used for food production globally, mostly as pasture, but including 35% of all cropland (Foley et al., 2011). Castanheira and Freire (2013) have pointed out that the large differences in net CO_2 emissions from soybean production (often used as animal feed) are correlated with differences in the amount of preexisting vegetation and soil organic matter removed and the type of tillage practiced (Section 4.4). An imbalance can also have major impacts over the long-term. There is evidence that deforestation and cultivation beginning as long as 7000 years ago, due to the increase in crop and animal agriculture, led to an imbalance that caused net release of CO_2 into the atmosphere, contributing to global warming (Kaplan et al., 2011; Ruddiman, 2013).

3.4 How Does Diet Contribute to Nitrous Oxide Emissions?

Nitrogen plays a significant role in climate change, in large part due to nitrous oxide (N_2O) emissions from the use of organic and synthetic nitrogen fertilizers in crop production (Galloway et al., 2008). N_2O has a very high GWP both short-term and long-term: 298 for a 100-year time frame and 268 for a 20-year time frame (including climate-carbon feedbacks) (Myhre et al., 2013, p. 714, Table 8.7). While it is released at a rate much lower than methane, its higher GWP makes it a significant contributor to climate change. Since ~35% of crop land is used to grow animal feed (Foley et al., 2011), it is not surprising that N_2O from feed production comprises about one-quarter of livestock total emissions of 53% of global N_2O emissions, while manure is the source of the remaining three quarters (Gerber et al., 2013, p. 15). In countries with highly industrialized agricultural systems, such as the United States, agriculture can represent 80% or more of the domestic N_2O sources (EPA, 2014), where animal feed accounts for about 45% of corn and 47% of soy production in the United States (http://www.ers.usda.gov/topics/crops/corn/background.aspx) (Olson, 2006). Even small reductions in animal foods in the diet can have important climate benefits from N_2O emission reductions. For example, reducing poultry meat consumption in most industrial countries by about 50% by 2020, the current level in Japan, would result in a reduction in global N_2O emissions from poultry of about 19% (Reay et al., 2012).

4. What Do We Know About the Relative Climate Impact of Different PBDs?

A number of studies have examined the diet–climate relationship for diets with a range of proportion of plant foods, and they are in general agreement that increasing the proportion of plant foods and decreasing the proportion of animal foods in diets results in reductions in GHGE per capita. Many of these studies have also documented reductions in mortality and morbidity with increasing proportion of plant foods as well. In one of the first systematic reviews of the environmental impact of dietary scenarios, Hallström et al. (2015) analyzed 12 studies published since 2009, and they found that vegan diets provided the largest reduction in GHGE of up to >50%, followed by ovolactovegetarian diets, although there was variation as a result of the type and amount of meat in the diet and the food substituting for meat in the scenarios. Those studies with results that have not supported this general conclusion are likely to have made questionable methodological or empirical assumptions (e.g., Tom et al., 2015) (Section 4.1).

However, while healthy PBDs generally have a much lower environmental impact than omnivorous diets, their impact will vary depending on the proportion of plant foods with different impacts (Section 4.4). Our understanding of the details of the impact of different diets is also limited due to uncertainty, lack of data, and methodological differences. Another complication is that, although climate impact is often positively correlated with other forms of dietary environmental impact, e.g., on water, soil, and biodiversity, in some cases, it may be negatively correlated. This means that PBDs could result in environmental burden shifting; e.g., PBDs or plant foods that have less GHGE than other diets and animal foods may be more water intensive (Goldstein et al., 2016). There is also the risk of burden shifting within climate impact; e.g., increasing carbon sequestration by adding reactive nitrogen (N) from fertilizers to grazing land could result in higher GHGE due to increased N_2O emissions (Henderson et al., 2015).

As discussed in Section 2, diet–climate studies have used two basic approaches: analyzing data for actual diets and estimating their current or projected climate impacts, and modeling changes in current diets following official national or international recommendations to create counterfactual diets, and then estimating the effects of these diets on health and GHGE. Other studies evaluate the climate impact of specific foods as components of diets. To estimate the total impact of diets, the kg CO_2e per kg of food can be multiplied by the food intake per person and the number of people following a diet. Many of the references cited in this section, and throughout this chapter, provide examples of kg CO_2e per kg estimates for different foods and diets and kg CO_2e per person for different populations.

4.1 What Functional Unit Can Be Used to Compare GHGE of Different Diets?

The most frequent metric used for measuring GHGE related to diets is kg CO_2e per some functional unit, for example, kg CO_2e per kg mass, per kcal, or per gram of protein. Using LCA, researchers can determine the GHGE per functional unit associated with different foods. The most comprehensive review of LCAs of climate impact of food and diets found that plant foods such as grains, soy, and other legumes, refined sugars, oils, and fruits, and vegetables generally had relatively low GHGE per kcal, per gram of protein, and per serving, while animal foods such as red meat, fish, and dairy had much higher GHGE per each of these units (Tilman and Clark, 2014). One exception was that due to their relatively low caloric content, vegetables had slightly higher emissions than dairy and eggs per kilocalorie.

A main reason for the higher GHGE intensity of animal foods is their lower efficiency in terms of resources required, and therefore more emissions, per unit of food output compared with plant foods. In other words, eating plants, which convert solar energy to food energy, is more efficient than eating animals that eat the plants since the animals consume primary production before humans consume the animals. While the degree of relatively greater efficiency varies according to the data and methods used, all studies support this conclusion. For example, one estimate for the United States is that per kcal consumed by humans, beef requires 163 times more land, 18 times more water, and 19 times more nitrogen, and produces 11 times more CO_2e than the average for three staple plant foods (wheat, potatoes, rice); and per gram of protein consumed, beef requires 42, 2, and 4 times these resources, and it produces 3 times the CO_2e than the three plant foods (calculations based on Eshel et al., 2014:SI). A study of the Swedish food system compared high-protein plant foods such as soybean, with beef, and found that per gram of protein, beef required 18 times the amount of energy, and it emitted 71 times the CO_2e as soybean (calculations based on Gonzalez et al., 2011). At the global level, an analysis of 120 LCA publications found that ruminant meat had the highest GHGE per serving, per gram of protein, and per kcal, mostly due to methane emissions; for example, per gram of protein, ruminant meat produces over 250 times as much GHGE as legumes (Tilman and Clark, 2014).

GHGE per functional unit is useful to get a sense of the impact of a given food. However, problems can arise when comparing diets based on a single functional unit, for example, energy (kcal), because the types of foods used to satisfy the energy requirement of alternative dietary scenarios can vary significantly in other ways. For instance, two studies (Tom et al., 2015; Vieux et al., 2012) analyzed dietary scenarios that included reduction in meat intake replaced by an increase in fruit and vegetable intake on a calorie for calorie basis and found that this resulted in equal or increased GHGE compared with current diets. The promotional material for Tom et al. (Rea, 2016), and subsequent popular media reports, emphasized the claim that lettuce has higher GHGE than bacon per kcal. However, replacing animal foods with plant foods on a caloric basis is a category error because these foods provide different nutrients; plant foods with high vitamin and mineral densities can have low energy density, leading to high CO_2e per kg.

One alternative to using individual functional units is to estimate the GHGE using a nutritional profile of a diet or food, but this can also be misleading. For example, Smedman et al. (2010) developed a Nutrient Density to Climate Impact (NDCI) index to evaluate different beverages in the Swedish diet, and they found cow milk more GHGE efficient than soy or oat milks, even though its CO_2e emissions per kg were over three times higher. However, Röös et al. observed that though it is important to include nutritional aspects of a beverage in the functional unit for populations with protein and micronutrient deficiency, for populations like that of Sweden that over consume most nutrients, the function of milk as a beverage may be to “wash down food and provide water.” So, a more appropriate functional unit than the NDCI would be 1 kg or 1 L of beverage (Röös et al., 2014, p. 89). Three of the four authors of the Smedman paper were also employed by the Swedish Dairy Association.

Therefore, while functional units are the necessary basis for comparing the GHGE of foods, and thus of diets, for meaningful results they need to be used in ways that reflect the overall goal of improving nutrition and health, while reducing GHGE, and be relevant to the context in which they are applied. This implies that, as Hamm pointed out in reference to the misinterpretation of their results by the authors of the Tom et al. paper, diet–climate studies require a broad interdisciplinary perspective (Hamm, 2016). In the following sections, we look at how this has been accomplished in some important studies relevant to PBDs.

4.2 How Do the GHGE of Existing Diets Compare?

Studies of existing diets show that those that are more plant based have lower GHGE. Scarborough et al.'s analysis of the self-reported dietary patterns of 65,000 participants in the United Kingdom found that high meat eaters had 1.9 times and medium meat eaters about 1.5 times the GHGE as a ovolactovegetarian, and an average meat eater had about 2 times and a high meat eater 2.5 times the GHGE as a vegan eater (Scarborough et al., 2014).

The future impact of existing diets can also be compared. In one of the most exhaustive analyses of the diet–climate connection globally, Tilman and Clark (2014) defined global regions and examined the environmental effects projected to 2050 of current dietary patterns: Mediterranean, pescetarian, ovolactovegetarian, and income-dependent projection of current conventional omnivorous diets. To forecast 2050 diets assuming continuation of past trends, they used about 50 years of data for 100 of the world's more populous nations, and to estimate the GHGE of foods from cradle to farm gate, they used data from 120 LCA publications. They found that an omnivorous diet had about 4 times the GHGE per kcal as a ovolactovegetarian diet, and animal foods had much higher GHGE per kcal, per protein, and per serving than plant foods. Although they did not examine vegan diets separately, dairy accounted for about 40% of GHGE in the ovolactovegetarian diet. In terms of land required to supply the diets, the income-dependent diet required more than two times the additional cropland as the alternative diets. They also estimated the effects of the three alternative diets on mortality, type II diabetes, cancer, and chronic coronary heart disease, based on 10 million person-years of observations on diet and health, which showed reductions in relative risk for these diseases of ~5%–40% for the more PBDs compared their regional conventional omnivorous diets.

Because of the difficulty of having participants follow assigned diets, intervention studies are less common. One intervention study assigned 63 adults randomly to one of five diets— vegan, ovolactovegetarian, pescetarian, semivegetarian (reduced meat omnivorous), and omnivorous—and evaluated their N-footprint (reactive nitrogen released into the environment) at 2 and 6 months (Turner-McGrievy et al., 2016). It found that the vegan diet had significantly lower N-footprint than the other diets, which would mean lower N_2O emissions.

4.3 What Can Model Diets Tell Us?

Most studies of the diet–climate connection look at the relative effects of different model diets, including comparisons with existing diets. Heller et al. looked at the effect of changing the US diet qualitatively, based on the USDA recommended food pattern diet (USDA and HHS, 2010), and quantitatively, by reducing energy intake from the current average of 2534 kcal per day to the recommended 2000 (Heller and Keoleian, 2015). They found that the qualitative change alone actually increased CO_2e per capita per day by 12% from 3.6 to 4.0, while also adding the reduction in energy intake resulted in an overall emissions reduction of only 1%. The main reason for these results is that GHGE reduction due to a reduction in meat consumption was balanced by an increase in GHGE from an increase in dairy consumption, and to a lesser extent by an increase in seafood, fruit, oils, and vegetables. However, 2000 kcal per day USDA recommended ovolactovegetarian and vegan diets reduced emissions from the current diet by 33% and 53%, respectively, which suggests that reducing or eliminating dairy may be critical for reducing the climate impact of PBDs, and that increases in beans/peas, nuts, and soy are also highly beneficial.

Bajželj et al. (2014) created a model relating global land use and agricultural biomass flow, and six scenarios of future impacts based on predictions of future food consumption and required production to 2050. Three of the scenarios were based on current yield trends, and three on the difference between actual and potential yield via sustainable intensification to the point of yield-gap closure, which included improved irrigation efficiency and elimination of overfertilization. Food waste reduction of 50% and dietary change (reduction in sugars, saturated fats, livestock products) were the two demand-side measures that further defined two each of the yield scenarios. For each scenario they estimated forest losses, carbon emissions (from land use change and agricultural production), fertilizer use, and irrigation.

They then compared the annual GHGE of the six scenarios in relation to the estimated GHGE target for 2050 required to stay under a 2°C increase in average global temperature, and they found that the business as usual (BAU) scenario (current yield trends with no food waste reduction or diet change) would almost reach this target, meaning that all sources of GHGE other than food would have to reduce emissions to almost zero to avoid >2°C increase. Even the scenario with yield-gap closure and 50% reduction in food waste reached half of the target GHGE by 2050, but adding diet change reduced this to one-quarter. This implied to the authors that avoiding catastrophic climate change requires changing diets by reducing animal foods. They concluded that when mitigation strategies include significant demand-side measures (food waste reductions and diet change), it is possible to prevent increased agricultural expansion and to decrease GHGE, and that the implementation of healthy diets would greatly benefit both the environment and the general health of the population in regions where excessive consumption of energy-rich food occurs, or may develop.

Springmann et al. (2016) modeled the regional and global effects on GHGE, morbidity, and the economy by 2050 of three model diets—a healthy global diet, ovolactovegetarian diet (VGT), and a vegan diet (VGN)—in comparison with a BAU reference diet (REF) based on FAO projections. They used a risk assessment model to assess the effects on mortality of exposure to dietary changes in red meat and fruits and vegetables, and they linked model diets for different regions to GHGE using a previously published analysis of LCAs (Tilman and Clark, 2014).

They found that with the REF diet, CO_2e would increase >50% by 2050 to >11 Gt per year, whereas the VGT and VGN diets resulted in CO_2e emissions in 2050 that were

45%–55% lower than in 2005–07, and 63%–70% less than REF emissions in 2050 (Springmann et al., 2016). Their estimates for reduced GHGE were conservative because they did not include GHGE from land use change or better health outcomes. They found that the largest absolute reduction in emissions occurred in the Global South, while the largest per capita reduction in emissions occurred in the Global North (which would contribute to food and climate justice). Their most important result was that for a GHGE reduction pathway that would limit global temperature increase to 2°C, the ratio of food-related CO_2e emissions to all emissions increased from 16% in 2005–07 to 52% by 2050 for the REF diet, but it decreased by 1% for the VGN diet. In other words, supporting the conclusion of Bajželj et al. (2014), for the food system to make a pro rata contribution to GHGE reductions to keep global warming <2°C, the vegan (VGN) diet would be necessary.

While most estimates of GHGE from foods or diets do not include LUC because of difficulty in measuring it, it likely accounts for a large portion of diet GHGEs, especially if historical LUC is included (Ruddiman, 2013; Ruddiman et al., 2015) (Section 3.3). Erb et al. (2016) created scenarios based on assumptions about future yields, agricultural areas, livestock feed, and human diets, and they evaluated them in terms of their potential to avoid deforestation. They found that diets were the strongest determinants, and that vegan diets had the largest number of feasible scenarios. "A vegan or [lacto-ovo-]vegetarian diet is associated with only half the cropland demand, grazing intensity and overall biomass harvest of comparable meat-based human diets," and it would also have health benefits. They concluded that this reinforced the importance of demand-side measures for sustainability.

4.4 What Are the GHGE of Different Foods?

As we have seen, PBDs in general are clearly more climate friendly than omnivorous diets; however, the specific food choices can have a large effect on the magnitude of this difference. A number of studies have compared the climate impact of plant and animal foods in terms of different functional units, and we summarized some of these in Section 4.1. Also important for understanding the relative climate impact of PBDs are differences in GHGE among animal foods and among plant foods, and differences for the same foods depending on their life cycles, e.g., how they were grown, transported, processed, stored, or cooked. Extensive data bases of GHGE of different foods in Excel format are available online for the Barilla double pyramid (BCFN, 2015) and Tilman and Clark's analysis of global diets (Tilman and Clark, 2014), and one company makes their database on food carbon footprint available to researchers (http://www.cleanmetrics.com/).

As PBDs increase in popularity, so have plant-based substitutes for animal foods and studies of their comparative climate impacts. For example, a study comparing oat and dairy milk on two model Swedish farms compared the environmental impact of producing oat drink with cow milk in terms of biodiversity conservation, requirements for beef and protein, the opportunity cost of land, and the different protein content of oat and cow milk (Röös et al., 2016). They found "great potential for reduced climate impact" with oat milk, even while keeping some cow milk production.

The relative climate impact of PBDs will depend on the animal foods in the omnivorous diets they are compared with, and there is variability in GHGE between animal foods. Eshel et al.'s 2014 top-down EIO-LCA found that for the United States, beef had much higher GHGE than other animal foods. However, there can also be high variability within categories of animal foods, depending primarily on different production methods, as found in a study of meat consumed in Sweden, where the CO_2e per kg of beef varied from 20 to 41 kg (Hallström et al., 2014). Land use change can make large contributions to animal food emissions, and thus it is important to include if possible when comparing PBDs with standard omnivorous diets. For example, Nijdam et al. (2012) found an upper bound of 129 kg CO_2e per kg beef for extensive systems in Brazil, which involve a significant amount of land use change.

There can also be high variability within plant food categories due to differences in land use change. Soy is a common component of PBDs, valued for its high protein content (~8 g protein per cup, similar to cow milk), and it is often assumed to have a smaller climate impact than animal foods. Castanheira and Freire (2013) compared the GHGE of soybean grown in different ecozones, on different types of land, and using different tillage methods, and they found a very high degree of variability due to LUC, with the highest for conversion of tropical rainforest (17.8 kg CO_2e per kg of soybean) and the lowest for degraded grassland (0.1 kg CO_2e per kg of soybean). When land use change is not considered, the GHGE intensity only varied between 0.3 and 0.6 kg CO_2e per kg of soybean. In addition, all tillage systems had higher GHGE than the corresponding no-till system.

Fruits and vegetables are a major component of PBDs, and increasing their consumption in most diets for their nutritional benefits is commonly recommended (Katz and Meller, 2014), yet there can be a great deal of variation in their GHGE. For example, a study in Switzerland found large differences in CO_2e per kg for different fruits and vegetables, and for individual fruits and vegetables, depending on origin and mode of transport, and on whether they were produced in heated greenhouses (Stoessel et al., 2012). Another study found the kg CO_2e per kg for Swedish tomatoes was approximately 3–4 times that of Swedish carrots, due to the emissions from building and heating greenhouses (Röös and Karlsson, 2013).

Local foods, especially fruits and vegetables, are often assumed to be more climate friendly than imported foods, primarily because of less GHGE from transport (Cleveland et al., 2015). However, regardless of the many other benefits of local food systems, local fruits and vegetables may not have significantly lower GHGE than imported ones. A study of one county in California found that completely localizing fruit and vegetable consumption from the current level of 94% of fruits and vegetables imported from outside of the county to zero imported would reduce GHGE by less than 1% of a household's total emissions for food (Cleveland et al., 2011), in part because direct transport (farm gate to retail, or food miles) only accounts for 11% of GHGE for fruits and vegetables in the United States (Weber and Matthews, 2008). Similarly, a study in the United Kingdom found that if consumers drove more than 7.4 km to purchase organic produce at a farm stand, the GHGE would be more than from a large-scale delivery system that included imported produce, cold storage, packing, and transport to the consumer (Coley et al., 2009).

Food waste is a major contributor to climate impact because a large proportion of food produced is never eaten, and every kilogram of food wasted adds to GHGE and increases the amount of food that needs to be produced to replace it. However, the level of waste differs between foods and combined with different emissions rates, results in different total effects, and here again, PBDs appear more climate friendly than omnivorous ones. One study that modeled the effect of reducing food waste in the United States found that animal foods contributed to GHGE from waste disproportionately, accounting for 74% of CO_2e emissions, but only 33% of waste by mass, with ruminant meat (beef, veal, lamb) having the largest disparity, accounting for 31% of emissions from waste but only 3% by mass (Heller and Keoleian, 2015). Fruits and vegetables by contrast accounted for 33% of waste by mass but only 8% of CO_2e emissions.

4.5 What Are the Climate Impacts of the Effect of PBDs via the Healthcare System?

The food we eat also affects the climate after we eat it, through its influence on health and the healthcare system, and standard diets today have a high burden of disease. For example, the current US health system contributes upward of 16% or more of the US gross domestic product, healthcare GHGE is 8% of the domestic GHGE (Chung and Meltzer, 2009), and diet is a major contributor to the healthcare costs of noncommunicable diseases (Frazão, 1999). As we have seen, PBD's not only have lower GHGE than omnivorous diets, but they are generally healthier.

Hallström et al. (2017) modeled healthier alternative diets (HADs) and analyzed the associated reductions in relative risk of three noncommunicable diseases (type 2 diabetes, coronary heart diseases, and colorectal cancer) strongly linked to diet. They calculated the healthcare costs of each disease and the GHGE of those costs. They found that diets with reduced red and processed meat and refined grains, and increased fruits, vegetables, whole grains, beans, and peas, had 20%–45% lower relative risk for the three diseases and, therefore, lower healthcare costs and associated GHGE. Differences in healthcare costs contributed to differences in GHGE. For example, hospital services and pharmaceutical manufacturing have higher GHGE per dollar of economic activity than physician office services, and different diseases, such as coronary heart disease and type II diabetes, utilize such medical services in different proportions and magnitudes. More specifically, pharmaceuticals make up about 30% of economic activity for diabetes but only about 9.7% for coronary heart disease.

While the study did not consider a complete PBD, the HAD that eliminated red and processed meat resulted in 84 kg CO_2e savings per capita per year from reduced health care costs. Although this is a small portion of a typical American's total carbon footprint (about 0.5%), it likely greatly underestimates the potential because many diseases (e.g., hypertension, stroke, and forms of cancer other than colorectal cancer) associated with the foods changed in the HADs were not included due to lack of adequate documentation of relative risk. In addition, there are also potential diet–disease links for animal foods not changed in the HADs, e.g., dairy.

A less direct diet–climate link is via the effect of diet on body weight. Overweight and obesity have been increasing dramatically worldwide (Ng et al., 2014); they accounted for 6.2% of total human biomass in 2005 (Walpole et al., 2012), and they are associated with dietary change including higher intake of animal foods (Tilman and Clark, 2014), as well as with lower levels of physical activity. Overweight and obesity can increase GHGE via several pathways: increased healthcare system emissions due to association with increased incidence and prevalence of diseases such as diabetes and cancer (Hua et al., 2016) discussed earlier; increased consumption leading to increased food production, which increases emissions throughout the food chain, including from increased human waste; and increased body weight leading to increased transportation burden (Michaelowa and Dransfeld, 2008). Because healthy PBDs compared with standard diets are associated with weight loss (Barnard et al., 2015), and overweight and obesity lead to higher GHGE, a move to more PBDs has the potential to contribute to climate change mitigation, as well as improved health.

A survey of 3463 people in Australia found that both overweight and obesity were independently associated with higher CO_2 emissions from transport, which was mostly explained by greater use of motorized travel, while active transport (walking or cycling) was associated with lower CO_2 emissions (Goodman et al., 2012). The increase in food system GHGE is also evident as increased metabolic rate and respiration CO_2 emissions: based on changes in resting metabolic rate in a 6-month weight loss study, Gryka et al. (2012) estimated that if all obese and overweight adults over 20 years worldwide reduced their weight by 10 kg and maintained it over one year, it would result in a reduction in CO_2 emissions equal to 0.2% of CO_2 from fossil fuel burning and cement manufacture. However, it is important not to double count respiration CO_2 due to obesity and overweight and the life cycle CO_2 emissions from the extra food consumed (Section 3.3).

In addition, the reduction in GHGE and resulting climate change mitigation from a change to more PBDs would also reduce the negative health impacts of climate change itself, which are both direct due to increased temperatures, air and water pollution, extreme weather events, and vector borne diseases (e.g., in the United States USGCRP 2016), and indirectly as the result of disruptions to food production and distribution (Porter et al., 2014). This would, in turn, contribute to reduced GHGE from the healthcare system.

5. Conclusion

While there are many uncertainties, data gaps, and methodological issues that make discerning the detailed effects of PBDs on the climate in comparison with omnivorous diets difficult, the broad picture is clear: most PBDs have much lower GHGE than omnivorous diets, and they can make an important contribution to the urgent task of avoiding catastrophic climate change. Thus, the potential of PBDs to mitigate climate change, as well to increase human health and benefit the environment in general, strongly suggests the need for increasing adoption of PBDs. One of the biggest challenges may be the food industry, which, as mentioned in the introduction, has challenged the inclusion of environmental criteria in dietary guidelines and has actively opposed plant-based food alternatives to animal foods, like mayonnaise, in the market place (Charles, 2015). Meeting this challenge will likely require strong government positions to counter animal food industry resistance (Gonzalez Fischer and Garnett, 2016, p. 63). Another related major challenge is motivating diet change. To support change to more PBDs to mitigate climate change, we will need more action-oriented research on the determinants of diet change by individuals and communities, on the policies that can best support them in that change, and how to motivate the policy makers (Garnett et al., 2015).

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