Toward Healthy Diets from Sustainable Food Systems

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ABSTRACT

This article is based on a session at ASN 2019 entitled "Addressing the Four Domains of Sustainable Food Systems Science (Health, Economics, Society and the Environment): What Will It Take to Harmonize the Evidence to Advance the Field?" A summary of presentations is included. The presentations addressed the 4 principal domains of sustainability defined as nutrition/health, economics, environment, and society and the ways in which they are represented in current research. The session also introduced metrics and measures that are specific to each domain. Participants discussed next steps to move toward consensus and collaboration among scientific communities, especially those of health/nutrition science and environmental science. Food systems may need to be restructured to ensure that the global food supply provides adequate calories and nutrients at an affordable cost. Finally, the session addressed strategies to implement research concepts and move toward policies that encourage consumers to choose healthy diets from sustainable food systems. *Curr Dev Nutr* 2020;4:nzaa083.

Keywords: food system, sustainable, environment, climate, diet quality, food security, economics, society, metrics, measurement

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Abbreviations: CO_2-e, carbon dioxide equivalents; DGAs, Dietary Guidelines for Americans; GHGE, greenhouse gas emissions; HIC, high-income country; HLPE, High Level Panel of Experts on Food Security and Nutrition; LMIC, low- and middle-income country; NRF, Nutrient-Rich Food; SDG, Sustainable Development Goal; %DV, percentage daily value.

Introduction

Global and local food systems face urgent and complex challenges. Population growth, coupled with increasing wealth and urbanization, has led to a rise in global food demand. The goal of food systems enterprises should be to provide food security for all, while minimizing the environmental impact of intensive food production. Supplying adequate dietary energy for the global population is one component of food security; providing adequate nutrients along with calories at an affordable cost is another. A sustainable food system should also promote livelihoods and food cultures while being fair, just, and equitable.

As of 2018, 821 million people worldwide suffered from hunger due to insufficient energy intake (1), and an estimated 2 billion people did not consume adequate nutrients (2). At the same time, >2 billion people consumed excess calories and were overweight or obese (2). This triple burden of malnutrition has been noted as the "new normal" (3, 4), and it affects all countries of the world. Meanwhile, approximately one-third of all food produced is wasted (5). Furthermore, the prevalence of diet-related noncommunicable diseases has been increasing at an alarming rate. In 2017, 11 million deaths and 255 million Disability-Adjusted Life Years were attributable to dietary risk factors (6). In 2015, the global cost of diabetes was estimated at \$1.31 trillion (7). The anticipated growth in the world population to 9 billion people by 2050 (8) will have an influence on future food patterns (9). Projections indicate that overall global food production must increase by ∼70% from 2005/2007 amounts to meet the projected global population needs in 2050 (10). Food production must supply both adequate calories and nutrients to ensure nutrition security (10).

Food systems need to respond to economic and sociocultural shocks, deal with stagnating rural economies, tackle depletion of natural resources, and address climate change. Unless a food systems transformation occurs soon (8), rates of global hunger and nutrient deficiencies will increase, and so will the rates of overweight and obesity. We need food systems that are economically viable and that enhance food security, prevent all forms of malnutrition and minimize further environmental degradation. Achieving healthy diets from sustainable food systems is a global public health goal.

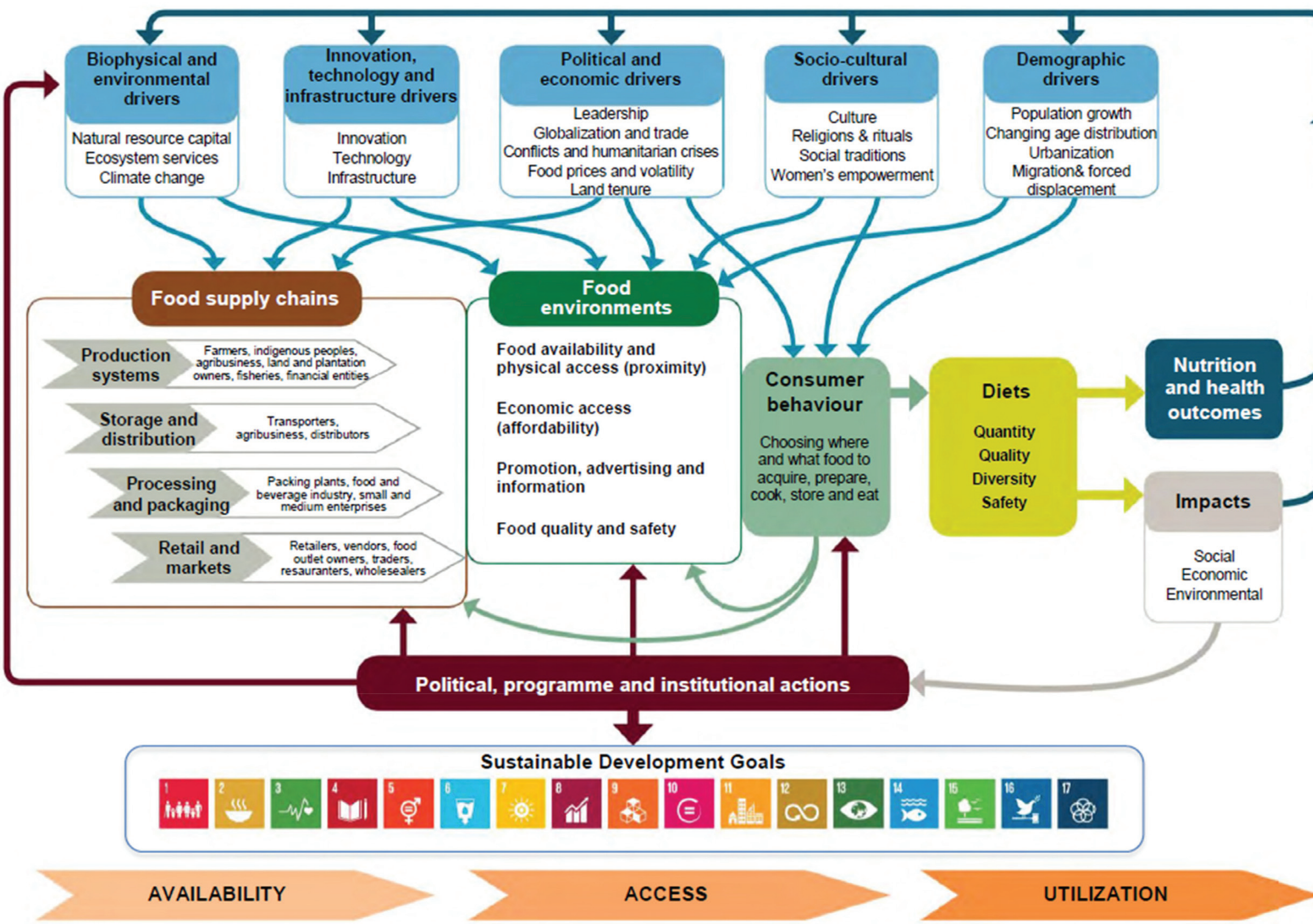

FIGURE 1 Conceptual framework of food systems for diet and nutrition [reproduced from (8) with permission].

Overview of Food Systems

Complexity and scale of food systems

Food systems encompass much more than what people have access to and choose to eat. A food system can be described in terms of activities and outcomes, where activities are "what we do" and outcomes are "what we get" (11, 12). As a type of system, by definition, food systems are the product of an interaction of their parts, not the sum of the parts. A 2017 framework from the High Level Panel of Experts on Food Security and Nutrition (HLPE), the science–policy interface of the UN Committee on World Food Security, has captured the intricacy and breadth of food systems (**Figure 1**) (8). This diagram includes the many drivers of food systems and provides a broad look at their many potential impacts on food consumption, nutrition, and health (8). Food production and supply chains, food environments, consumer behavior, diets and their health outcomes as well as the social, economic, and environmental impacts of each of these drivers are all part of food systems. Each of these components (activities, outcomes, drivers, supply chains, etc.) is composed of several more subcomponents.

The HLPE framework also depicts links between food systems and the 17 Sustainable Development Goals (SDGs) adopted by the UN in 2015. The SDGs, viewed as the main accountability tool for sustainable development over the next 15 y (8), prioritize food security, human health, and the protection of the planet through the participation of all countries, all stakeholders, and all people (13). The adoption of the SDGs signals a global commitment to sustainability. Food systems affect and are affected by every single one of the SDGs. Both the SDGs and the HLPE conceptual food systems framework acknowledge the multifaceted nature of sustainability, including as it applies to food systems.

There are many conceptual models of food systems, in addition to the HLPE's proposed framework. Models can vary based on their purpose and objectives, framing (worldviews and/or type of user), boundaries (what is included and excluded), and their limitations (assumptions, omissions, and uncertainties). Whereas the HLPE framework notes the importance of food environments and the SDGs, another model of food systems (**Figures 2–4**) was developed primarily to highlight the 2-way interaction between global environmental change and food systems (11). This model, especially with details in Figure 4, shows that socioeconomic and environmental drivers affect the food system in an interactive manner. It also showcases how intervening in either food system activities or context (environments in Figure 2) results in different outcomes, which then feed back to both socioeconomic and environmental drivers. A change in drivers leads to a system response, which feeds back to either enhance or dampen the drivers.

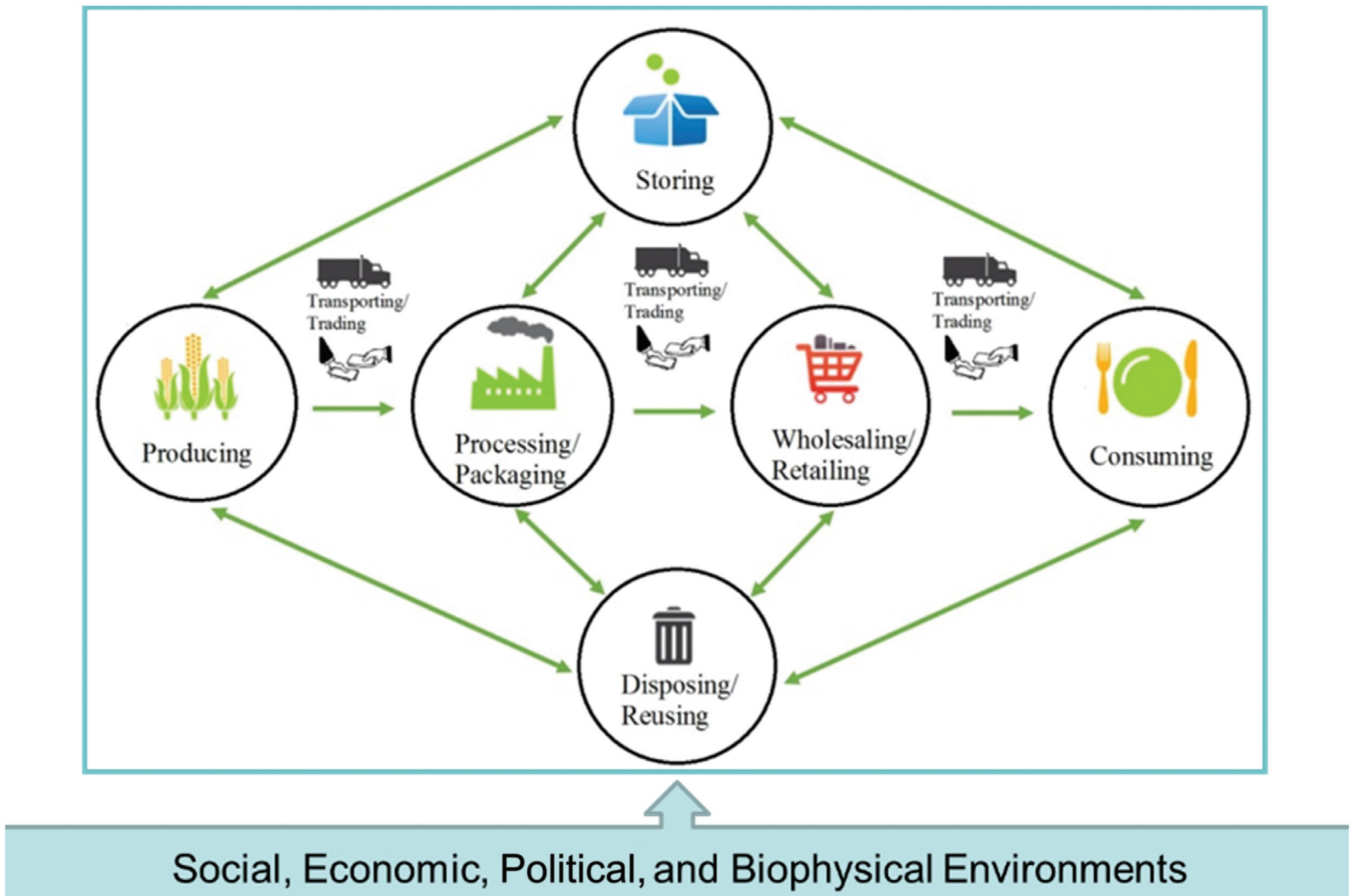

FIGURE 2 Food system activities as driven by a wide set of environments.

Food system activities, outcomes, and drivers

Food system activities are undertaken by a wide range of direct actors (i.e., people doing the activities) and encompass a network of these actors and their actions. Their activities can be grouped into 4 main categories: Producing, Processing and Packaging, Wholesaling and Retailing, and Consuming (Figure 2). These activities correspond to the functions of food supply chains as depicted by the HLPE Food Systems diagram (Figure 1). Those activities are affected by several factors: socioeconomic and environmental goals, influencers (e.g., policy makers, advocacy groups), and the social, economic, and biophysical contexts in which they exist.

Producing food, the first food system activity in Figure 2, encompasses all actions involved in the production of the raw food materials. Key actors include farmers, hunters, fishermen, and suppliers of production inputs like agrichemicals, machinery, agricultural laborers, and landowners. Processing and packaging food includes the various transformations that raw food material (e.g., biomass, such as grain, vegetable, fruit, animal) undergoes before going to the retail market for sale. Key actors include the middlemen who buy from producers and sell to processors, the managers and workers in processing and packaging plants, and trade organizations that set standards for products. Wholesaling and retailing includes a range of middlemen who operate between the producers, processors, packers, and the final consumer. Finally, consuming includes all the activities related to purchasing, cooking, preparing, and consuming food. Some actions take place across the system, such as those involved with logistics and waste management, transport, delivery, and storage. Some actors like major supermarkets are also engaged in activities across the system.

Food system activities lead to food system outcomes. Three categories of food system outcomes relate to food security (food access, food utilization, and food availability), socioeconomic goals (e.g., income, employment, and health), and environmental impacts (e.g., climate change, water availability, and water quality) (Figure 3). As one example of socioeconomic outcomes of food systems, the array of food system activities are a major source of livelihoods and a driver for numerous businesses and enterprises (14). In the United Kingdom, for instance, food is the biggest manufacturing sector, contributing £28.2 billion to the economy annually and employing 400,000 people (15). The sector also contributes to social, economic, and political stability. Food system outcomes from all 3 categories—socioeconomic, food security, and environmental—interact with each other, with the balance driven by the influences on the food system actors aforementioned. An overview of the complex adaptive framework with feedback loops is shown in Figure 4.

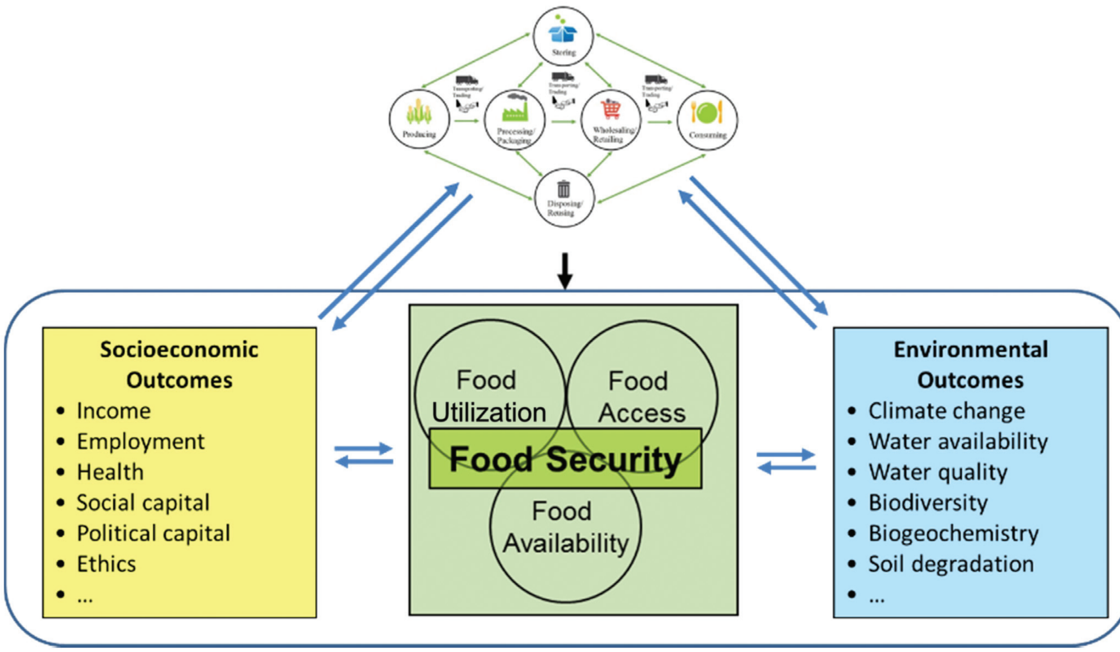

FIGURE 3 Food system outcomes for food security, other socioeconomic goals, and environment.

Four Domains of Sustainable Food Systems and Their Models, Metrics, and Measures

Ensuring that people around the world have access to safe, nutritious, affordable, and culturally acceptable diets now and in the future requires appropriate functioning of global and local food systems (16). The FAO of the UN has formally defined sustainable diets as diets with low environmental impact, which contribute to food and nutrition security and to healthy life for present and future generations (16). Sustainable food systems produce nutrient-rich foods that are affordable, socially and culturally acceptable, and sparing of both human and natural resources (8). The 2016 Chicago Consensus on Sustainable Food Systems Science (Chicago Consensus) proposed that the 4 interconnected domains of sustainable food systems are health, economics, society, and the environment. These 4 domains need to be considered concurrently to address potential trade-offs and consequences of food system transformations (17, 18).

Sustainable food systems: the importance of space and time

Like food systems, the 4 domains of sustainability have been graphically represented in a variety of ways. In 2010, the FAO proposed a "petal" diagram, with sustainable diets at the center surrounded by their key components (**Figure 5**) (16). However, this representation does not consider how food systems vary by region or change as a function of time. Components of the 4 domains of sustainability, including the affordability and social value of foods as well as the environmental impacts of food production, vary greatly across different geographies (space) and evolve with time. Data collected in a given part of the world at a single point in time do not necessarily apply to other locations or to other times. Therefore, a more accurate depiction of how the domains of sustainability can vary across space and time might be a more contemporary 4-dimensional hypercube or tesseract (**Figure 6**).

The health, economic, social, and environmental components of dietary patterns are all context dependent. Diet quality, food security, and population health vary across regions depending on national or household socioeconomic status, as indicated in the food systems diagrams (Figures 1–4). Affordability of different foods also varies by region and nation, depending on tariffs, trade, and the relation between household food budgets and local food prices. Social and cultural factors like ethnicity and religion can influence dietary patterns at the local level, and the environmental impact of food production is region-specific as well. As one example, although the global dairy sector contributes ∼4% of total global anthropogenic greenhouse gas emissions (GHGE), not all regions of the world produce milk with the same efficiency or GHGE intensity (19). North American and European dairy cows produce 4 times more milk than the global average cow and generate the lowest GHGE per gallon (19).

Time also affects the definition of healthy diets from sustainable food systems. Agricultural practices, commodity trades, food processing, and retail all evolve over time. For example, agricultural practices are not static and change, even measurably improve, over time. Consumer behavior changes, too, with protein consumption as one example. In low- and middle-income countries (LMICs), rising incomes have provoked a shift from plant to animal proteins, a culture-sensitive component of the nutrition transition. In high-income countries (HICs), an opposite protein transition is under way. People are encouraged to replace animal-source proteins with more proteins from plants (20).

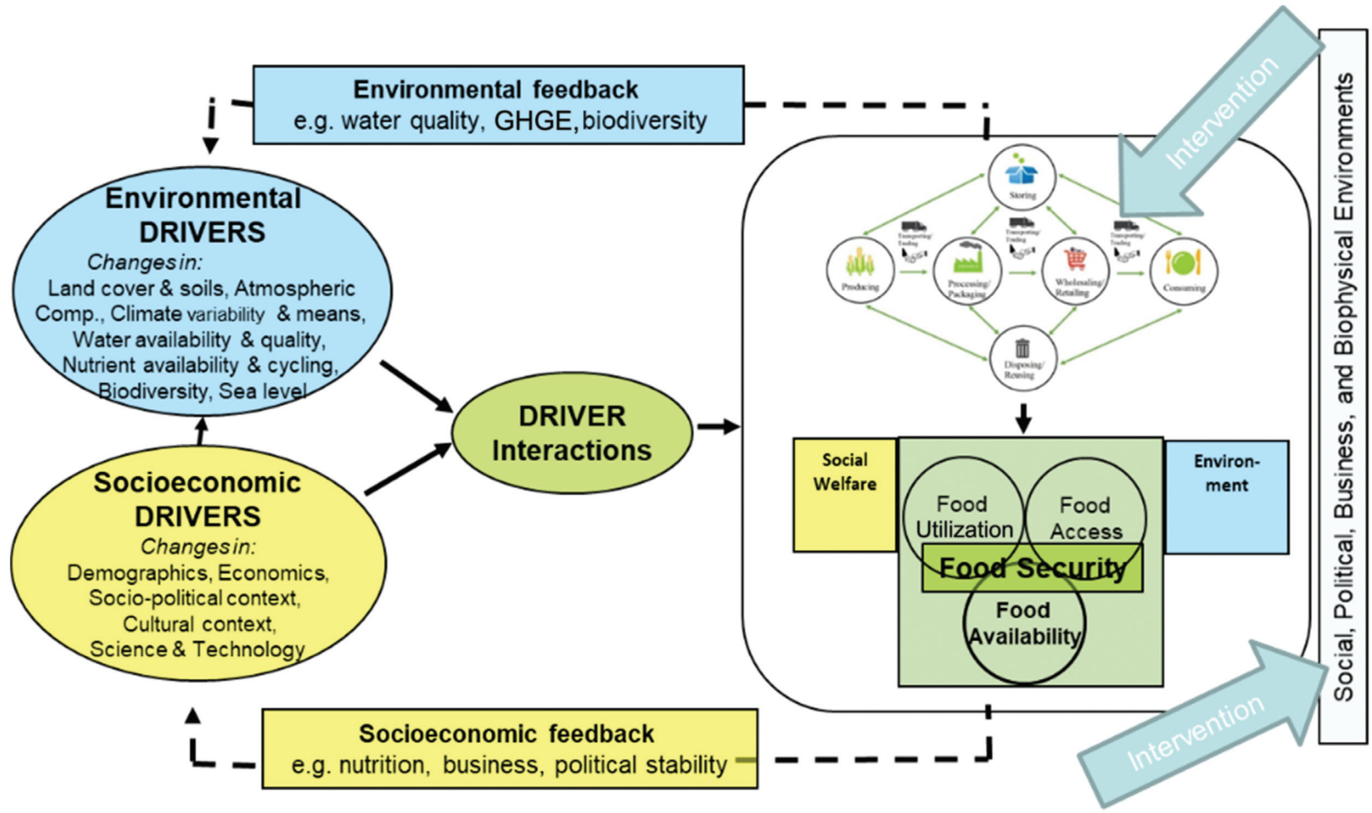

FIGURE 4 A "Complex Adaptive System" framework showing points of intervention, actors, drivers, and feedback.

Four domains of sustainable food systems: metrics and measures

As part of a system, the 4 domains of sustainable food systems—health/nutrition, economics, society, and the environment—are interconnected. Yet, they are evaluated using different metrics and measures (21, 22), which have not always been thoroughly characterized. Much of the research conducted to date focuses on 2 domains—health/nutrition and the environmental impact of food production—and has been conducted predominantly in HICs (23). Significant gaps in research, collaboration, and integration remain, especially when it comes to the social and economic domains of sustainability. The body of research remains relatively small and, perhaps as a result, the social and economic components of sustainable diets have not been included in models of the future of food demand. The remainder of this section focuses primarily on research conducted on measuring the nutritional and environmental aspects of healthy diets from sustainable food systems, providing only a brief overview of the social and economic domains, where the data are more scarce.

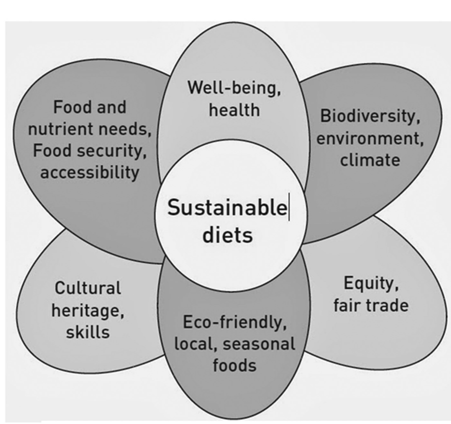

FIGURE 5 The "petal" schematic representation of sustainable diets developed by the FAO of the UN. Reproduced with permission.

Energy and nutrient density.

Nutrient density of individual foods and composite food patterns has been measured in a variety of ways. Linking the nutritional value of individual foods and overall eating patterns with nutritional status and population health outcomes is the province of nutritional epidemiology (24–26). The measures discussed here primarily focus on the nutritional value of individual foods and composite food patterns rather than the nature of the relation between foods and noncommunicable disease risk. The 2005 Dietary Guidelines for Americans (DGAs) introduced the concept of nutrient density by recommending that Americans give priority to nutrient-dense foods in order to satisfy nutrient needs without excess calories. Nutrient-dense foods were defined as those foods that "provide substantial amounts of vitamins and minerals (micronutrients) and relatively few calories" (27). The 2010 and 2015 DGAs

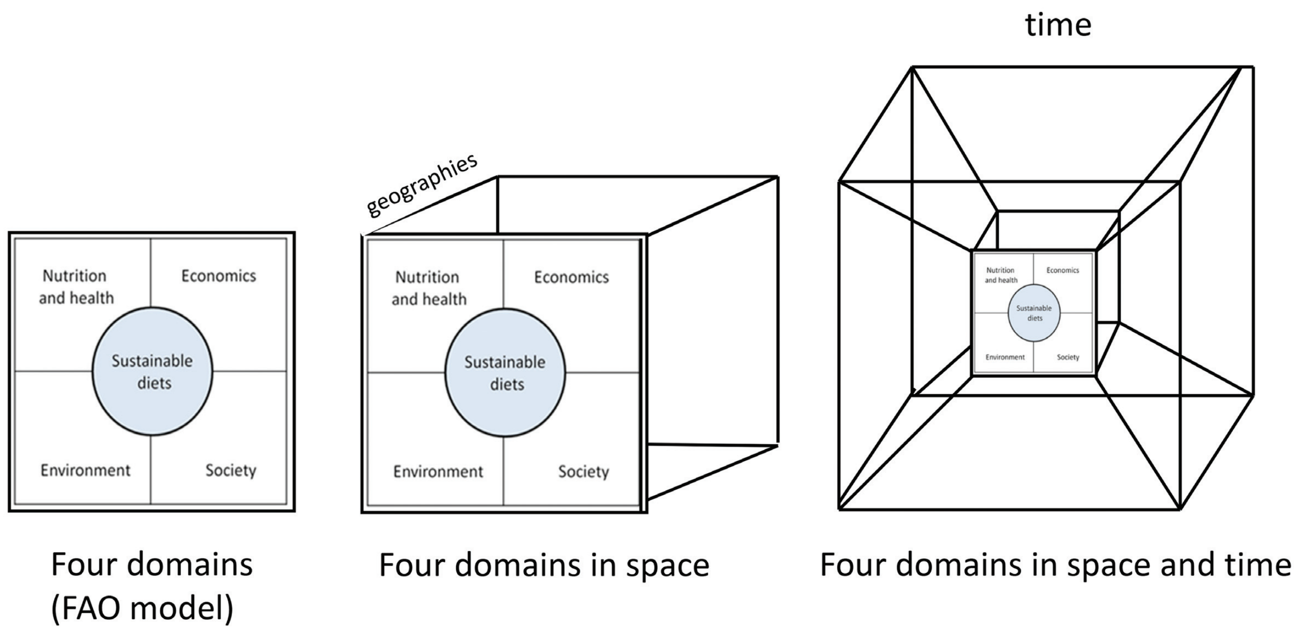

FIGURE 6 The 4-dimensional tesseract model of sustainable diets adding space and time.

further stated that nutrient-dense foods provide few or no solid fats or added sugars, refined starches, and sodium (28, 29). Subsequently, new and objective approaches to assessing the nutrient density of individual foods have become known as nutrient profiling (27).

One role of nutrient profiling models is to identify nutrient-rich foods and separate them from foods of high energy density but low nutritional value (25, 30). The concept of energy density is commonly expressed as kcal/100 g. The concept of nutrient density is more complex. Most algorithms calculate the amounts of nutrients of interest contained in a reference amount of food, which can be 100 g, 100 kcal, or a serving of food (24). Nutrients of interest can include nutrients to encourage, sometimes known as nutrients of public health concern. Those nutrients are consumed by the population in insufficient amounts. Typically, nutrients to encourage include protein, dietary fiber, and a variety of vitamins and minerals. In the United States, the 2015 DGAs pointed to inadequate intakes of fiber, calcium, potassium, and vitamin D (28). Nutrients to limit generally include added sugar, saturated fat, and sodium, although some models have also included calories. Some nutrient profiling models are based on nutrients to limit only, whereas others balance nutrients to limit against nutrients to encourage.

Deciding which vitamins and minerals ought to be included in nutrient profiling models can depend on the population health status and nutritional needs. For example, most dietary protein in HICs comes from animal-source foods. In LMICs, protein quality is a major concern, especially among lower-income groups, and there are significant deficits in dietary iron and zinc. As a result, nutrient density scores developed for supermarket shoppers in the United Kingdom may not be suitable for use elsewhere, especially not in LMICs. Developing nutrient profiling models for global use requires making decisions about what nutrients to include. That requires having access not only to food and nutrient composition databases but also to population dietary intake data, preferably linked to diet-related health outcomes.

Energy density of foods, expressed as kcal/100 g, depends almost entirely on water content or food moisture (21). Fluid milk, juices, soft drinks, vegetables, and fruit are high in water content and therefore have low energy density, often <1 kcal/g. Yogurts and cheeses, and meats, poultry, and fish typically contain 30%–60% moisture and have energy density of 2–4 kcal/g. At the other extreme, the most energy-dense foods are foods that are dry. Those include fats and oils but also dry grain snacks, candy, and chocolate.

More complex nutrient profiling models can be based on as many as 40 different nutrients (24, 26). The Nutrient-Rich Food (NRF) family of nutrient density scores is based on a variable number of nutrients to encourage and the same 3 nutrients to limit: saturated fat, added sugar, and sodium. The total NRF nutrient density score is calculated by adding percentage daily values (%DVs) for nutrients to encourage and then subtracting the sum of the %DVs for nutrients to limit. In past studies, the preferred method of validating NRF scores was to compare them to Healthy Eating Index scores, an independent measure of dietary quality and compliance with the DGAs. The NRF9.3 nutrient density score is based on 9 nutrients to encourage (protein; fiber; vitamins A, C, and E; calcium; iron; potassium; and magnesium) and 3 nutrients to limit (25). In recent studies, the NRF index has been applied to the nutrient density of snacks (31), foods and beverages (32), and the total diet (33).

Figure 7 shows the relation between energy density (kcal/100 g) and nutrient density of foods, as measured using the NRF9.3 score. The graph is based on foods consumed by participants in the nationally representative NHANES (2009–2010) (21). More than 2000 foods listed by NHANES participants were aggregated into food categories following the What We Eat in America coding scheme. The size of the

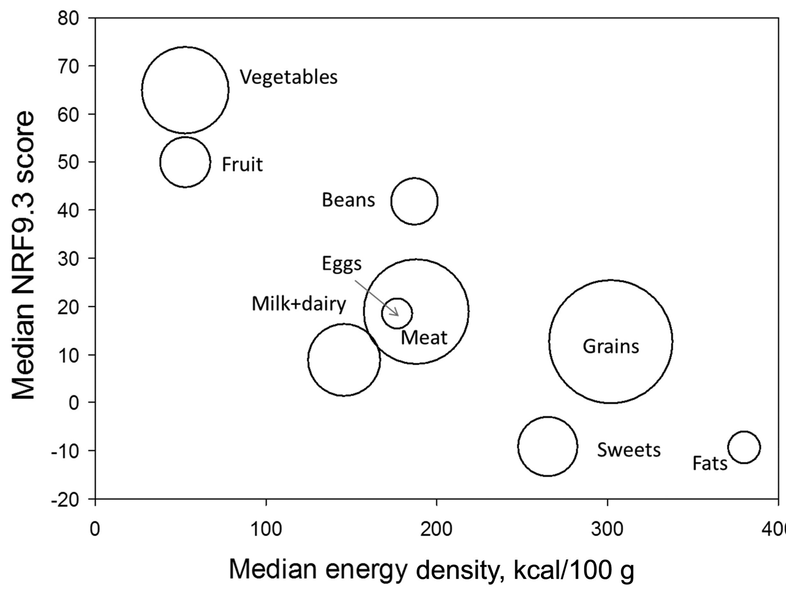

FIGURE 7 The relation between energy density (kcal/100 g) and nutrient density of foods, measured using the NRF9.3 nutrient density scores by selected USDA food categories. NRF, Nutrient-Rich Food.

bubble reflects the number of foods in each category. Citrus fruit and juices, berries, vegetables, and low-fat dairy had lower energy density and higher nutrient density scores than more energy-dense foods. Dry energy-dense foods containing saturated fat, added sugar, and sodium had lower NRF scores. Ice cream nutrient density was reduced by added sugar content, whereas pizza and cheese were penalized for their content of sodium and saturated fat.

The environmental impact of food production.
Environmental sustainability covers a wide array of phenomena. As with all of the domains, specifying goals, targets, and indicators for environmental outcomes is essential to measuring progress toward environmental sustainability (34). Within the environmental domain, metrics and measures include the impact of food production on global warming and climate change as well as the land, water, and energy costs of food production.

Impact on climate change. The contributions of the food system to climate change are measured using carbon dioxide equivalents (CO_2-e), a composite indicator that generally accounts for the aggregate impact of carbon dioxide, methane, and nitrous oxide. Each of these gases has a different global warming potential per unit mass. CO_2-e standardizes this impact.

One common way of estimating the climate change implications of eating patterns is to compare the relative CO_2-e impacts of individual foods and food groups. Such comparisons, often conducted at the farmgate level and varying by agricultural management process and many other factors, can reveal a wide range in emissions amounts, with ruminant meats having emissions (per kg) 2–3 orders of magnitude greater than most plant foods (33, 34). These comparisons also show that, although animal-based foods generally have higher impacts than plant-based foods, the impact varies by product. Eggs, dairy, pork, and poultry tend to have a lower impact than ruminant meats and some fisheries products. This method has a significant limitation: people do not subsist on single foods. They eat diets composed of many foods. The range of dietary GHGE is much narrower than the range of GHGE for individual foods (35). There is ongoing research on how dietary GHGE can be reduced without affecting the nutritional adequacy, affordability, and accessibility of the diet (36).

In addition, several analyses (35, 20, 37) that have been conducted on the emissions related to foods or eating patterns include only the emissions associated with the production of commodities. Downstream emissions, such as those that occur in food processing or preparation, are not included in the calculations. Analyzing downstream emissions requires input from life cycle assessments, which most commonly assess foods in a raw or primary processed form. Analysis using environmentally extended input-output methods leverages data on dollar flows through the economy to estimate emissions in different sectors of the food system [see, e.g., (38, 39)]. A recent study of the US food system shows that almost half of the emissions associated with actual diets come from processing, packaging, transportation, retail, and foodservice—not agriculture (40). Certain foods affect climate emissions more than others; however, their impact should be evaluated in the contexts of overall eating patterns and emissions from all food system activities (producing to consuming).

Impact on other environmental factors. Despite the complexity involved in calculating GHGE emissions for foods or eating patterns alone, this single indicator does not suffice as a holistic assessment of environmental sustainability. Focusing on GHGE when talking about sustainability leads to shortsighted solutions for food systems. Although climate change emissions are a critically important indicator, the field of life cycle assessment recognizes that analysis of the environmental impacts of diets must expand beyond climate emissions (41). The environmental impact analysis field has expanded. Both country-level and global analyses of the environmental impacts of diet that consider multiple impact categories exist [see, e.g., (42, 43)]. GHGE from food production are 1 metric of 1 domain of sustainable food systems. The environmental domain also includes the impact of eating patterns on energy and fuel use, land capacity, water, and biodiversity as well as the impact of producing, transporting, and wasting food on each of these components (8, 23, 20).

Modeling environmental impacts. As with the health/nutrition domain, several conceptual models frame environmental sustainability in a systematic way. The Millennium Ecosystem Assessment group's 2005 "ecosystem services" model divides food systems functions into 4 distinct categories: provisioning services, regulating services, cultural services, and supporting services (44). Provisioning and cultural services give us direct benefits in the form of either products, like food or fresh water, or nonmaterial goods, like recreation or a sense of place. Regulating services, like water purification or pollination, tend to be noticed by their absence when an ecosystem has been degraded. Supporting services, like soil formation and nutrient cycling, enable ecosystems to provide the other types of services.

Whereas the concept of ecosystem services helps to organize environmental functions by category, natural services also need to be organized by priority. The concept of planetary boundaries measures environmental indicators against an estimate of the "safe operating space" of the biosphere—the amount of impact within which ecosystems can still function (45). A subset of indicators has been developed to assess these boundaries. They include biodiversity loss, climate change, land use, and water use, which have all been identified as key indicators of environmental sustainability in food systems (20, 46).

Radar diagrams, for example, have also been used to show the relative severity of human impacts on various environmental measures relative to planetary boundaries (45). Likewise, color-coded matrix diagrams have been used to show performance of different food system scenarios across multiple environmental indicators relative to planetary boundaries (43).

Economics and affordability of foods

For the economics domain, measures and metrics encompass not only food prices and diet costs but also the economic viability of food production, food processing, and retail (8). Assessing and comparing the cost and affordability of foods is a complex task. Food prices must be considered in the context of local incomes. Even when food prices are comparable, their affordability across socioeconomic strata is not. In addition, calculating food prices per kilogram of food does not account for differences in the energy density or nutritional value of foods (47). Effective food prices are calculated in relation to the energy and essential nutrients that foods provide. Added sugars, refined grains, and vegetable oils cost less per 1000 kcal and have a lower carbon footprint than many animal-source foods (48). However, the nutritional value of many of these foods is low. Although affordable and appealing with a low environmental impact, sugar is not a sustainable food per the FAO definition, because it does not meet the criteria for health/nutrition. Excessive consumption of low-cost empty calories, including from sugar, also contributes to the triple burden of malnutrition (49).

The social domain

Based on the FAO definition, sustainable diets need to be healthy, affordable, and socially acceptable as well as equitable and fair (8). Within the social domain, the concept of "fair" includes gender equity issues, including the uncompensated work, mostly done by women, of acquiring and preparing foods for the household and feeding children inside the home (50). Gender equity and empowerment of women feature prominently among the UN SDGs (13). The contribution of foods and food systems to social identity, community values, tradition, and culture must also be considered, because sustainable diets need to be healthy, affordable, and socially acceptable per the FAO's definition (8, 51). In addition to these factors, the social domain also includes moral and ethical considerations related to topics such as intergenerational environmental legacy, child labor, farmer and animal welfare, workers' rights, equity, and civil harmony. Issues of food waste also have a social and ethical component.

Combining multiple indicators

To define healthy diets from sustainable food systems, metrics and measures from the different domains need to be combined. Although this has been done in some publications, there are no recognized ways of making sure that all aspects of sustainability are included in future models of healthy diets from sustainable food systems (21).

Based on the FAO definition of sustainability, sustainable food patterns need to be nutrient-rich, affordable, culturally acceptable, and appealing. However, not all nutrient-rich foods are equally affordable. In some past studies, food affordability was expressed in calories or nutrients per penny (52). **Figure 8** shows median energy density (kcal/100 g) in relation to median cost ($/100 kcal) for the USDA major food groups. Vegetables, fruit, and meat, poultry, and fish groups cost more per calorie than did grains and fats. Milk products had low energy density, were relatively inexpensive, and were of high nutritional value. Whereas dairy and sweets were equivalent in terms of price per calorie (in the United States), dairy products were nutrient dense and, therefore, provided nutrients at a lower cost.

However, foods that are nutritious and culturally appropriate in one setting may not be in another. Rates of lactose malabsorption due to lactase nonpersistence vary throughout the world (53). Fermented dairy products such as yogurt and cheese may have less lactose or contain lactose that is easier for those with lactose intolerance to digest, thus making these products more culturally relevant in regions of the world with high prevalence of lactase nonpersistence (54–56). Furthermore, some foods that are both nutrient-rich and affordable may in some cases be socially or culturally inappropriate. They can contribute nothing to the diet when their use falls outside the accepted social norms (57). For example, studies on the development of healthy food plans in France for low-income groups, using linear programming models, found that satisfying nutrient needs only was far less expensive than satisfying both nutrient needs and social norms. The least expensive food patterns that provided the necessary energy and required nutrients cost as little as 1.50€/d. However, such food patterns provided little dietary variety and were viewed as socially unacceptable. Such foods may have no place in realistic dietary guidelines (57). More work is needed to ensure that sustainable diets are culturally and socially acceptable.

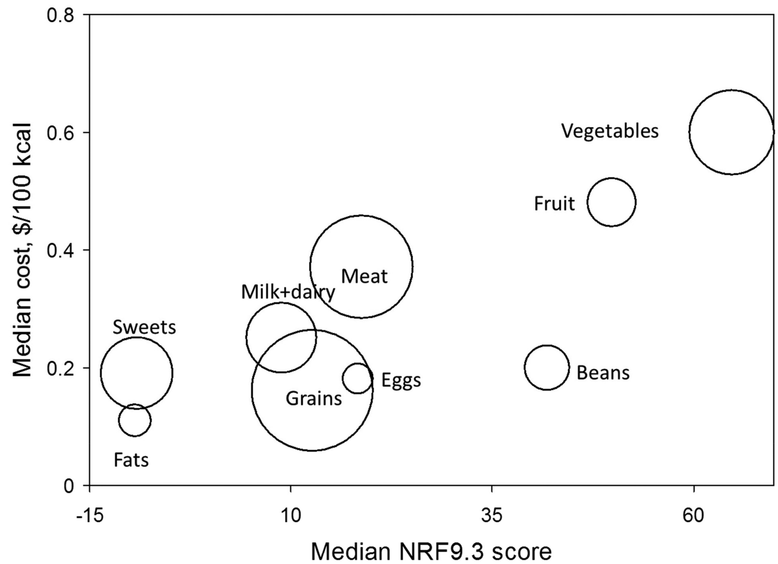

FIGURE 8 The relation between median NRF9.3 nutrient density scores and median national food prices by USDA major food group. NRF, Nutrient-Rich Food.

Nutrition needs and environmental cost.
Studies on the impact of food production on the environment have largely focused on agricultural production and GHGE (23). However, the common perception that plant-based foods have a lower environmental impact than do animal-source foods (20) may be driven by the common practice of calculating the environmental footprint of food production per kilogram of the food product. There are limitations to this approach. Work on energy and nutrient density of foods suggests that different values will be obtained when the environmental cost, including GHGE, is calculated per 1000 kcal or in relation to nutrient requirements (58). A kilogram of cabbage differs substantially from a kilogram of meat or cheese in terms of both energy and nutrient content. Low-energy-density foods, including many vegetables and salad greens, can contain 90% water which provides weight but no calories and few nutrients. When cost is calculated per kilogram, vegetables and fruit have a low environmental cost.

However, the environmental cost can increase when calculations are adjusted for energy density of different foods. Human daily energy requirements are invariably expressed in calories; there is no human requirement for a daily "weight" of foods (59). Diet quality measures, such as the Healthy Eating Index, are adjusted per 1000 kcal to separate diet quality from total energy intakes (28). Based on lifecycle analysis (LCA) data from France, animal-source foods, vegetables, and fruit groups had higher nutrient density and higher per calorie carbon cost than did refined grains, fats, and sweets (36). An increase in diet quality was associated with an increase in GHGE (59). Identifying the point at which the higher carbon footprint of some nutrient-dense foods and eating patterns is offset by their higher nutritional value is a priority area for additional research on the intersection of these 2 domains.

In addition to these limitations, GHGE from food production are also only 1 aspect of environmental sustainability. A systematic review confirmed the finding of the 2015 Dietary Guidelines Scientific Advisory Committee that "a dietary pattern that is higher in plant-based foods, such as vegetables, fruits, whole grains, legumes, nuts, and seeds, and lower in animal-based foods is more health promoting and is associated with lesser environmental impact (GHGE and energy, land, and water use) than is the current average US diet" (60). Even the addition of energy, land, and water use to these calculations does not indicate a comprehensive assessment of the environmental impact of an eating pattern. Land and water use, for example, should be contextualized in terms of their impacts on biodiversity loss and water scarcity (61). In addition to GHGE, the environmental domain includes the impact of foods and eating patterns on energy and fuel use, land capacity, water use, and biodiversity loss, as well as how these factors interact (8, 23, 20).

Next Steps for Research Collaboration, Consensus, and Implementation

Moving toward consensus on how to integrate nutrition/health with environmental issues

Although health and the environment are only 2 of the 4 aspects of sustainability, these 2 have the largest bodies of research supporting their integration. Given the many facets to consider within both domains, there is little consensus about how to move forward with either research or policy.

One possible strategy for moving toward collaboration and consensus about the environmental implications of dietary patterns in research is to identify gray areas—situations that seem to simultaneously confirm and refute the conventional wisdom. For example, analysis of the US agricultural land base suggests that the lowest agricultural land footprints can be achieved by ovo-lacto-vegetarian, lacto-vegetarian, and vegan diets (62). The same analysis also shows that the agricultural land base of the United States could support remarkably similar numbers of people following flexitarian diets (omnivore diets with lower amounts of meat consumption than current American diets) as it could people following vegetarian (inclusive of ovo-lacto- and lacto-vegetarian and vegan) diets (62). These 2 apparently contradictory findings occur because not all diets make equal use of the large areas of land unsuited to cultivation. Specifically, flexitarian diets include some foods produced on nonarable grazing lands and croplands best suited to permanent perennial forage crops or crop rotations.

Further delving into these gray areas may help to better demarcate the limits of the generalization that animal-source foods tend to have higher environmental impacts. Focusing work in this area may offer opportunities for productive collaboration among scientists with differing views on the role of animal agriculture and livestock in sustainable diets and sustainable food systems.

Transdisciplinary research

The key to enabling people to eat healthy diets from sustainable food systems is to balance nutrient requirements, food costs, and cultural acceptance against environmental impact and other societal needs. Yet, although the nature of the task may be clear, the way forward will not be easy. Considering all 4 domains of sustainable food systems when defining healthy diets requires collaboration among scholars and stakeholders from multiple disciplines and sectors. How do we manage to work together in an integrated fashion?

One way forward is to embrace transdisciplinary research. Distinct from multidisciplinary and interdisciplinary research, transdisciplinary research requires people from multiple disciplines to integrate their individual perspectives into a collective understanding of a problem or question (63). Transdisciplinary inquiry may also require researchers to engage with stakeholders early in a project, involving them in research design and knowledge production (64). Conducting research in this manner presents some daunting challenges, such as framing a project coherently, integrating methods from different fields, and engaging stakeholders in a meaningful way throughout the research process (65).

Despite the challenges, transdisciplinary research may be the right approach. There is a significant knowledge gap about social and economic aspects of healthy diets from sustainable food systems, and the body of research on these topics remains relatively small. Moving forward, research on these aspects must be integrated with research focused on health and environmental aspects of food systems, focusing on relations between the 4 domains. This systems approach helps ensure that consequences of changes to food systems and trade-offs are "known," or at least anticipated, and can be addressed (66).

Identifying points of intervention

Moving from research to food system change requires identifying where evidence-based interventions should and could occur. Such interventions should depend on accurate metrics and measurements which are sensitive to different food system geographies and their changes with time.

One approach is to change the way the activities are conducted: do the "doing things" differently along the value chain. Reardon et al. (67) defined the food system as a "dendritic cluster" of value chains. They see these as linking *1*) input suppliers to farmers ("farm input value chains"); *2*) farmers upstream to wholesalers and processors midstream, to retailers then consumers downstream ("farm output value chains"); *3*) "lateral service value chains" to all segments of the aforementioned 2 value chains (such as the transport supply chain as input to the wholesale segment of the output value chain); and *4*) research, development, and extension suppliers to all the segments of the aforementioned value chains (such as the generation of new crop varieties by breeders in research institutes to extension agents to farmers). This approach has been particularly valuable for analyzing food system transformation increasingly seen across the developing world, because, as Devaux et al. (68) argue, standard value chain analysis has failed to tackle the problems in a holistic way. Although changes in agriculture are important, a more systemic approach is needed (69, 70).

Given the health/nutrition and environmental outcomes of the current food system, the drivers of diet and constraints on dietary choice and diversity are another area to consider for intervention. A principal driver of food choice is affordability, or the relation between the price of food and the amount of income a person, family, or organization (e.g., a hospital) can spend on it. Affordability is largely determined by postfarmgate actors who control processing, packaging, trading, shipping, storing, advertising, retailing, etc. These actors are themselves influenced by other actors (market regulators, safety standards, and consumer groups). Preference, allocation, convenience, and cultural norms also inform food choice (71).

There is also a need to better understand the environments that influence the activities of actors within the food system. This would include understanding incentives on "better" practices and taxes on "poorer" practices. However, the better and poorer practices have yet to be defined. Greater consumer awareness of the need for more sustainable food systems may also help drive transformation. However, any intervention has winners and losers, and trade-offs need to be navigated. A systems approach to change may help ensure that the consequences of changes to food systems and trade-offs are "known," even planned, entities and can be addressed proactively. This process requires careful stakeholder engagement and communication.

Evaluating food system sustainability

Although the need for a more sustainable food system is clear, there is also need to develop a method to assess progress toward it. This will involve establishing a set of metrics that can measure change over time from a baseline. Gustafson et al. (21) developed an approach for national assessment for use in characterizing sustainable nutrition outcomes of food systems by defining 7 metrics, each based on a combination of multiple indicators. However, steering food systems toward a sustainability transformation requires a vast and actionable knowledge base available to a range of public and private actors as presented by the Sustainable Food and Nutrition-Visualizer (72). Designed to communicate complex policy change–impacts and trade-off questions, this visualizer enables an informed debate about trade-offs associated with options for change among food system actors as well as in the policy-making arena. This helps identify Sustainable Food System Activities, which are not only environmentally sound and socially acceptable but also economically and enterprise viable.

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