Sustainability of plant-based diets: back to the future[1–3]

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ABSTRACT

Plant-based diets in comparison to diets rich in animal products are more sustainable because they use many fewer natural resources and are less taxing on the environment. Given the global population explosion and increase in wealth, there is an increased demand for foods of animal origin. Environmental data are rapidly accumulating on the unsustainability of current worldwide food consumption practices that are high in meat and dairy products. Natural nonrenewable resources are becoming scarce, and environmental degradation is rapidly increasing. At the current trends of food consumption and environmental changes, food security and food sustainability are on a collision course. Changing course (to avoid the collision) will require extreme downward shifts in meat and dairy consumption by large segments of the world's population. Other approaches such as food waste reduction and precision agriculture and/or other technological advances have to be simultaneously pursued; however, they are insufficient to make the global food system sustainable. For millennia, meatless diets have been advocated on the basis of values, and large segments of the world population have thrived on plant-based diets. "Going back" to plant-based diets worldwide seems to be a reasonable alternative for a sustainable future. Policies in favor of the global adoption of plant-based diets will simultaneously optimize the food supply, health, environmental, and social justice outcomes for the world's population. Implementing such nutrition policy is perhaps one of the most rational and moral paths for a sustainable future of the human race and other living creatures of the biosphere that we share. *Am J Clin Nutr* 2014;100(suppl):476S–82S.

WHAT ARE SUSTAINABLE DIETS?

Definitions of sustainability generally address aspects of ecology, economy, and society and have different meanings depending on the context. A sustainable diet will not necessarily be defined the same way for consumers as for farmers or food manufacturers. In 2010 the FAO defined sustainable diets as "those diets with low environmental impacts which 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" (1). Furthermore, according to Fanzo et al (2), the determinants of a sustainable diet are as follows: nutritional adequacy, environmental sustainability, cultural acceptability, and low-cost accessibility.

In the arena of environmental sustainability, the focus of this article, 2 important dimensions are considered: efficiency and environmental protection. Efficiency is a measure of how natural resources are used to obtain the foods of a given diet and is quantified by the ratio of inputs to outputs. Environmental protection addresses the preservation of ecological systems that allow life on earth: the biosphere. It is measured by environmental indicators such as global warming potential, biodiversity, and eutrophication. Thus, both key dimensions of environmental sustainability, the efficient use of natural resources, and the avoidance of environmental degradation in the production, preparation, and disposing of the food consumed are to be considered in assessing the sustainability of a diet.

ARE CURRENT FOOD PRODUCTION AND CONSUMPTION PATTERNS SUSTAINABLE?

Evaluating the food systems in light of these 2 dimensions provides a framework for assessing the environmental sustainability of current practices. The basic inputs and outputs of the food system as a whole are shown in **Figure 1**. The food system takes inputs from the natural world in the form of natural resources—that is, land, sun radiation, water, fossil energy, and chemicals. Working together, these aforementioned inputs produce food for human societies. Food is the desired output of the system; however, the food system also produces undesirable outcomes in the form of solid, liquid, and gas waste. Societal demand, which includes consumer preferences, is a major driver of the food system (3). The life cycle of foods is determined by the production, processing, transportation, storage, retail, and disposal practices used; and consumer demands in a given society define these interactions within the food system.

Agriculture is the practice of producing crops and raising livestock. From an ecological perspective, agriculture involves managing resources to capture solar energy and the transferring of it to people for their use. For millennia, agriculture was a spatially complex system of polycultures, and a variety of crops and animals inhabited the same farm lands. Compared with output (food produced), inputs were low and consisted of solar energy, rain water, and animal waste for fertilizer (4). By efficiency standards, the system was sustainable. With the advent of industrial agriculture, farms became a monoculture enterprise,

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First published online June 4, 2014; doi: 10.3945/ajcn.113.071522.

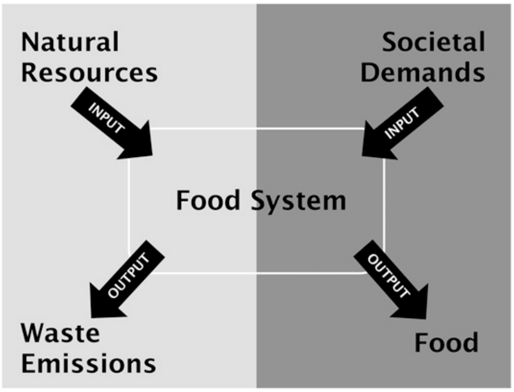

FIGURE 1. Major drivers and outcomes of the food system.

with a single farm generally producing a single food item (5). The main inputs are nonrenewable energy from fossil fuel and high amounts of chemicals, and oil is also used to produce nitrogenous fertilizers and irrigation water (5). These enormous inputs of energy in modern agricultural practices have greatly increased food production but have resulted in an energy imbalance.

The increase in energy usage for food production from traditional to current practices is depicted in **Figure 2**. Originally, agricultural activity resulted in a net gain in energy as more energy was obtained from food than expended on its production. One farmer could feed a family by using only the energy of his labor and that provided by nature. As food production intensified with the use of fossil fuel energy, the ratio increased for the energy input to energy output from food (6). The imbalance between the total energy required by the US food system and the total food energy produced by the effort was reported by the Center for Sustainable Systems (7). On-farm production amounts to 21% of the total system energy usage, and 40% of agriculture production energy go into making chemical fertilizers and pesticides. Large amounts of energy go into processing, transporting, storing, and serving food. For every 10.3 quads of the total energy used to produce food, only 1.4 quads of food energy is created, yielding an overall energy efficient ratio of >7:1 (7). From the energy perspective, the industrial food system is very inefficient and because most of the energy inputs are from nonrenewable sources such as fossil fuels, the current system is unsustainable (5).

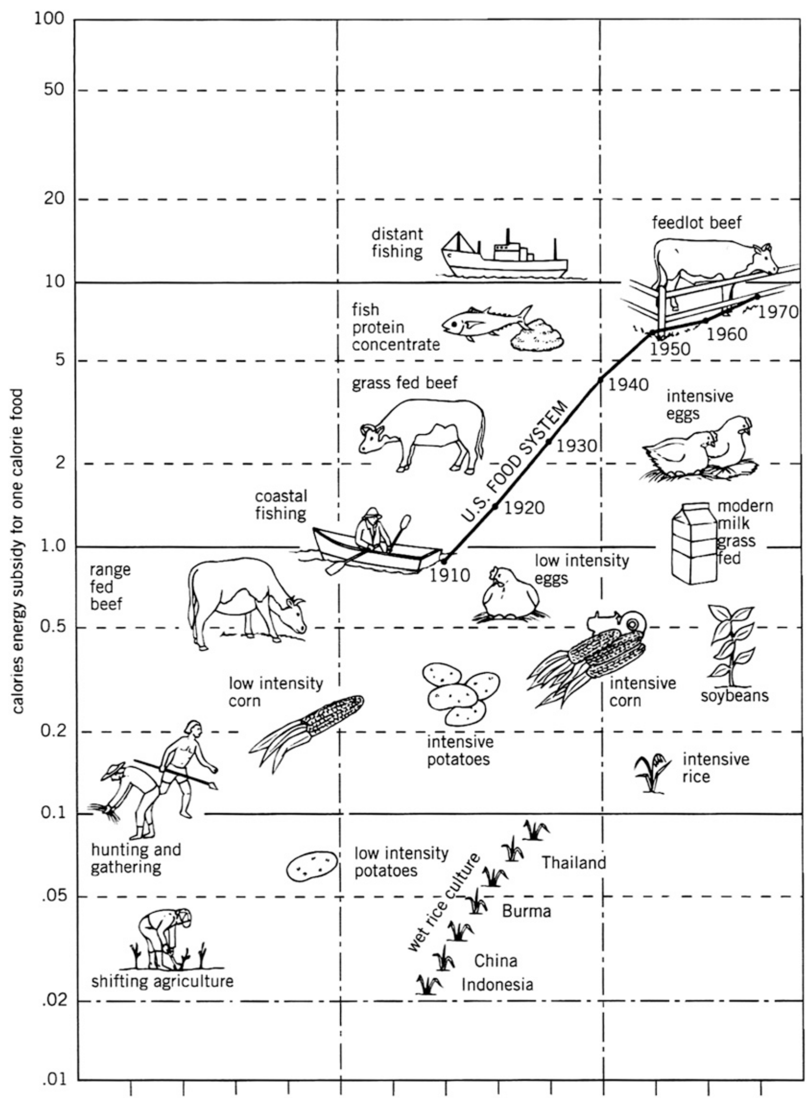

FIGURE 2. Graphic summary of the various types of food production: ratio of energy required to food energy delivery. Reprinted with permission from reference 6.

EFFICIENCY: ANIMAL COMPARED WITH PLANT FOODS

Raising animals for human food is an intrinsically inefficient process. As we move up in the trophic chain there is a progressive loss of energy. Grass-fed livestock subsists, but this is not the main source of meat for human consumption in developed nations. Modern husbandry (animal farms) is based on intensive feeding of grain crops to animals (5). This grain could be a source of food for humans. The same standards apply to the production of other animal products such as eggs and dairy. Several authors have computed the efficiency ratios of animal compared with plant foods for human consumption. The amount of grain needed to produce the same amount of meat varies from a ratio of 2.3 for chicken to 13 for beef (**Table 1**). Pimentel and Pimentel (8) established that, on average, 11 times greater fossil energy is required to produce animal protein than plant protein for human consumption. However, the energy-to-protein efficiency ratio varies greatly by type of meat. More specifically, it is only 4 times greater for chicken protein compared with grain protein but 40 times greater for beef protein compared with grain protein. We have previously reported that the ratio for water used in the production of soy protein compared with the same quantity of animal protein is from 4 to 26 and showed that the ratio between soy protein and the different types of animal proteins varies from 6 to 20 for fossil fuel usage (9). The land required to raise the feed to produce animal protein is 6–17 times greater than for soy protein (9).Thus, the conversion of plant foods to foods of animal origin is an intrinsically inefficient process (∼10:1).

The ratio of energy inputs to protein delivery is also qualitatively different for animal compared with plant foods. As the concentration of protein increases in plant foods, so does the efficiency. It does not change or may even decrease in animal protein sources (**Figure 3**) (10). High-protein plant foods such as soy beans and other legumes have greater protein delivery energy efficiency than cereals, which have a lower protein concentration. Therefore, less energy is needed to produce the same amount of protein from soy than from corn. However, very similar amounts of energy are used to produce equivalent amounts of protein from different sources of animal protein. In animal foods, the degree of protein concentration seems to decrease the efficiency ratio of energy inputs compared with protein outputs.

ENVIRONMENTAL INDICATORS: ANIMAL COMPARED WITH PLANT FOODS

Research has been conducted on individual food items to determine the impact of production and consumption on the environment. The production of food for human consumption, particularly by industrialized agricultural practices, causes significant emissions of greenhouse gases (GHGs). These may occur directly from carbon dioxide emissions from fossil fuel use on the farm or in the supply chain, nitrous oxide emissions resulting from fertilizer application, and methane emissions from animals or indirectly as a result of land use change. In addition to agricultural production process, the transport, processing, packaging, marketing, sales, purchasing, and cooking of food also contribute to GHG emissions. Berners-Lee et al (11) computed the GHG emissions from 61 food categories at point of purchase. With one exception, each food with GHG emissions >10 kg CO_2 equivalents/kg of product is a meat or dairy food.

Approximately half of all food-related GHG emissions are generated during farming. Farm-stage emissions include nitrous oxide and methane from livestock and carbon dioxide from agriculturally induced change in land use, especially deforestation. Nitrous oxide from pasture land and arable land used to grow food crops and methane from the digestive processes of ruminant animals (eg, cows and sheep) account for 80% of all agricultural GHG emissions (12). The emissions per unit of livestock product vary by animal type and are much higher in ruminant animals such as in cattle, sheep, and dairy farming than in pig and poultry farming (13).

Beyond contributing disproportionately to GHG emissions to the atmosphere, industrial husbandry operations damage the environment by chemical runoff to water and land and animal waste. This chemical pollution may cause acidification, algal blooms, and dead zones in lakes and coastal areas; soil quality degradation; habitat change; and biodiversity loss (5, 12, 14). We previously computed 3 environmental degradation ratios of meat compared with soy protein production and reported that the emissions of acidifying substances, pesticides, and metals are respectively 7, 6, and 100 times greater for meat protein compared with soy (9). Thus, the intensive production of meat is considerably more taxing to the environment than nutritionally equivalent plant protein foods.

TABLE 1
Ratio of different inputs to animal outputs in US husbandry practices[1]

	Grain fed:meat produced	Fossil fuel energy:protein energy
	kg:kg	*kcal:kcal*
Beef	13:1	40:1
Eggs	11:1	39:1
Pork	5.9:1	14:1
Milk	—	14:1
Turkeys	3.8:1	10:1
Chickens	2.3:1	4:1

[1] Adapted from reference 8.

COMPARING ENVIRONMENTAL INDICATORS OF PLANT-BASED AND MEAT-BASED DIETS

Compared with plant foods, meat and dairy products are clearly responsible for a hefty share of the natural resource utilization and environmental burden of food production. However, looking at dietary patterns, instead of single foods, is a more integrated and realistic approach in the assessment of the environmental impacts of producing foods for human consumption. We previously compared the environmental impacts of producing the foods differentially consumed by vegetarians and nonvegetarians from California and showed that the agricultural inputs required for producing the nonvegetarian diet were 2.9 times more water, 2.5 times more primary energy, 13 times more fertilizer, and 1.4 times more pesticides than for the vegetarian diet (15).

Earlier studies reported several-fold increases in GHG emissions and/or in environmental degradation scores for conventional meat diets compared with vegetarian diets (16, 17). However, these notable differences between dietary patterns also encompassed factors other than the diet composition, such as agricultural production methods, food processing, and transportation. Such factors, albeit important contributors to the overall environmental footprint, are confounders in the assessment of the strict impact of the composition of the diet.

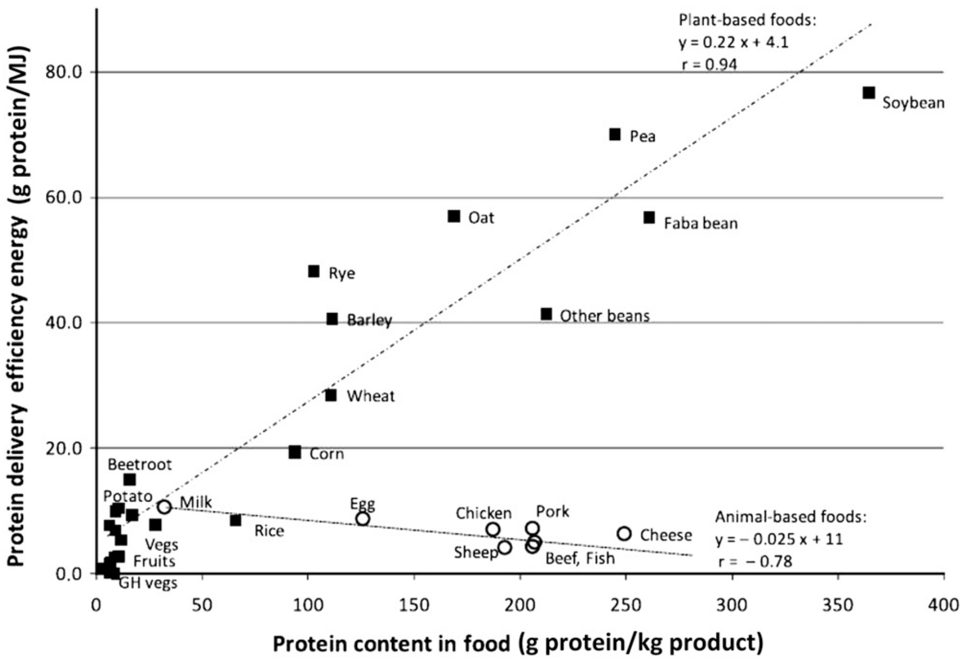

FIGURE 3. Protein delivery efficiency in terms of energy use as a function of food protein content. Squares, plant-based foods; circles, animal-based foods. The correlation coefficient *r* is shown in linear interpolations. Reprinted with permission from reference 10. GH, greenhouse; Vegs, vegetables.

Most of the research on the environmental impact of dietary patterns has focused on the quantification of GHG emissions. Berners-Lee et al (11) contrasted 6 meatless daily meal scenarios with the average UK diet. Under the different dietary scenarios, meat was replaced with either dairy products or plant-based alternatives. Compared with the benchmark UK diet, reductions in GHG emissions of 22% for vegetarian and 26% for vegan scenarios were estimated (**Figure 4**). With the use of data from Finland, Risku-Norja et al (18) estimated that a vegan diet would reduce 48% of the agricultural and 34% of the overall food system GHG emissions compared with the average Finnish diet. Reductions in agricultural and overall food system GHG emissions of only 33% and 23%, respectively, result when dairy is removed and beef and mutton are replaced in the diet with pork and poultry. Eshel and Martin (14, 19) estimated the decrease in GHG emissions for a vegan diet compared with the mean US diet on the basis of national food disappearance data. They calculated a per capita annual decrease of 1.5 tons of CO_2 equivalents, which is equivalent to 33% fewer emissions from the vegan food pattern than from the average US diet. This represents an 8% reduction in the per capita total GHG emissions in the United States, which is similar to the reduction found for the Finnish consumer (18).

Modeled reductions in GHG emissions ranging from 19% to 30% were estimated for several dietary scenarios involving the partial replacement of animal products, meat and dairy, in the average UK diet (20, 21). Furthermore, Stehfest et al (22) estimated reductions in GHG emissions of 17% for CO_2, 24% for CH_4, and 21% N_2O at the global level from a complete switch to meatless diets, in which all protein is derived from plants.

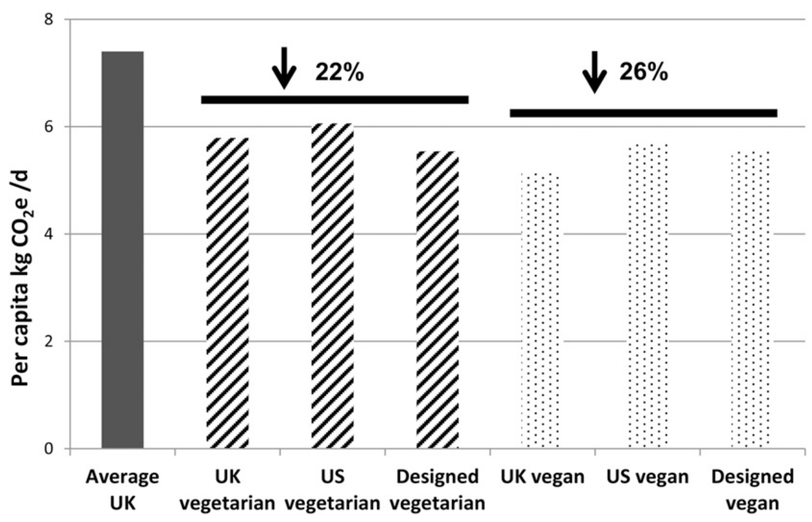

FIGURE 4. Reduction in greenhouse gas emissions of different prototype vegetarian and vegan diets compared with an average UK diet. Adapted by using data from reference 11. CO_2e, CO_2 equivalents.

The aforementioned studies provide useful estimates of environmental impacts, but researchers relied on prototype vegetarian diets for the comparative estimates, an approach that has inherent limitations. Prototype vegetarian diets may reflect the preferences and potential bias of the researcher, and they do not capture the variability and complexity of the foods consumed on a daily basis by free-living individuals. Thus, impact assessments based on ideal or designed diets may produce only theoretical results and are not grounded in reality. We recently conducted an assessment of the carbon footprint of dietary patterns using a novel approach (23), and our methodology was based not on researcher-designed, but on subject-defined food consumption for a large and geographically representative study population across North America. Furthermore, our study population exhibits a great dietary variability with respect to the intake of animal and plant foods, and we determined the emissions with global warming potential (CO_2, CH_4, and N_2O) of 210 foods included in a validated food-frequency questionnaire by implementing a life-cycle impact assessment. We estimated the GHG emissions for each of the >73,000 participants in the Adventist Health Study 2 according to self-reported dietary preference. A reduction in emissions of 31% and 22% was estimated for vegetarians and semivegetarians, respectively, compared with nonvegetarians (23). These estimates should be regarded as conservative because the average meat consumption of 64 g/d for nonvegetarian Adventists contrasts with the much higher 220 g/d in a typical Western diet.

THE CASE FOR PLANT-BASED DIETS AT THE GLOBAL LEVEL

Is food security in the context of the current and projected dramatic increase in global demand for animal products compatible with environmental sustainability? The answer to this question must be considered against the backdrop of the world's demographic explosion and the increase in wealth among large segments of the population in transitional and developing nations (24, 25). These trends result in a dramatic increase in the global demand for foods of animal origin, particularly meats and dairy foods. Industrial livestock production is intrinsically resource-inefficient and highly taxing on the environment, rendering the current food system environmentally and societally unsustainable. We argue in this section that for a sustainable future, a drastic reduction in the consumption of meat and dairy foods by large segments of the world's population is unavoidable. Thus, plant-based diets at the global level are imperative (26).

The overall size and economic activity of humankind are exceeding the biocapacity of the world. Until recently, it was assumed that the world's living and physical resources were inexhaustible. However, this is a false assumption attributable to a rapidly growing reliance on nonrenewable natural resources, ie, fossil fuels. Many human activities, including industrial agriculture, have reached a level that could damage the systems that keep Earth in a desirable state of ecological balance. The outcome could be irreversible and, in some cases, lead to abrupt environmental change. Rockström et al (3) identified 9 Earth-system self-regulatory processes and associated thresholds that, if crossed, could generate unacceptable environmental change. Their analysis suggests that 3 of the boundaries—climate change, rate of biodiversity loss, and interference with the nitrogen cycle—have already been trespassed. Although the planetary boundaries are described in terms of individual quantities and separate processes, the boundaries are tightly coupled. Humankind does not have the luxury of concentrating its efforts on any one of them in isolation from the others (27). If one boundary is transgressed, then other boundaries are also under serious risk.

The world population is growing exponentially and is expected to reach 9 billion by the year 2050 (25). The parallel increase in wealth in large segments of the population of transitional and developing countries has resulted in a markedly increased demand for foods of animal origin, particularly meat and dairy foods. Since 1963, there has been a 62% increase worldwide in meat consumption, but a much greater increase of ∼300% has occurred in developing nations. China has experienced a 9-fold increase in per capita meat consumption of meat since the 1980s (**Figure 5**) (28). In addition to wealth, other factors driving the worldwide consumption of meat include urbanization, trade liberalization, transnational food corporations, retailing growth, food industry marketing, and consumer attitudes and behaviors (29).

The projected increased size of the world's population and the increase in the appetite for meat are pushing our food systems to unsustainable levels. Reports from authoritative agencies have accumulated in the past few years that document the negative environmental impacts of industrial meat production (12, 30–32). Industrial meat production is intrinsically resource-inefficient and requires high inputs of nonrenewable natural resources and growth-promoting antibiotics. It damages the environment through gaseous emissions and chemical runoff into water and soil. Meat and dairy production accounts for >80% of all GHG emissions from the food sector (30) and for 24% of global GHG emissions (12). Thus, the livestock industry is a major contributor to anthropogenic GHG emissions liable for global climate change, one of the planetary boundaries already transgressed by humanity and directly threatening its sustainability.

Animal waste has become a public health problem and environmental hazard. Annually, 7 billion livestock in the US meat industry generate 1.4 billion tons of waste—or ∼5 tons of waste for every US citizen (5). These wastes, most of which go untreated, not only contain high concentrations of nitrogen, phosphorous, and potassium compounds and traces of metals but also antibiotics, and are the source of >100 zoonotic pathogens that may contaminate food and water supplies (33), thus representing a direct threat to human health.

Food security and food sustainability are on a collision course. The past half-century has seen a marked growth in food production, allowing for a dramatic decrease in the proportion of the

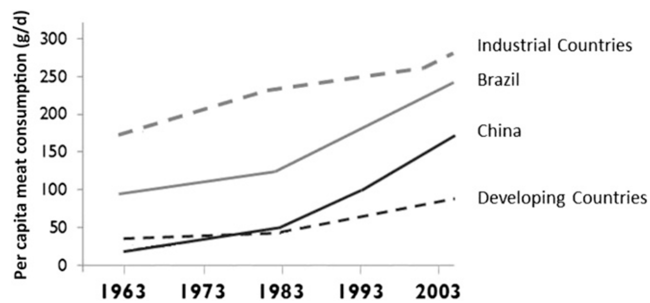

FIGURE 5. Trends in per capita meat consumption. Adapted by using data from reference 28.

world's people who are hungry despite a doubling of the total population. Nevertheless, 1 in 7 persons today consume diets insufficient in protein and energy, and 2 in 7 persons have some micronutrient deficiency. With a larger-than-ever world population that has a greater appetite for meat and with the threat of lower food yields because of substantial climate change (34), the world food system is facing a set of intersecting challenges. These challenges require radical changes not only in the way food is produced, processed, stored, distributed, and accessed but also in the types of food consumed.

Previously, the main solution to food shortages was to bring more land into agriculture and to exploit fish stocks. These are not sustainable options. Neither is increasing the intensification of existing underperforming agricultural landscapes. Closing the food yield gap, while considering sustainability goals, will require new approaches, including the adaptation of conventional agriculture to more low-input and precision practices (35–37). Waste and losses along the supply chain are estimated to involve more than one-third of the food produced in the world (36). Reducing food waste could substantially improve food security and simultaneously decrease environmental degradation. Improving food yields, reducing agriculture's environmental impacts, and reducing waste are necessary but are not sufficient strategies to ensure global food security. More food can be delivered by realigning agricultural and dietary preferences.

Shifting diets from animal-based to plant-based at the global level is of paramount importance in achieving food security and sustainability goals. Decreasing consumption of meat and other animal products will free up large amounts of food that could be consumed directly by humans—for example, soy and grains. Foley et al (36) recently estimated the potential to increase the global food supply by shifting 16 major crops from the current mix of uses (eg, human consumption, livestock feed, and biofuels) to human food consumption only: they estimated a 28% increase in food availability, or the equivalent of a 49% increase in dietary energy for human consumption. These staggering figures, resulting from the implementation of a single strategy, have profound implications for both food security and environmental sustainability. By 2050, the world's population is expected to plateau at 9 billion, a 28% increase from the current 7 billion (25). Shifting the portion of current crops directed to livestock feed and nonfood uses to human consumption could fill the future food gap and exceed dietary energy needs. In addition, the proposed dietary shift would result in major environmental benefits because it does not require an overall increase in plant crops at the global level, and it would eliminate the environmental impacts related to livestock. As presented above, industrial livestock production contributes disproportionally to numerous forms of environmental degradation. For example, livestock-related GHG emissions are >80% of those generated by the food sector and 24% of global GHG emissions.

ISSUES AND CHALLENGES

The proposal to drastically reduce meat consumption at the global level is ground-shaking. Some have even branded it a "revolutionary approach" and have argued that wholesale dietary shifts may not be realistic (36). However, the proposed transition does not need to be an "all or nothing" process because even only incremental steps could be extremely helpful in solving food availability and sustainability challenges. We are fully aware that such a drastic dietary shift is complex and implicates behavioral and policy challenges at many levels.

The adequacy of meatless diets has been a recurrent theme in the nutrition literature. On the basis of a higher concentration of essential nutrients in animal products, meat and dairy were considered essential in large proportions for adequate nutrition in the daily diet, and consumption of plant-based diets was considered inadequate. This nutritional paradigm has changed in the past few decades (38) as data now support that most plant-based diets are healthier than meat-based diets and yield greater longevity and lower chronic diseases among those who consume vegetarian diets (39–42). Furthermore, there is growing evidence linking meat consumption, in particular red meat and processed meat, with detrimental health outcomes (43–45). From a strict health perspective, there is no need to consume meat.

For millennia, large segments of the world's population thrived on diets with little or no meat. In the past century, however, the concept of eating meat as the paramount source of protein has become deeply engrained in the psyche and culture of Western countries and now pervades many other cultures and nations. Undertaking a drastic downshift in meat consumption will face serious obstacles and opposition at many levels: the consumer's taste preferences; some culinary traditions; established social norms; economic forces, such as the livestock industry; and current national and international food policies. Several proposals have been advanced to accomplish the transition from animal protein to plant-based protein consumption. Some of them include consumer education focused on the environmental and health merits of plant-based diets, the promotion of food guidelines based on health and sustainability criteria, developing attractive and culturally acceptable plant-based meat-alternative foods, and realigning current fiscal policy (food subsidies and taxation) with efficiency and environmental criteria (46–50).

CONCLUSIONS

Plant-based diets in comparison to meat-based diets are more sustainable because they use substantially less natural resources and are less taxing on the environment. The world's demographic explosion and the increase in the appetite for animal foods render the food system unsustainable. Food security and food sustainability are on a collision course. Changing course (to avoid the collision) will require extreme downward shifts in meat and dairy consumption by large segments of the world population. Although other approaches should be pursued, they are insufficient to make the global food system sustainable, and therefore the dietary shift is an inevitable strategy.

Throughout history, forced either by necessity or by choice, large segments of the world's population have thrived on plant-based diets. In the past, meatless diets have been advocated on the basis of religious, ethical, or philosophical values, not science. It is only in the past 150 y that empirical evidence has yielded dietary recommendations.

Will "going back" to plant-based diets be the best way forward for a sustainable future? Agricultural and nutritional policies that lead to the adoption of plant-based diets at the global level will simultaneously optimize the food supply, health, environmental, and social justice outcomes for the world's population. Implementing such policies is not free of political challenges but is perhaps the most rational, scientific, and moral path for a sustainable future of the human race and other living creatures of the biosphere that we share.

The authors' responsibilities were as follows—JS: wrote the first draft of the manuscript; and SS: contributed to the content and editing of the manuscript. The authors had no conflicts of interest to declare.

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