

What Current Literature Tells Us about Sustainable Diets: Emerging Research Linking Dietary Patterns, Environmental Sustainability, and Economics^{1,2}

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ABSTRACT

The concept of sustainable diets, although not new, is gaining increased attention across the globe, especially in relation to projected population growth and growing concerns about climate change. As defined by the FAO (Proceedings of the International Scientific Symposium, Biodiversity and Sustainable Diets 2010; FAO 2012), “Sustainable diets are those diets with low environmental impacts which contribute to food and nutrition security and to healthy life for present and future generations.” Consistent and credible science that brings together agriculture, food systems, nutrition, public health, environment, economics, culture, and trade is needed to identify synergies and trade-offs and to inform guidance on vital elements of healthy, sustainable diets. The aim of this article is to review the emerging research on environmental and related economic impacts of dietary patterns, including habitual eating patterns, nutritionally balanced diets, and a variety of different dietary scenarios. Approaches to research designs, methodologies, and data sources are compared and contrasted to identify research gaps and future research needs. To date, it is difficult to assimilate all of the disparate approaches, and more concerted efforts for multidisciplinary studies are needed. *Adv Nutr* 2015;6:19–36.

Keywords: sustainability, sustainable diet, environmental impact, diet, dietary patterns

Introduction

Global population growth, which is expected to reach >9 billion by 2050, together with environmental concerns, including climate change, is placing greater pressure on our planet’s finite natural resources (1). In the past century alone, population growth and modernization of human societies have led to unprecedented changes in ecosystems and increased demands for food, fresh water, fiber (e.g., textiles), and energy (e.g., fossil fuel). The food system of the future must meet the nutritional requirements for the health of our future generations but will also depend on the sustainability of natural ecosystems in ways that are economically, socially, and environmentally viable (2, 3).

Beyond increasing agricultural production, meeting future demands for food will require sufficient amounts of nutrient-rich foods to ensure availability of nutritionally adequate, high-quality diets across the globe (4, 5). Nutritionally adequate diets are essential for normal growth and development and play an important role in lowering disease risk, including both communicable and noncommunicable chronic diseases (6, 7). Agricultural systems are part of a larger food system that includes producing, processing, food manufacturing, and distribution to consumers. The food choices that form dietary patterns, in turn, affect the demand for production of agricultural products. Sustainable food systems are critical for achieving healthy, sustainable diets.

Although the concept of sustainable food systems is not new (8), how foods and dietary patterns interconnect with ecosystems and use of natural resources in ways that are environmentally, economically, socially, and culturally sustainable is garnering increasing interest. Whether framed as sustainable food systems (1), sustainable agriculture (2), sustainable diets (9), or sustainable food consumption (1), the common theme is production of sufficient amounts of

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nutritious foods to support the health of future generations while conserving natural resources and minimizing environmental impacts (Table 1). Given the complex nature of this challenge, systems-based frameworks for food and sustainable nutrition have been proposed (10, 11).

Studies examining environmental impacts of individual foods and dietary patterns are now beginning to emerge, but they vary considerably in design and research methodology. The aim of this article is to examine published research on environmental impacts of dietary patterns, specifically habitual eating patterns, dietary recommendations, and a variety of different dietary scenarios. Different approaches to research designs, methodologies, and data sources are discussed and considered within the larger framework of achieving population health and global sustainability.

Methods

Research on this topic cuts across multiple disciplines, including agriculture, nutrition and health, animal science, environmental sciences, social sciences, economics, and policy. Articles included in this review were identified through conventional keyword searching strategies by using PubMed, bibliographies of published papers, and searches of sustainability-related journals. Only studies that examined impacts of dietary patterns on at least one indicator of environmental sustainability were included. Every effort was made to include all relevant published literature across the globe as of 2 April 2014; however, given the cross-disciplinary nature of this topic, some articles inadvertently may have been omitted.

Results

Studies of environmental impacts of current dietary patterns across the globe

Socially and culturally diverse dietary patterns are evident across the globe and within individual countries. Thirty-one studies that examined impacts of dietary patterns on at least one environmental indicator were identified, with more than two-thirds published between 2010 and 2014. Twenty-one were from Europe, 5 from the United States,

1 from New Zealand, 3 from developing regions of India and China, and 1 comparing regions across the globe (Tables 2–5). Two-thirds of the studies worldwide and half from Europe included assessment of the climate impact of eating patterns, specifically greenhouse gas emissions (GHGe)⁵. Impacts of dietary patterns on indicators of land capacity were examined in 12 studies, energy/fossil fuel use in 4 studies, water use in 7 studies, and environmental impacts to human health in 2 studies. One study compared environmental impacts of different dietary patterns on natural resource use, ecosystem quality, and human health; and 2 studies reported environmental impacts of dietary patterns as a combined index.

Environmental impacts of habitual eating patterns, dietary recommendations, and theoretical diets were examined by using various indicators of GHGe, land and agricultural capacity, primary energy use, and water use. Indicators of economic impacts were included in a few studies, although not from all relevant perspectives. Limitations and inconsistencies of research in this emerging area underscore the need to standardize methodology. It remains critical before recommendations for sustainable diets can be made to build a strong scientific foundation of high-quality studies; comprehensively weigh multiple aspects of the environmental, economic, and social dimensions of sustainability; and concurrently address the global challenges of overconsumption and obesity and underconsumption and food insecurity.

Diet-related research on climate impact

Interest in the impact of dietary patterns on climate change is evident by the relative number of studies examining links between diet patterns and GHGe. Global climate change is associated with increased emissions from greenhouse gases, which typically include emissions from carbon dioxide, NH₄ and N₂O, collectively reported as carbon dioxide equivalents (CO₂eq). Although many studies have examined the impact of diet patterns on climate change, the research to date remains inconclusive. The considerable variability in the diet patterns examined, inconsistencies in methodologies used, and lack of agreement on the appropriate unit of expression for diet comparisons are important considerations when reviewing this collective body of literature. In addition, given only a limited number of foods have been evaluated using life cycle assessment (LCA), considerable extrapolation is needed to make many of these assessments. Understanding the impact of extrapolating limited LCA values to an entire diet is critical to making proper and informed dietary guidance recommendations. Summaries of individual studies can be found in Tables 2–5.

Variability in diet patterns. GHGe associated with a variety of highly diverse diet patterns, which included habitual, recommended and theoretical diets, has been reported. Comparability across studies, however, is hampered in many cases by limited information about the composition

TABLE 1 Sustainability definitions

Term (reference)	Definition
Sustainable food systems (1)	Sustainable food systems enable the production of sufficient, nutritious food, while conserving the resources that the food system depends on and lowering its environmental impacts. Such systems are based on the idea that all activities related to food (producing, processing, transporting, storing, marketing, and consuming) are interconnected and interactive.
Sustainable diets (9)	Sustainable diets are those diets with low environmental impacts that contribute to food and nutrition security and to healthy life for present and future generations. Sustainable diets are protective and respectful of biodiversity and ecosystems, culturally acceptable, accessible, economically fair and affordable, nutritionally adequate, safe, and healthy, while optimizing natural and human resources.

⁵ Abbreviations used: CO₂eq, carbon dioxide equivalents; GHGe, greenhouse gas emissions; LCA, life cycle assessment.

TABLE 2 Associations between the nutritional quality of different self-selected diets and GHGe¹

Study, year (reference), country	Diets	Environmental impacts	Key results	Author conclusions	Limitations of study
Vieux et al., 2013 (27), France	Food consumption patterns of adults from a French national diet survey (2007–2008) grouped by quartiles on the basis of nutrition quality	GHGe based on: LCA farm to consumer (except transportation retail to home); LCA ISO 14040; 391 representative foods GHGe reported as: CO ₂ eq/100 g; CO ₂ eq/100 kcal	Higher intake of starches, sweets, salted snacks, and fats associated with lower GHGe. Higher intake of fruits and vegetables associated with higher GHGe. After adjustment for calorie intakes, high nutritional quality diets associated with higher GHGe compared with low nutritional quality diets.	“Our results therefore seem to contradict the widely accepted view that diets that are good for health are also good for the planet.”	Diet-related GHGe limited to 391 representative foods in the French diet
Masset et al., 2014, (13), France	Food consumption patterns of adults from a French national diet survey (2006–2007). Diets classified as “lower carbon” (GHGe below the median), “higher quality” (nutritional adequacy score higher than median), or “more sustainable” (combination of both)	GHGe based on: LCA farm to consumer (except transportation retail to home); LCA ISO 14040; 391 representative foods GHGe reported as: CO ₂ eq/100 kcal	“Lower-carbon” diets had 20% lower GHGe, lower cost, but also lower nutritional quality scores. “Higher nutritional quality” diets had higher GHGe and higher diet cost. Diets defined as “more sustainable” had ~20% lower GHGe, no extra cost, and were consumed by 1 in 5 adults.	Reducing diet-related GHGe and increasing nutritional adequacy are possible through frugality and wiser dietary choices such as a lower intake of meats and alcoholic drinks, higher intake of plant-based foods, and moderate food intake.	Diet-related GHGe limited to 391 representative foods in the French diet. There are no standard definitions for the 3 diet pattern classifications.

¹ CO₂eq, carbon dioxide equivalents; GHGe, greenhouse gas emissions; ISO, International Organization for Standardization; LCA, life cycle assessment.

of the diets studied, differences in sources of GHGe data across studies, and whether the diet-related GHGe were based on consumption (eating patterns), agricultural food commodities, or food supply data inherently accounting for food spoilage and waste.

Descriptive information on the diet patterns studied was wide-ranging, from scant in some studies to very comprehensive and well referenced in others. In the absence of clear descriptive accounting of the diets studied, systematic comparisons of diet-related impacts on GHGe across different studies are not feasible. For example, national dietary recommendations, which are designed to help consumers choose foods to construct healthful diets, generally provide food group–based guidance (e.g., increase consumption of fruits and vegetables, etc.), which can be applied broadly to socially and culturally diverse diets (6). However, how broad recommendations actually get implemented (e.g., which fruits and vegetables actually get increased) may matter considerably when looking at environmental impacts. Unfortunately, details of the foods included in the recommended diets were lacking in most studies.

Another limitation of the research on diet-related impacts on GHGe to date is that GHGe data are available only for a limited percentage of food items relative to the thousands of foods that are available and consumed. Whereas country-specific standard nutrient databases are used to determine the nutrient composition of diet patterns, similar national standard databases of GHGe are not available.

GHGe data for foods among the diets studied ranged from 9 to 391 food groups or food items (12–24). By comparison, in the United Kingdom and the United States, for example, the nutrient composition of the habitual diets is based on the nutrient content of ~5000 foods consumed by the respective populations (25, 26).

In many studies, diet-related GHGe were based on consumption-level data (foods as consumed) (12, 13, 15, 19–21, 23, 27); however, in others, GHGe from agricultural commodities were the source of the diet-related GHGe (16, 18, 28, 29). Some studies (14, 17, 18, 28) reported daily per capita GHGe, taking into account food spoilage and waste. Food waste occurs across the entire supply chain and has been estimated in the range of 10–40% of all food produced; however, a reliable evidence base for assessing food waste globally is lacking (30). Understanding the impact of limitations and differences in available GHGe data on conclusions of environmental impacts of diets is needed.

Inconsistencies in methods to determine GHGe. LCA is the primary method used to assess the GHGe of diet patterns (31); however, flexibility in international standards [International Organization for Standardization (ISO) 14040 and ISO 14044] (32, 33) and the absence of standard LCA databases for representative foods in the marketplace has led to methodologic variability across studies. A critical assessment of LCA methods in food- and diet-related research was published by Heller et al. (31). LCA data for foods

TABLE 3 Environmental impacts of habitual diets, recommended diets, and/or theoretical diets¹

Study, year (reference), country	Diets	Environmental impacts	Key results	Author conclusions	Limitations of study
Berners-Lee et al, 2012 (14), UK	Habitual UK diet National diet survey scaled to per capita intake on the basis of FAO food supply data (FAOSTAT 2001) Theoretical diets: Vegetarian: 1) UK habitual diet with meat kcal replaced with dairy kcal 2) US vegetarian 3) UK habitual diet with meat kcal replaced with nondairy alternatives Vegan: 1) UK habitual diet with meat kcal replaced with dairy kcal 2) US vegetarian 3) UK habitual diet with meat kcal replaced with nondairy alternatives	GHGe based on: LCA farm to retail; LCA by hybrid input-output; 61 retail food categories GHGe reported as: kg CO ₂ -eq/person per day	Theoretical diets compared with habitual UK diet: 1) vegetarian had 18–25% lower GHGe and 9–15% lower diet costs; 2) vegan had 23–31% lower GHGe and 4–14% lower diet costs; 3) all vegetarian and vegan diets had lower protein intakes. One vegan diet scenario had the lowest GHGe but with protein intake below the recommended daily allowance and more added sugars. None of the theoretical diets had higher sodium than the average UK diet.	If UK population changed to vegetarian or vegan diets, GHGe and food costs would be lower. Informed dietary choices can make a difference to GHGe, potentially reducing food-related emissions by ~25%, with potential health benefits.	Diet-related GHGe limited to 61 food categories. LCA for GHGe only farm to retail and from multiple sources. Per capita GHGe from diets was based on national diet survey and FAO food supply database with adjustment assuming food waste similar for all food categories.
Aston et al, 2012 (15), UK	Habitual UK diet National Diet Nutrition Survey (2000–2001) by quintiles of red, processed meat consumption and vegetarian eating patterns; theoretical large reductions in red and processed meat consumption and doubling of vegetarian eating patterns by UK population	GHGe based on: LCA farm to retail; LCA from published data; 45 food categories; GHGe reported as: kg CO ₂ -eq/kg food	Habitual intakes of red, processed meat were 2.5 times higher in top vs. bottom quintile of nonvegetarians. If the number of vegetarians in the UK doubled and all others adopted the diet of the lowest red, processed meat quintile, projected 42–45% lower processed meat intakes, 3–12% lower incidence of coronary heart disease, diabetes mellitus, and colorectal cancer, and 3% lower GHGe.	Reduced consumption of red and processed meat could bring multiple benefits to health and environment.	Diet-related GHGe data limited to 45 food categories. LCA for GHGe only farm to retail and from multiple sources; also, limited information on LCA methods in paper. Theoretical diet assessed reductions in red and processed meat on GHGe and health but did not assess replacing meat with other foods (e.g., fruits, vegetables); see Vieux et al. 2012 (12).

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TABLE 3 (Continued)

Study, year (reference), country	Diets	Environmental impacts	Key results	Author conclusions	Limitations of study
Risku-Norja et al., 2009 (16), Finland	Habitual Finnish diet (daily per capita consumption) Finnish dietary recommendation (2003) Theoretical diets: 1) Ruminants excluded (no milk products; no ruminant meat; beef and mutton replaced with pork and poultry) 2) Vegan diet with no milk or meat (milk replaced with oat-based milk substitute) Farming practices: conventional vs. organic	GHGe based on: Farm only; Published resources; 24 agricultural products GHGe reported as: kg CO ₂ -eq/person per year; Reduction in CO ₂ -eq as % of total from agriculture, from food consumption, from all goods and services, and in the Finnish economy	GHGe from habitual Finnish diet 2 times higher than Fvegan diet, 20–30% higher than Finnish recommended diet, and ruminants-excluded diet. Diet shifts could reduce GHGe by 3–8% of per capita emissions from Finnish goods and services. When accounted for exports, emissions could decrease by 2–7% of Finnish economy. GHGe were ~20% higher for organic than for conventional farming.	Giving up animal husbandry could have maximum reduction of 7% GHGe; however, large-scale changes in the diet of the whole population would be needed. Environmental impacts for food should not be restricted to GHGe. Attention is needed on overall sustainability of food supply.	Diet-related GHGe limited to 24 food groups from agricultural production (on farm only). Limited amount of information provided about the diet patterns.
Saxe et al., 2012 (17), Denmark	Habitual Danish diet, based on >300 foods/beverages Recommended diet: New Nordic diet (more local foods; 75% organic foods) Theoretical scenarios, compared to 3 base diets: 1) Conventional farming 2) Conventional farming with factor for transport of imported foods; 3) Organic farming with factor for transport of imported foods; Other scenarios: 4, 5) Type of meats varied 6, 7) Amounts and types of organic foods varied 8) Ovo-lacto version of scenario 7	GHGe based on: LCA farm to retail; LCA ISO 14040 (GHGe/kg food; based on consequential LCA method); Converted to CO ₂ -eq (IPCC 2007); Accounted for wasted and spoiled food; 31 food categories, derived from >300 foods/beverages GHGe reported as: kg CO ₂ -eq/person per year	GHGe were lower in diets with less meat and dairy. Type of meat in diet can impact GHGe. Within methodologic constraints, local produce may help reduce GHGe. May be negative effects from organic vs. conventional farming. Alcoholic beverages, sweets, and hot drinks (coffee, tea, cocoa) in habitual diet accounted for 22% of diet-based GHGe (meat at 37%). Theoretical vegetarian diet did not reduce GHGe more than optimized omnivore diet.	A well-designed diet could lead to lower climate impact and improved health. A change to Nordic diets (less animal foods, more fruits and vegetables) could support climate change mitigation, but must be cautious with diet recommendations. Reducing alcoholic drinks, hot drinks, and sweets by 50% would reduce GHGe the same as reducing meat intake by 30%.	Diet-related GHGe limited to 31 food categories. LCA for GHGe only farm to retail and from different sources (Danish LCA food database and from literature).

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TABLE 3 (Continued)

Study, year (reference), country	Diets	Environmental impacts	Key results	Author conclusions	Limitations of study
Vieux et al., 2012 (12), France	Habitual diet based on a French national diet survey (2006–2007) Theoretical diets: Habitual diet with 1) 240 fewer kcal 2) 20% less meat/deli with a) no replacement of kcal or b) replacement of kcal with fruits/vegetables, dairy, or mixed dishes 3) Red meat limited to 50 g/d; no deli with a) no replacement of kcal or b) replacement of kcal with fruits/vegetables, dairy, or mixed dishes	GHGe based on: LCA farm to retail; LCA ISO 14040; g CO ₂ eq/100 g of edible portion food; 73 representative foods GHGe reported as: g CO ₂ eq/d	GHGe were lower with 240 fewer kcal and less meat intake (when kcal not replaced with other foods). GHGe were moderately reduced when meat and deli kcal replaced with kcal from dairy or mixed dishes. GHGe were negated or slightly higher when meat and deli kcal were replaced with kcal from fruits and vegetables.	GHGe linked to amount of food and kcal eaten. Substituting fruits and vegetables for meat (especially deli meat) may be desirable for health but is not necessarily the best approach to decreasing diet-associated GHGe.	Diet-related GHGe limited to 73 foods. LCA for GHGe only farm to retail, via conventional production and distribution.
Eshel and Martin, 2006 (28), USA	Food consumption based on per capita food disappearance Theoretical diets: semirealistic mixed diets with animal-based foods at 0–50% daily kcal based on: 1) Average, habitual US diet 2) Lacto-ovo-vegetarian 3) Omnivore with fish source 4) Omnivore with red meat 5) Omnivore with poultry	GHGe based on: Farm only (CO ₂ from direct energy use + non-CO ₂ from agricultural production; NH ₄ , CH ₄ , N ₂ O); LCA ISO 14040 (consequential LCA method) GHGe reported as: g CO ₂ eq/kcal; Tons of CO ₂ /person per year; Energy efficiency (% fossil fuel energy input retrieved as edible energy from protein output)	Energy efficiency of animal-based portion of diets: lacto-ovo-vegetarian, omnivore with poultry > average US diet > omnivore with red meat, omnivore with fish. GHGe estimates from theoretical diets (tons CO ₂ eq/person per year): omnivore with red meat > mean US diet > omnivore with fish > lacto-ovo-vegetarian > omnivore with poultry.	A mixed diet at average US calorie intake has 1485 kg CO ₂ eq higher emissions than the same number of calories from plant foods.	Diet-related GHGe limited to CO ₂ eq from agricultural production (on farm). GHGe from direct energy (primarily fossil fuel) and non-CO ₂ emissions from numerous sources. Theoretical diets described as “semirealistic.”

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TABLE 3 (Continued)

Study, year (reference), country	Diets	Environmental impacts	Key results	Author conclusions	Limitations of study
Popp et al., 2010 (29), 10 global economic regions ²	Habitual diets in 10 regions across the globe (1995 food consumption patterns) Theoretical diets based on habitual diets with: 1) Increased meat and dairy products with or without technological mitigations in agriculture sector 2) decreased meat and dairy products with or without technological mitigations in agriculture sector	GHGe based on: NO ₂ (soil; manure storage) + CH ₄ (rice cultivation; enteric fermentation; manure storage); Farm only; IPPC guidelines Non-GHGe reported as: Metric tons of non-CO ₂ GHGe Projections (2005 to 2055) based on: Global land use model coupled with a vegetarian diet scenario; accounted for crop yields, land and water constraints; trade Modeled global projections to 2055 based on the 10 economic world regions ²	Projected 63% increase in average global non-CO ₂ emissions by 2055 if no change in diet or crop efficiency from 1995 level; wide variability across 10 global regions. Higher meat and dairy with higher incomes globally could further increase non-CO ₂ emissions. A 25% lower demand for meat could lead to lower non-CO ₂ emissions, even lower than in 1995.	The highest reduction potential for non-CO ₂ emissions would be from the combination of technological mitigations in the agricultural sector and changes in food consumption patterns. Important to recognize livestock-based food products are important sources of nutrition, especially for poor and undernourished people in developing regions at risk of protein and nutrient deficiencies.	Diet-related GHGe only from non-CO ₂ sources (NO ₂ , CH ₄) and only from agricultural production (on farm).
Fazeni and Steinmuller, 2012 (18), Austria	Habitual German diet (2001–2006) German Nutrition Society–recommended diet; 9 food categories Theoretical diets: Austria as self-sufficient in agricultural production; Austria as importer and exporter of some agricultural products	Cumulative energy demand and GHGe based on: LCA on farm only; LCA ISO 14040 (2006) Results reported as: Cumulative energy demand (mJ per capita); CO ₂ eq (kg/capita per year); Agricultural land availability (hectares)	If Austrians met dietary guidelines: 1) lower meat consumption could lead to more arable land; 2) energy could be made from renewable feedstock; 3) up to 8% of agricultural land could be available for renewable energy crops; 4) cumulative energy demand and GHGe could decrease by 30–38%.	It is feasible to mitigate GHGe, reduce use of fossil energy and help meet energy demand through renewable energy crops. Agricultural land will always be needed for food and feed production, even with large changes in diets.	Diet-related GHGe, land, and energy demand estimates limited only to 9 food categories and only agricultural production (on farm, conventional). Limited information on estimate for agricultural production needs from recommended diets.
Gerbens-Leenes and Nonhebel, 2002 (34), and Gerbens-Leenes and Nonhebel, 2005 (35), Netherlands	Theoretical diets: 1) Basic diet meeting daily calorie needs to prevent starvation 2) Subsistence diet that meets calorie and nutrient requirements 3) Cultural diet, based on 1950–1990 habitual Dutch diets	Land needed for Dutch food production plus for trade Land needs reported as: Land units relative to a benchmark of 100 land units (defined as Dutch per capita land needs in 1990)	Basic diet needed 23 land units. Subsistence diet needed 67 land units. Cultural, habitual diets with varying composition needed from 23 to 143 land units.	Nutrient-rich foods (fats, foods of animal origin, fruits) must help meet nutrient needs in developing countries. Social and cultural drivers of food consumption claim large parts of available land.	Results are relative to Dutch per capita land requirements in 1990. Land requirements based on only 27 food items/categories. Information on diet compositions is limited.

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TABLE 3 (Continued)

Study, year (reference), country	Diets	Environmental impacts	Key results	Author conclusions	Limitations of study
Temme et al., 2013 (36), Netherlands	Habitual Dutch diet (Dutch dietary survey, 2003) for subset of women, 19–30 y Theoretical diets: Replaced dairy and meat with plant-based meat replacers and soy-based foods at 30% or 100% by weight; Nutrition variables were iron and saturated fat	Land requirements (m ² year/kg) for individual foods and diets estimated from best-available land use data in published literature	Replacing 30% of meat and dairy with plant-based foods would lead to 16% lower land use, 0.7 mg/d higher iron intakes, and 1% lower saturated fat intake. Replacing all meat and dairy with plant-based foods would lead to land use halved, 2.5 mg/d higher iron intake, and 4% lower saturated fat intake.	Replacing meat and dairy foods with plant-based foods could reduce land use and lower saturated fat in young Dutch women and not compromise total iron intake. Sugar intake would probably increase.	Study limited to subset of the population (women, aged 19–30 y). Assumption that all replacement foods would be consumed not validated.
Buzby et al., 2006 (37), USA	Habitual diet based on US national diet survey (2003–2004) US diet recommendation (2005 <i>Dietary Guidelines for Americans</i>)	Land needs: Estimated agricultural production needs to meet dietary recommendations; Assumed consumption of recommended amounts of fruits, vegetables, whole grains, and dairy products by population Land needs reported as: Increase in crop acres needed for population to meet diet guidelines	To meet the fruit, vegetable, and whole-grain recommendations, crop acreage would need to increase by ~7.4 million acres (1.7% of total 2002 US cropland). To meet the dairy guidelines, consumption of dairy products would need to increase by 66%.	Estimates for adoption of the 2005 US Dietary Guidelines gives an indication of the potential long-term agricultural needs.	Estimates based on simple extrapolations. Continuing advances in production efficiencies over time not included in estimates.
Peters et al., 2007 (38), USA (NY)	Theoretical diets: Based on US dietary recommendations (USDA Food Guide Pyramid (2000)); Included 42 diets that differed in consumption of meat/eggs (0–340 g/day) and calories from fat (20–45% of kcal/d)	Land needs: Estimated amount of land needed for all 42 diets Land needs reported as: Hecta-acres of land needed to meet dietary recommendations per person per year in NY	Land needed for NY population to meet dietary recommendations ranged from 0.18 to 0.86 hecta-acres. More land was needed at higher meat/egg intakes but not for all diets; e.g., diets with 56 g (2 ounces) of meat and 27% of kcal from fat needed same amount of land as vegetarian diet with 31% of kcal from fat.	Meat increases land requirements of diets more so than dietary fat. However, diets that include modest amounts of meat and fat can feed slightly more people than higher-fat vegetarian diets.	Results limited to the capacity of land in NY to support MyPyramid dietary recommendations for the NY population.

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TABLE 3 (Continued)

Study, year (reference), country	Diets	Environmental impacts	Key results	Author conclusions	Limitations of study
Peters et al., 2009 (39), USA (NY)	See Peters et al., 2007 (38)	Model of potential food sheds in NY to evaluate capacity to localize food production and reduce distances food travels from the farm to consumer	NY does not have the capacity to produce food for NY residents to meet USDA MyPyramid recommendations. Most NY cities, except New York City, could meet dietary recommendations with in-state foods.	Food-shed approach may be a useful tool for cities and retailers to reduce GHGe and energy needs for transporting food. Results may apply to regions with similar climate, land base, and population density.	See Peters et al., 2007 (38). Study did not estimate minimum distances for all food needs of NY cities.
Peters et al., 2011 (40), USA (NY)	See Peters et al., 2007 (38) Theoretical diets: 11 scenarios; 0–100% of population eating a “local” diet by food group (grains, vegetables, fruits, dairy, meat, and eggs)	Land use value attained by allocating food groups to meet NY food needs	Maximum land use value increased as consumption of NY state local food increased. Competition for best use of land in NY favors dairy, eggs, fruits, and vegetables relative to grains and meat. Up to two-thirds of NY food needs could be supplied by in-state land.	Local and regional food systems in NY could specialize on high-value crops and livestock. This approach is more realistic than a simple food miles–based approach.	Proof-of-concept study. Study limited to the capacity agricultural land in NY to support “local” diets of NY population centers.
Vanham, 2013 (47), Austria	Austrian habitual diets (1996–2005) German dietary recommendations Theoretical diets: Vegetarian diet; Combined dietary recommendations and vegetarian diet	Water footprint of consumption Based on food supply (FAO balance sheets) Reported as L/capita per day	German-recommended diet had lower water footprint of consumption than the Austrian habitual diet; theoretical vegetarian diet had lowest water footprint of consumption.	For all diets, Austria is a net virtual water importer for agricultural production.	Water footprint of consumption is a partial indicator of the total water footprint. Water footprint estimates based on 9 food categories and from different sources.

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TABLE 3 (Continued)

Study, year (reference), country	Diets	Environmental impacts	Key results	Author conclusions	Limitations of study
Vanham et al., 2013 (48), EU28	EU28 habitual diets (1996–2005) German dietary recommendations Theoretical diets: Vegetarian diet; Combined dietary recommendations and vegetarian diet	Water footprint of consumption Based on food supply (FAO food balance sheets); Foods “as purchased”; Foods converted to “primary equivalents” (e.g., bread as wheat equivalent) Reported as: m ³ /capita per year, L/capita per day	German-recommended diet had lower water footprint of consumption than the EU28 habitual diet; theoretical vegetarian diet had lowest water footprint of consumption.	A reduction in meat intake in EU28 would be the greatest opportunity to reduce water footprint of consumption. A shift from current EU28 habitual diet or German-recommended diet at current production systems to vegetarian or combination diet would shift EU28 from net virtual water importer to net exporter.	Water footprint of consumption of individual EU28 countries and regions varies widely depending on land, climate, etc.; results from study not generalizable for individual countries. See also Vanham, 2013 (47) (Austria)
Capone et al., 2013 (49), Italy	Habitual diets Italy (2005–2006); USA (2006); Finland (2006) Italian recommended diet based on the Mediterranean diet	Water footprint of consumption based on food supply (based on FAO food balance sheets) m ³ /capita per year	Average water footprint of Italian food supply is 66% higher than in Finland and 16% lower than USA. Meat and dairy products account for more than half of the water footprint. Water footprint of habitual Italian diet is 70% higher than recommended Italian diet	Adherence of the Italian population to the Mediterranean dietary pattern would have health benefits and can reduce food-related water footprint.	Preliminary assessment of water footprint of Italian diet. Water footprint data were derived from published data on crops, crop products, farm animals, animal products.
Meier and Christen, 2013 (19), Germany	Habitual German diets (1985–1989; 2006) German recommended diet Theoretical diets: Lacto-ovo-vegetarian diet, based on 2010 US Dietary Guidelines; Vegan diet, based on 2010 US Dietary Guidelines	Multiple indicators for 16 food groups GHGe based on: LCA hybrid input-output; LCA farm to retail; NH ₃ emissions; CO ₂ eq/person per year Land use (m ² /person per year) Blue water (fresh surface and groundwater; m ³ /person per year) Phosphorus use (kg/person per year) Primary energy use (GJ/person per year)	Reduction potentials for NH ₃ emissions and primary energy use were greatest for the theoretical vegetarian and vegan diets, followed by German-recommended and habitual diets. Blue water needs were higher for vegan and vegetarian diets.	Diets that may be most beneficial for the environment could lead to nutrient deficits.	Diet-related impact estimates at food consumption level and based on 16 food groups. Multiple data sources with conversion factors needed for diet comparisons based on 2000 kcal/person per day.

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TABLE 3 (Continued)

Study, year (reference), country	Diets	Environmental impacts	Key results	Author conclusions	Limitations of study
Baroni et al., 2007 (50), Italy	Habitual, normal Italian diet Theoretical diets: Omnivore diet; Vegetarian diet; Vegan diet Conventional and organic farming practices	Select environmental impacts based on: LCA ISO 14040; Midpoint indicators Aggregated impacts reported as endpoint indicators (natural resources; ecosystems quality; human health impacts) using point system	Directional environmental impacts of diets studied: normal Italian diet > all other diets; theoretical vegan diet had lowest impacts regardless of farming practices. Most other differences were not large.	Shift in eating patterns toward vegetarian and vegan diets could help preserve resources and reduce malnutrition in poorer nations.	Information about diet composition was very limited. LCA data for individual impact categories from many different sources.
Wolf et al., 2011 (51) and Tukker et al., 2011 (52), EU27	A typical European base diet Recommended diets: WHO diet; World Cancer Research Fund diet; Mediterranean diet	Aggregated environmental impacts based on: LCA ISO 14040 1) A supply-driven model 2) A supply and global demand model for price and substitution effects [Common Agricultural Policy Regionalized Impact (CAPRI)] Environmental impacts reported as: Single score based on aggregation of mid-point indicators	Environmental impact of food production for all 4 diets was 25–27% of total (supply-driven model). Environmental impact of diets did not differ significantly when accounted for trade balance and substitution effects for agricultural production (supply and global demand model). Environmental savings from reduced meat consumption was only 1–2% of total food plus nonfood product impacts.	Promotion of less-meat-rich diets in the EU27 could lead to limited but positive environmental and health effects. Moderate diet changes are not enough to reduce impacts from food consumption drastically.	Water and land use not covered. Impact assessment did not allow for analysis of specific price or substitution effects from dietary changes. Although aggregated impact scores were weighted, they were not based on authoritative methods.

¹ CO₂-eq, carbon dioxide equivalents; EU27, Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, and the United Kingdom; EU28, EU27 plus Croatia; GHGe, greenhouse gas emissions; IPCC, Intergovernmental Panel on Climate Change; ISO, International Organization for Standardization; LCA, life cycle assessment; NY, New York State; UK, United Kingdom.

² The 10 regions were as follows: sub-Saharan Africa, centrally planned Asia including China, Europe including Turkey, independent states of former Soviet Union, Latin America, Middle East/North Africa, North America, Pacific region (including Japan, Australia, New Zealand), Pacific (or South East) Asia, and South Asia including India.

TABLE 4 Diet modeling to identify nutritionally adequate diets with lower GHGe and diet costs¹

Study, year (reference), country	Diet model using linear programming method	GHGe and diet costs	Key results	Author conclusions	Limitations of study
Macdiarmid et al., 2011 (21) and Macdiarmid et al., 2012 (20), UK	Diets modeled to meet UK dietary recommendations for 19- to 50-y-old women while minimizing GHGe. Diet models run with and without acceptability constraints (e.g., foods commonly consumed in sensible amounts; food costs; recommended energy; macronutrient, and 7 select micronutrient intakes). Realistic 7-d menus were developed.	GHGe (kg CO ₂ eq/kg food) determined for 82 food groups; database created from published literature. Modeled GHGe were compared to 1990 emission values. Food costs were based on midrange supermarket products (2010).	Without acceptability constraints, diet could achieve 90% lower GHGe but with only 7 food items. With acceptability constraints, diet could achieve 36% lower GHGe with 52 foods including meat and dairy at cost similar to UK average. Modeled diets formed basis for WWF Livewell diet for UK.	A diet that meets dietary requirements with lower GHGe is possible without eliminating the meat or dairy or increasing the cost to the consumer.	Diet-related GHGe limited to 82 food groups and only up to regional distribution center (re-tail). LCA for GHGe were from multiple sources. Subpopulation of 19- to 50-y-old women studied.
Thompson et al., 2013 (22), France Spain, Sweden	The UK diet modeling study (21) was adapted for France, Spain, and Sweden. Diets modeled to meet national food and nutrition guidelines with acceptability constraints (foods commonly consumed; current diet costs; country-specific nutrient recommendations) and 25% lower GHGe.	Country-specific GHGe and diet cost modeling method similar to that published by Macdiarmid et al. (21).	Modeled diets meet diet recommendations and have 25% lower GHGe, meet food cost goals, and produce acceptable food choices. Optimized diets had less meat, but enough meat and fish to maintain traditional meal patterns, and had more legumes for protein, more cereals and starchy foods (bread, pasta, and potatoes), and similar amounts of dairy products.	Healthy, sustainable food choices are possible in a variety of countries. Further research and analysis should be done to improve precision and assist in guidance to stakeholders.	Diet-related GHGe limited to available LCA data from multiple sources; substitutions from other countries used, especially for Spain.
Wilson et al., 2013 (23), New Zealand	Diet modeling study (16 diets) to meet New Zealand nutrient recommendations for men with inputs for energy, macronutrients, and 10 select micronutrients in foods, food prices, food waste, and food-specific GHGe. Models designed to 1) minimize cost and meet nutritional needs; 2) minimize GHGe and meet nutritional needs; 3) be relatively healthy diets (Mediterranean and Asian style); 4) be familiar New Zealand meals.	GHGe determined for 76 food items. GHGe data were scant for New Zealand foods, so used UK GHGe data; estimates made for some foods. Sensitivity analysis conducted.	Increasing dietary variety and likely acceptability of modeled diets had increased daily cost when optimized for both low-cost and low GHGe. Several diet scenarios had small number of foods (e.g., 9, 10, or 14 foods). All modeled low-cost and low-GHGe diets had likely health advantages over the current New Zealand model. Diets that included "more familiar meals" for New Zealanders had higher costs.	Low-cost, low-GHGe modeled diets are complementary but with trade-offs of higher daily food costs. This is partly because of reduction in higher GHGe foods, such as eggs and milk; pushes food choices to more costly alternative foods containing nutrients such as calcium. Milk is a relatively efficient beverage for nutrient provision (i.e., nutrients per GHGe generated).	Diet-related GHGe limited to 76 food items. LCA for GHGe of foods in New Zealand limited; substituted data from the UK (see Berners-Lee et al. (14), with approximations for foods not covered.

¹ CO₂eq, carbon dioxide equivalents; GHGe, greenhouse gas emissions; LCA, life cycle assessment; UK, United Kingdom; WWF, World Wildlife Fund.

TABLE 5 Environmental impacts of diets in developing regions of the world¹

Study, year (reference), country	Diets	Environmental impacts	Key results	Author conclusions	Limitations of study
Pathak et al., 2010 (24), India	Five common nutritionally balanced diets in India: 1) vegetarian, 2) lacto-vegetarian (vegetarian with milk), 3) ovo-vegetarian (nonvegetarian with egg), 4) nonvegetarian with poultry meat, 5) nonvegetarian with mutton	GHGe (g CO ₂ -eq/d) were determined using LCA (production, processing, transportation, and preparation) based on published data	GHGe were 40% higher for nonvegetarian vs. vegetarian meals. Nonvegetarian meal with mutton had 1.8 times more GHGe than vegetarian, 1.5 times more than non-vegetarian with chicken and ovo-vegetarian, and 1.4 times more than lacto-vegetarian. In nonvegetarian meal with mutton, GHGe from mutton (35%) were similar to those from rice (34%). In lacto-vegetarian meal, 49% GHGe were from rice, 22% were from milk.	A change in food habits could offer a possibility for GHGe mitigation. Some potential options to reduce GHGe from food may be consumption of locally produced foods; less mutton; substitute meat and milk with vegetable protein	Diet-related GHGe limited to 16 food products. LCA for GHGe covered on farm production, transport, processing, and preparation (consumer) but not storage and handling losses during production or storage at households. LCA for GHGe from different sources.
Zhen et al., 2010 (41), rural Guyuan, China	Habitual diets - Surveys of household food consumption in rural Guyuan, China, compared with rural China	Land requirements for 8 food categories (25 foods/subcategories) determined per capita (m ²) and per household (m ² per household)	Food consumption pattern in Guyuan depends on wheat; meat consumed than plant foods; land requirement for meat was only 5.7% of arable land (national average, 8.4%). Animal protein intake was 7.5% of total protein, below recommended 30% protein intake.	In Guyuan, food consumption met only basic energy needs for survival, with protein, especially animal protein, and fat below recommendations. Meat consumption expected to increase with projected increasing incomes of local people, thus toward a more balanced diet.	Several uncertainties and assumptions in estimates of food consumption and land requirements.
Dong-dong et al., 2010 (42), rural China	Diet patterns from Rural Household Survey, National Bureau of Statistics of China, based on 8 main food categories: grains, fresh vegetables, edible vegetable oil, meat (pork, mutton, beef, poultry, fish), fresh milk, eggs, sugar, and alcoholic beverages	Ecological footprint from 1980 to 2006 based on food consumption data and land requirements for foods (energy land, fishing land, grassland, cropland, arable land for grain, and arable land for meat)	In rural areas, per capita land requirements decreased, not expanded, over the decades. Higher productivity of arable land has greatly reduced pressure on resources for food consumption by rural residents in China.	Approach can serve to link how food consumption patterns relate to aggregated demands for resources. New framework to apply ecological economy methodology in agro-ecosystem.	Proof-of-principle study; broad applicability to other regions not examined.

¹ CO₂-eq, carbon dioxide equivalents; GHGe, greenhouse gas emissions; LCA, life cycle assessment.

in the studies reviewed were largely from the published literature, and in some studies, assumptions, extrapolations, and substitutions were used for missing LCA data. Some studies, for example, relied on LCA data from other countries because within-country GHGe data for foods were lacking (22, 23). Some studies of diet-related impacts examined only GHGe from agricultural production of food commodities on farms (16, 18, 28, 29), whereas others included the aggregate of GHGe across multiple points in the food supply chain. Several studies included GHGe across most of the food supply chain (farm-to-retail) but not from the point of purchase to the home (retail-to-home; i.e., transportation to the home, storage, preparation, and food waste by the consumer) (12, 15, 19–23). Only 2 studies of dietary impacts on GHGe covered the entire life cycle; farm-to-consumer (with the exception of transportation from retail to home) (13, 27).

Basis for assessing diet comparisons. The basis on which environmental impacts of food-related LCAs are reported, known as the functional unit in LCA research (31–33), traditionally has been on a mass basis (i.e., per 100 g food) (31). The goals and scope of the research question at hand are critical when determining the appropriate functional unit (31). As shown by researchers in France (27), the functional unit selected can have implications for the results of a study and subsequently the interpretation of the findings. Consumption data from adults participating in the French national dietary survey were used to assess the carbon footprint (GHGe) of diets on the basis of their nutritional quality (13, 27). GHGe were assigned to each of 391 representative foods in the French marketplace in accordance with international standards (i.e., LCA across the life cycle, farm-to-consumer, except for transport from retail to home). When the functional unit was determined on the basis of food weight (GHGe/100 g food), GHGe for dairy, mixed dishes, pork, poultry, eggs, and fish were 2- to 5-fold higher than for fruits and vegetables. However, when determined on the basis of energy density (CO₂eq/100 kcal of food), GHGe for fruits and vegetables were 25% higher than for dairy products and similar to those of mixed dishes and pork, poultry, and eggs. When French diet patterns were compared on the basis of nutritional quality, after adjustment for energy intake higher-quality diets, which included more fruits and vegetables and fewer sweets and salted snacks, were associated with significantly higher GHGe than lower-quality diets (27). Diets with higher amounts of sweets and salted snacks were associated with lower GHGe; however, striving for such a dietary pattern would be inconsistent with dietary guidance to help consumers build healthy diets. In a related study, diets were classified as “low carbon,” “high quality,” or “more sustainable” (13). Similarly, higher nutritional quality diets were associated with higher diet-related GHGe (CO₂eq/100 kcal).

The comparability of studies that use different functional units for assessing diet-related GHGe is confounded [see Heller et al. (31) for further discussion]. Future research could benefit from guiding principles for the selection of

the functional unit appropriate to the specific diet-related research objectives or, at a minimum, multiple functional unit bases should be evaluated simultaneously.

Diet modeling to define nutritionally adequate diets with lower GHGe and diet costs

Diet modeling by using linear programming methodology was used in the United Kingdom to optimize the nutritional adequacy of recommended diets while concurrently limiting diet-related GHGe (20, 21) (Table 4). This approach was later used to model diets in France, Spain, and Sweden (22); and similar modeling was conducted by researchers in a New Zealand study (23). Diet modeling was conducted with and without acceptability constraints (e.g., foods commonly consumed and in reasonable amounts by the population; reasonable food costs; energy, macronutrients, and from 7 to 26 select micronutrients from country-specific recommended intakes). Without acceptability constraints, the United Kingdom diets could achieve 90% reductions in GHGe but with only 7 foods in the diet (21). Similar results were also found in the New Zealand study (23). When the United Kingdom linear programming model included acceptability constraints, a diet that met dietary recommendations and had 36% lower GHGe would be possible with 52 of 82 representative food groups and without eliminating meat or dairy or increasing the cost to the consumer. Similar results were obtained with the modeled diets in France, Spain, and Sweden (22). The New Zealand study modeled a total of 16 diets optimized for nutritional adequacy, cost-effectiveness, and limiting diet-related GHGe (23). Increasing diet variety and likely acceptability of the optimized diets tended toward higher costs in this model. When the modeled diets included meals more familiar to New Zealanders, for example, diet costs tended to be higher than the other optimized diets.

Future research using this or similar approaches should also consider other aspects of environmental impacts (e.g., land use, water quality, food waste, and biodiversity), supply and pricing, including subsidies for farmers, and other social and economic aspects of sustainability.

Diet-related research on land requirements to support sustainable diets

In the face of the anticipated global population growth, research on how different diet patterns may affect the capacity of regional land bases to meet the nutritional needs of populations is beginning to emerge. The diet-related research to date has focused largely on methodologic approaches to quantify the capacity of regional land bases to meet nutritional needs of those populations (34–42). Concurrently, increasing the productivity of agricultural systems continues to be a priority in both developed (2, 43) and developing (44) regions of the world.

One of the earliest studies on diet-related land capacity questions compared estimates of the land need to support Dutch habitual diet patterns with diets that meet only basic calorie needs to prevent starvation (basic; daily energy from

wheat only) or that met energy and nutrient requirements (subsistence; select nutrient-dense foods) (34, 35). Land requirements were reported as relative “land units,” on the basis of Dutch per capita land use in 1990. To simply meet calorie needs to prevent frank starvation (largely from bread consumption), 23 land units would be needed; and to meet calorie and nutrient recommendations, a minimum of 67 land units would be needed. When Dutch habitual diets were examined, 23–143 “land units” were needed, reflecting the socially and culturally diverse eating patterns in The Netherlands.

In a more recent study, habitual Dutch diets of a subset of the population (19- to 30-y-old women) served as the baseline to estimate the amount of land that would be needed under a scenario of replacing calories from dairy and meat with plant-based foods (36). Although up to 50% lower land requirements was projected, such a dietary shift was not considered realistic. Plant-based substitutes for dairy and meat are not commonly consumed by young Dutch women and therefore would require a huge shift in daily food choices by individuals across the population.

Another approach developed by US researchers examined the capacity of the New York State land base to meet dietary recommendations [USDA Food Guide Pyramid (2000) <http://198.102.218.57/dietaryguidelines/dga2000/document/frontcover.htm>] for the in-state population (38–40). One study that examined 42 diets with different amounts of meat and eggs (0–340 g/d; 0–12 ounces/d) and calories from fat (20–45%/d) projected a 5-fold difference in acreage needs between diets with the least and most amount of fat and meat (38). Fruits, vegetables, and grains require high-quality land, whereas lower-quality land is suitable for forage crops, which are not consumed by humans. In New York State, land suitable for forage crops and dairy and meat production is more readily available than that for fruits, vegetables, and grains, making it theoretically possible that more people could be fed with modest amounts of meat in the diet than with a completely vegetarian diet. The concept of local food sheds, areas capable of supplying the food needs of a population from nearby sources, was also examined for urban areas of New York State (39, 40). Many towns and cities in the state outside of New York City theoretically could have the majority of their food needs met from foods produced within short distances (“local foods”). Application of these scenarios to regions with different macro- and microclimates and land bases could help expand our understanding of the relations between diet, land requirements, and agricultural capacity of other regional food systems.

In the United States, as in other developed countries, consumption of fruits, vegetables, dairy products, and whole grains falls short of national dietary recommendations. In 2006, Buzby, Wells, and Vocke (37) estimated the amount of land that would be needed if all Americans met the 2005 *Dietary Guidelines for Americans* recommendations. Projected improvements in agricultural productivity, which has a long history and continues to be a priority (2), were not reflected in these estimates. Meeting recommended intakes of fruits and vegetables would require more than a

doubling of acreage, plus more imports. For grains, whole-grain consumption would need to increase substantially, but total grain consumption would need to decrease; thus, less total acreage would be needed. Meeting recommended intakes of dairy product consumption would mean substantially more milk produced annually. Concurrently, more acreage for feed grains and/or grazing would be needed depending on the type of dairy production system used. We recognize that eating patterns of populations generally do not change quickly; therefore, these estimates serve as a reference for future shifts in eating patterns and for projecting implications of increased production efficiencies of the agricultural land base.

The potential for self-sufficiency in agricultural production in Austria through dietary changes and renewable energy crops was also examined with diet scenarios (18). Researchers examined implications of the population meeting the German Nutrition Society’s dietary guidelines on land availability for food production, associated GHGe, and the potential for renewable energy from feed stocks (18). It was projected that if dietary recommendations for specific product groups (e.g., fruits) were met, lower meat consumption would lead to a decrease in livestock numbers, lower cumulative energy demand for agricultural production, lower GHGe, and a reduction in the amount of land needed. Furthermore, potentially more than half of the cumulative energy demand from agricultural production in Austria could be met through renewable energy crops. Advancing ways to harness renewable energy in animal agriculture holds promise for increasing production efficiencies and mitigating climate impacts of agricultural systems. In the United States, the Environmental Protection Agency’s AgSTAR Program, for example, promotes the recovery and use of methane from animal manure to produce electricity, heat, or hot water (<http://www.epa.gov/agstar/about-us/index.html>).

Studies from developing regions of China have used other approaches to assess diet-related impacts on land requirements. In one study in a developing rural area, Guyuan, habitual food consumption currently meets only basic energy needs for survival, with protein, especially animal protein, and fat intakes well below recommendations (41). It was projected that if Guyuan follows the same trends as the rest of China, higher incomes and meat consumption will increase the region’s land requirements for food. In another study, an approach was developed to assess how food consumption patterns of rural Chinese residents relate to aggregated demands for land resources (42). The ecological footprint of the land, as defined in this study, consisted of land subdivided to energy land, fishing land, grassland, cropland, arable land for grain, and arable land for meat. This study assessed the ecological footprint between 1980 and 2006 and showed that higher productivity of the arable land over the past 2 decades in rural China has led to reduced pressure for resources to support regional food needs. This approach holds promise for assessing how food consumption patterns relate to aggregated demands for land resources in different ecosystems, particularly in developing countries.

Diet-related research on water resources to support sustainable diets

Both land and water are essential for the production of agricultural products. Although the concept of a water footprint has evolved as a standard in assessment of water consumption patterns (45, 46), there is only a limited amount of research examining the impacts of different diets on regional water needs.

The water footprint includes blue water, green water, and gray water (46). Blue water is the surface and groundwater (i.e., freshwater lakes, rivers, and aquifers), green water is rain water that does not run off or recharge the groundwater but is stored in the soil or temporarily stays on top of the soil or vegetation, and gray water is the volume of water that is required to dilute pollutants to such an extent that the quality of the water remains above agreed-upon water quality standards. The water footprint of production includes water use from domestic resources, whereas the water footprint of consumption (domestic consumption) includes the total volume of direct and indirect freshwater use from both domestic and foreign sources. It has been reported that one-fifth of the global water footprint is not used for domestic consumption but instead is exported (45). The water footprint of regions across the globe has been published; however, there is currently limited research assessing associations between diet patterns and water resources (19, 47–49).

Two studies from Europe examined the water footprint of consumption in relation to habitual diets: the German Nutrition Society's recommended diet, a theoretical vegetarian diet, and a "combination" diet (47, 48). Another study from Italy compared the water footprint of consumption for habitual diets in Italy, Scandinavia, and North America with the Mediterranean diet (49). Habitual diets had the highest water footprint of consumption (47–49). The German-recommended diet had a lower water footprint of consumption, and the vegetarian diet had the lowest water footprint (47, 48). The water footprint of agriculture is dependent on climate, irrigation and fertilization practices, and crop yields, with considerable variability in both developed and developing countries (45). More sustainable water use is expected from increased efficiency and changes in consumption patterns, such as replacing water-intensive commodities with those requiring less water (45).

Diet-related research on aggregated indicators of environmental impact

Although most studies focused on a single indicator, 2 studies aggregated sets of indicators for a more comprehensive, albeit not complete, assessment of dietary impacts on environmental sustainability. One study examined the impacts of 4 dietary patterns (habitual Italian diet and nutritionally balanced omnivore, vegetarian, and vegan diets) and 2 farming practices (conventional or organic). Eleven environmental indicators were aggregated as natural resources (land use and fossil fuels), ecosystems quality (ecotoxicity, acidification, and eutrophication), and human health impacts (respiration, organic/inorganic compounds, carcinogenesis, climate change, ozone, and ionizing radiations) (50). These were further aggregated to a single score by using a point system. Directionally,

environmental impacts of the habitual and different theoretical eating patterns and farming practices were as follows: normal Italian diet > omnivore (conventional farming) > vegetarian (conventional farming) > omnivore (organic farming) > vegetarian (organic farming) > vegan (conventional farming) > vegan (organic farming).

Another study assessed environmental impacts of habitual eating patterns in the European Union (EU27), diets recommended by the WHO and the World Cancer Research Fund, and the Mediterranean diet (51, 52). Eight impact categories (abiotic resource depletion, climate change, ozone depletion, human toxicity, ecotoxicity, photochemical oxidant formation, terrestrial acidification, freshwater eutrophication) were weighted and aggregated to a single environmental impact score. Compared with habitual eating patterns in Europe, the WHO diet had slightly less meat and more fish, fruits, and vegetables; the World Cancer Research Fund diet had less meat and similarly more fish, fruits, and vegetables; and the Mediterranean diet had less meat and less milk, significantly more fish, and more fruits and vegetables. This study projected that if the European population shifted to the recommended diets, there would be only a 1–2% reduction in the aggregated environmental impact score. Another level of analysis that accounted for potential impacts of shifts in eating patterns on agricultural trade balance between the EU27 and the rest of the world found that some of the limited environmental savings attributed to lower meat consumption would diminish.

Discussion

Although the concept of sustainable diets is not new, scientific research on how dietary patterns interface with ecosystems and the use of our planet's natural resources in ways that are environmentally, economically, socially, and culturally sustainable is only just emerging. Approaches to evaluate the sustainability of different dietary patterns vary widely, including differences in study designs and the specific environmental and other indicators examined. Inconsistencies in methods and assumptions to assess impact categories and the absence of national standard databases of LCA of foods in the marketplace hinder cross-study comparisons.

Approximately half of the studies assessing environmental impacts of diet patterns identified in this review examined climate impact as GHGe. The carbon footprint of foods relative to other major categories of goods and services in developing countries is notably higher than in developed countries (53). In China and India, for example, food accounts for 35–47% of total GHGe for those countries, but in the United States, New Zealand, and Europe, food-related GHGe account for only 8–19% of the total in the individual countries. This may partially explain the relatively small differences across diets found in the studies assessing diet-related GHGe on a per capita basis relative to all goods and services (16, 51, 52). Transportation (private vehicles and land and air transportation services), by contrast, accounts for 19–34% of total GHGe in the United States, New Zealand, and Europe but only 8–9% of the total in China and India. In another study, the carbon footprint of US households in 28 cities was

examined for 6 household sizes and 12 income brackets (54). GHGe reduction potentials from dietary shifts depend on household size and income, but mitigation potentials from transportation are large across all US household types. Considering that non-food-related GHGe account for >80% of total emissions globally (53) and shifts in eating patterns across populations occur slowly, reduction potentials in GHGe in developed countries may be greater across other sectors, such as transportation, than by population-based shifts in eating patterns.

Approaches to assess the capacity of regional and local land bases to feed urban and rural populations today and in the future are being developed and tested (36, 38–40, 42). Initial proof-of-principle studies have been published, but more research clearly is needed. Fewer studies have examined impacts of dietary patterns on water use and quality or other facets of environmental impacts. Only a few studies in the present review included economic implications of the various eating patterns studied. Remaining culturally sensitive to dietary preferences and considering cost constraints are real-world challenges that need considerably more research.

The nutritional quality of dietary patterns is a fundamental requisite when assessing environmental impacts of diets under a framework of sustainable diets, as eloquently illustrated in studies from France (13, 27). Under ideal conditions, the nutritional effects of diets on human health would be evaluated in a comparable unit or way similar to that for environmental impacts on human health, as suggested by Heller et al. (31). This could provide a further degree of integration of diet/nutrition and sustainability and a realistic way to assess the trade-offs that inevitably will need to be made on both personal and societal levels.

Systematic frameworks have been proposed to address the broad context of the many linkages among the environmental, economic, and social dimensions of food systems that are critical to sustain the nutritional needs and health of the world's populations (10, 11, 55). A review of possible GHGe mitigation measures in agricultural production illustrates through several examples that the evaluation of associated trade-offs within the ecological, environmental, economic, institutional, and societal categories cannot only address the potential for unintended consequences but also lead to benefits in one or more of these categories (55). A comprehensive and solid science base is needed before dietary recommendations for sustainable diets can be developed. A holistic approach to cross-disciplinary research relative to the concept of sustainable diets can help identify research gaps, set research priorities, systematically examine trade-offs, and ultimately avoid unintended consequences to planetary and population health.

Conclusions

Many studies point to the need for a far more complete assessment of the environmental, social, and economic impacts of foods and diets. Research needs cut across multiple fields, including agriculture, nutrition, animal science, environment, social sciences, and economics. A systems-based approach has been suggested (10, 11, 55); and advancing interdisciplinary

research through multiple venues such as support of collaborative research programs, workshops, and scientific conferences will help to develop the much-needed solid information base. It is also important to recognize advances and continued progress in mitigating environmental impacts and optimizing use of natural resources in agricultural systems (43), including dairy systems (56), the private sector, and others.

All food production incurs varying environmental impacts, and these need to be weighed against their role in providing nutritional and health benefits as part of overall dietary patterns. Whereas dietary guidelines across the globe, which are designed to help populations achieve healthy eating patterns, are based on a foundation of decades of nutrition science, studies examining interactions between diet and food choices, agricultural systems, the environment, and human health are only beginning to emerge. A strong scientific foundation through future research can inform future guidance on sustainable diets and avoid unintended consequences of well-intentioned dietary guidance based on currently limited information.

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