REVIEW

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Food and agricultural sustainability

Understanding the Intersection of Climate/Environmental Change, Health, Agriculture, and Improved Nutrition: A Case Study on Micronutrient Nutrition and Animal Source Foods

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ABSTRACT

With a growing global population, the demand for high-quality food to meet nutritional needs continues to increase. Our ability to meet those needs is challenged by a changing environment that includes constraints on land and water resources and growing concerns about the impact of human activity including agricultural practices on the changing climate. Adaptations that meet food/nutritional demands while avoiding unintended consequences including negatively affecting the environment are needed. This article covers a specific case study, the role of animal source foods (ASFs) in meeting micronutrient needs in a changing environment. The article covers our understanding of the role of ASFs in meeting micronutrient needs, evidence-based approaches to the development of nutrition guidance, the current issues associated with the relation between animal production practices and greenhouse gas emissions, and examples of how we might model the myriad sources of relevant data to better understand these complex interrelations. *Curr Dev Nutr* ;4:nzaa087.

Keywords: animal source foods, nutrition, micronutrients, greenhouse gases, environment

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Abbreviations used: ASF, animal source food; CH_4, methane; CONE, Combined Nutritional and Environmental; DALY, disability-adjusted life year; DGAs, Dietary Guidelines for Americans; DHHS, Department of Health and Human Services; FV, fruits and vegetables; GHG, greenhouse gas; GWP100, global warming potential; LCA, Life Cycle Assessment; LMIC, low- and middle-income country; N_2O, nitrous oxide; RCT, randomized controlled trial.

Introduction

As highlighted in the previous sections of this supplement, the challenges to meet food and nutritional needs via a sustainable food system in a changing environment are many. A need exists to recognize *1*) the reciprocal nature of the intersection of climate/environmental changes and food systems (i.e., each affects and is affected by the other); and *2*) that a sustainable food system will result in consumer and food system health. The following is an examination of a specific example of the nature and implications of these relations, i.e., the role of animal source foods (ASFs) to meet micronutrient needs in a changing environment. With due recognition of the importance of fish, insects, and other "animal" source foods, for the purposes of this discussion, the primary focus of this article will be on issues related to sustainable production of land animal source foods, i.e., beef, dairy, poultry, pigs, sheep, and goats.

Micronutrients (e.g., vitamins and minerals) are essential to life. Meeting micronutrient requirements via a diverse and sustainable food supply is a domestic and global challenge. The prevalence of micronutrient malnutrition has been estimated to approach 2 billion people worldwide (1) and is linked to a range of adverse health outcomes including poor birth, growth, and neurodevelopment outcomes, and increased susceptibility to infectious and noncommunicable diseases (2–4). Despite substantial improvement in agricultural practices leading to increasing food production, micronutrient insufficiency remains a daunting and intractable global challenge.

The problem is manifested through both food and more often nutritional insecurity that exists in both the United States and low- and middle-income countries (LMICs) and has its greatest impact on vulnerable segments of the population, most prominently women, infants, children, and the elderly. Myriad options exist to address these challenges, from improving dietary diversity to biofortification and other methods of dietary supplementation to meet nutritional needs. Despite these tools, the problems persist. How best to make decisions about ideal context-specific solutions is now complicated by a changing environment that includes demographic shifts, changing land use patterns, industrialization, and the growing impact of climate change.

Because they provide a balanced and more complete array of essential micronutrients, ASFs have historically been an important part of a healthy food system. It has been suggested that the higher prevalence of micronutrient deficiencies in LMICs may, in part, be associated with limited access to or use of ASFs. As a result, it has been suggested that improving access to and availability of ASFs should assume a larger role as part of the global toolkit to address the global micronutrient challenge (3). However, in addition to cultural resistance, problems exist in terms of both putative health consequences from greater consumption of ASFs, as well as our ability to sustain ASF production in a changing environment.

To address this conundrum, the Climate/environmental change, Health, Agriculture and Improving Nutrition Research Interest Section sponsored a symposium at the 2019 annual meeting of the ASN, entitled "Understanding the intersection of climate/environmental change, health, agriculture and improved nutrition—a case study: micronutrient nutrition and animal source foods." The session objectives were to bring together perspectives from key stakeholder communities to highlight the nature of the nutritional challenge, i.e., micronutrient insufficiency, the role of ASFs, and factors affecting its sustainability in a changing environment. An additional goal was to explore new approaches to exploit existing and emerging data sources to support the research and ultimate decision-making process for how to proceed in the development of context-specific approaches to meet these challenges. The following is not meant as an exhaustive review, but rather it serves to highlight some of the many complexities involved in developing sound nutritional guidance regarding ASFs.

Overview: Micronutrient Nutrition Challenges and the Use of ASFs to Address Them in the United States and Abroad

ASFs serve as a source of not just single nutrients, but a cluster of essential vitamins (e.g., vitamins A, B-1, B-2, B-6, and B-12) and bioavailable minerals (e.g., iron, zinc, and calcium). In regions where diets are low in ASFs, deficiencies in these micronutrients are common. Our ability to fully appreciate the short- and long-term implications of these deficits is limited by a lack of food/diet-based research. Despite these limitations, an evidence base does exist upon which to draw some useful insights.

In a study of 24,000 subjects in the United Kingdom consuming vegetarian, vegan, and omnivorous diets (the EPIC study) (5), vegans were found to be deficient in many micronutrients despite the use of fortified foods (e.g., calcium). The Collaborative Research Support Program, a multicountry study of women, infants, and children, reported that higher intake of ASFs across multiple countries (Mexico, Egypt, Kenya) predicted better outcomes in pregnant women and children through school age, including improved child growth and cognitive and physical performance (6). In a poor area in Kenya with 30% stunting, famine, low ASF intake, and wide-ranging nutrient deficiencies, Neumann et al. (7) gave 1 meal/d in school for 2 y. Meat (85 g/d) improved cognitive performance, test scores, and physical activity. Milk (250 mL/d) improved growth of stunted children and vitamin B-12 status.

Whereas a review of studies on ASFs and linear growth in LMICs found no profound effects on growth (8), a study in Ecuador found that 1 egg/d improved growth in stunted children after 6 mo (9). However, a replication of the study in Malawi found no effect, possibly because of population differences and higher fish consumption in Malawi (10). Clearly, existing amounts of ASF intake and levels of undernutrition are important to consider in the design of randomized controlled trials (RCTs) with ASFs.

Milk has been shown to consistently improve child growth. In the 1920s, daily milk intake increased height in UK schoolchildren (11) and Dutch infants suffering from stunting, rickets, and developmental delays grew more when given 3 servings of milk per week (12). Meta-analyses have shown that consumption of 750 mL milk/d in industrialized countries resulted in greater height (13) and 14 out of 17 intervention studies found milk intake was positively associated with growth (14).

Although evidence supports a role for ASFs, answers to the question of how much we need remain elusive. In the United States, the national nutrition monitoring system provides some indication of what Americans are consuming (15). Current estimates indicate that:

- Americans are generally assumed to eat too much red meat and ASF.
- Men and women consume about half of the recommended amounts of dairy (16).
- Women eat less than the recommended amount of total protein, whereas men eat about what is recommended (16).

A problem, however, is that recommendations are vague, and it is unclear how guidance can be used to address micronutrient adequacy. The 2010 Dietary Guidelines for Americans (DGAs) included recommendations for 4 groups: NHANES base, Plant-based, Lacto-ovo, and Vegan (17). In 2015, the DGAs recommended diets for 2 groups: the "Healthy US" and "Vegetarian" (16). Both groups included 3 cups dairy/d. The amount of ASFs in the Healthy diet is almost twice that recommended in the EAT diet (18), and the Vegetarian diet has limited amounts of daily ASFs. But micronutrient adequacy is not clearly elucidated; the 2015 DGAs state that both the "Healthy US" diet and the "Vegetarian" diet meet nutrient needs, but the vegetarian diet contains 3 cups dairy/d (or equivalent) and, thus, should more accurately be referred to as a lacto-ovo vegetarian diet. Moreover, adequacy of bioavailable iron and zinc is not mentioned. Therefore, although the Academy for Nutrition and Dietetics states that "appropriately planned" vegetarian diets are nutritionally adequate, they are actually talking about a diet that contains dairy and eggs.

Vitamin B-12 status is perhaps the perfect indicator of adequate ASF intake because it is unique to ASFs and vitamin B-12 deficiency is prevented if $>10\%–15\%$ kcal/d come from ASFs (whereas the EAT diet recommends 12%) (19, 20). Breast milk is an important source of vitamin B-12, but in many countries it is frighteningly low, and is not improved with supplements; thus, a continuous source of vitamin B-12 is needed.

A primary question is what should be the targeted outcomes? Usual targets include adequacy of micronutrient intake/status, growth, and functional outcomes. Challenges for such research include epidemiologic and observational study designs that account for confounders; and the cost, design, and logistical issues associated with randomized intervention studies.

Dietary diversity needs to be addressed, and some diversity indicators include ASFs:

- The Minimum Dietary Diversity indicator for women includes 10 food groups, and the criterion for diet adequacy is ≥ 15 g/d from ≥ 6 of the 10 groups; ASF is not included as an indicator (21).

- The 2017 WHO Infant and Young Children Feeding Indicator recommends 4 of 7 food groups for infants aged 6–23 mo to achieve MDD (a proxy for micronutrient density adequacy); this also does not specify the amount of ASFs, and it does not consider the contribution of breast milk (22).

ASFs are important to meet nutritional needs, but concerns have been voiced about the sustainability of ASF production in a changing environment. The 2019 EAT–*Lancet* report (18) is an effort to evaluate this relation and provide guidance. This report has a reference diet that includes a range of ASFs totaling 84 g/d, as well as 150 mL milk/d. Debate has ensued with regard to the ability of the EAT diet to meet micronutrient needs. Some consequences of this diet are as follows: based on the Global Burden of Disease 2016 (23) database, meat, egg, dairy, and fish consumption would need to increase greatly in the poorest regions to meet recommendations; changes to the EAT reference diet would potentially increase intakes of iron, zinc, folate, vitamin A, and calcium, according to the report; the diet would not be adequate in vitamins B-12 and B-2 (riboflavin), necessitating fortification. Further, another analysis of the EAT diet (18) concluded that although most nutrient amounts were adequate, calcium, iron, vitamin D, and vitamin B-12 intakes would be inadequate (24).

In summary, ASFs are needed to meet micronutrient requirements (supplements/fortification are of limited value) and ASFs have positive functional outcomes particularly in women, infants, and children. However, better domestic and global data, as well as intake guidelines for ASFs, are needed; vitamin B-12 status has been suggested as a proxy for population ASF adequacy. In general, ASF intake is adequate to excessive in wealthier regions and inadequate in poor regions, but few RCTs have tested doses. In addition, dietary quality indicators do not capture ASFs adequately or quantitatively and further studies are needed. Dietary guidance around vegetarian, plant-based diets, etc., is confusing and micronutrient concerns are not adequately addressed.

Challenges in the Development of Dietary Guidance and the Importance of Dairy and ASFs to Meet Micronutrient Needs

As discussed, better dietary guidance is needed regarding the consumption of ASFs. It is recognized that there are many sources of guidance across countries and cultures. Here we focus on the guidance given for Americans, the challenges to developing such guidance, and especially how that guidance intersects with ASF, specifically dairy. Early nutrition science focused on the identification of essential nutrients and their importance to human biology, which was subsequently translated into guidelines and policies to promote health and prevent disease. In the United States, the first such effort was via the first set of "recommended dietary allowances." The RDAs, along with their translation to public health interventions (e.g., enrichment and food fortification) and extensive educational efforts, resulted in the virtual elimination of nutritional deficiencies in the United States. In order to provide evidence to support healthy dietary patterns, the US Senate Select Committee on Nutrition and Human Needs in 1977 issued the first Dietary Goals for Americans. The goals included reducing fat, sugar, and salt in the diet, and increasing carbohydrates. The underlying premise was that too much fat, sugar, and salt were linked to major chronic diseases.

In 1980, concerns were raised over what were viewed as unrealistic expectations engendered by the Dietary Goals (25, 26), which in part led to the development of the DGAs, a partnership between the US Department of Health and Human Services (DHHS) and the USDA, that are intended to provide evidence-based support for dietary patterns for healthy Americans. The DGAs provide the scientific underpinning for the development of all food, nutrition, and health policies and relevant US government programs, e.g., the Supplemental Nutrition Assistance Program, administered by the USDA Food and Nutrition Service. Beginning with the 2020 edition, the DGAs will include specific guidance for infants and children from birth to 24 mo and pregnant women (27).

A core challenge for the DGAs process is the paucity of evidence needed to answer questions generated by the systematic review process (e.g., limited studies with whole foods); this places significant constraints on the decision-making committee (Dietary Guidance Advisory Committee) because they must review data, determine what is known and has changed since the last iteration of the DGAs process, determine how best to translate this evidence into public health policy, and develop a technical report that is communicated to the DHHS/USDA for development of the updated DGAs.

The 2015–2020 DGAs process shifted emphasis from individual foods and ingredients to healthy eating patterns. For dairy foods, the emphasis is on low-fat and fat-free, not because full-fat dairy is unhealthy, but because low-fat and fat-free are lower in calories, making a 2000-kcal/d diet easier to plan. The Dietary Guidelines Advisory Committee concluded that a healthy eating pattern includes a variety of vegetables and proteins, fresh fruits, whole grains, low-fat and fat-free dairy, and limited intake of saturated and *trans* fats, added sugars, and sodium. The inclusion of 3 cups dairy/d was a recognition by the Committee that this is the only way to get the recommended amounts of calcium. The emphasis on low-fat and fat-free with no added sugars, and a shift to eating more vegetables, fruits, and whole grains, was a new emphasis in the 2015 DGAs (16).

In contrast to much of the world, which relies on plant proteins, about two-thirds of dietary protein in the United States comes from ASFs (28). Historically, improving economic development has resulted in an increased dietary proportion of ASFs. Based on the Protein Digestibility-Corrected Amino Acid Scores (29), ASF and isolated soy protein are high-quality proteins, whereas other plant proteins are of comparatively low quality. Exchange lists are used to estimate protein content of foods, with meat, fish, legumes, and dairy being sources of high-quality protein. In the United States, calcium, potassium, fiber, and vitamin D continue to be nutrients of concern, especially for women and children (29). These nutrients, plus choline, magnesium, and vitamins A, C, and E, are under-consumed. Fortified breakfast cereals, yogurt, fortified foods, and supplements are useful in providing under-consumed nutrients.

A good example of how the intersection of food/diet/nutrients might be addressed comes from the DRI for calcium (30). In order to understand when added sugar causes a nutrient density problem for calcium intake in children, modeling with different amounts of added sugar showed that calcium intake was diluted when added sugar was $\geq$25% of energy. Such examples show the need for creative solutions to these complex interactions, particularly as they affect efforts to provide dietary guidance like the DGAs.

Similarly, Canada's Food Guide 2019 (31) recommended water as the drink of first choice, a message that may negatively affect the recommendation for 3 cups dairy/d and contribute to loss of the essential nutrients provided by dairy. Clearly, a balanced evidence-based process is essential.

Perceptions and definitions present additional challenges for the DGAs process, as exemplified by the definition and role of "processed" foods. A key element of this challenge is the common perception, as expressed by Moodie et al. (32), that commodity industries should have no role in the formation of national or international food policy, suggesting that "Public regulation and market intervention are the only evidence-based mechanisms to prevent harm." However, the reality is that *1*) by necessity, much of the research data used (e.g., food/nutrient composition data) and needed to generate such policy/guidance are industry-generated; *2*) there is a dearth of rigorous research and data linking dietary patterns and, more specifically, consumption of "ultra-processed" foods to outcomes, such as BMI or other indicators of chronic disease; and *3*) the challenge of meeting many dietary requirements is made more difficult in the absence of tools such as enrichment and fortification (i.e., processing). Moreover, processing improves the bioavailability of many essential nutrients, and also may remove harmful substances. So, the blanket condemnation of any role of processed foods or the food industry in such endeavors presents significant obstacles to a balanced analysis of these difficult issues in public health.

The objective of efforts like the generation of the DGAs is to promote health and prevent disease across the life span. In the discourse about dietary guidance in a changing environment, a move toward "plant-based" diets has been suggested both as a solution to a sustainable food system and to address current public health priorities. As noted in the previous section, this one-size-fits-all approach has its own limitations: most prominently the need to provide safe, efficacious, and sustainable sources of those essential nutrients lacking in plant-based diets. In general, plant sources are lower in protein quantity and quality than ASFs, although this can be improved by processing. However, much distrust surrounds the role of food technology and processing. The issues are complex, and making decisions regarding food systems and dietary guidance moving forward will require a stronger and more balanced evidence base. The generation of such evidence will require a multisectoral approach that encompasses food technology, sustainable production/agriculture, nutrition, health, and economics.

Sustainability of Animal Production Systems

ASFs have many desirable nutritional attributes, but many have suggested that consumption must be limited to reduce environmental impacts. Consumption of ASFs from ruminant animals is especially targeted because of their contribution to greenhouse gases (GHGs) resulting from ruminal fermentation. But the relation between ruminant animals and GHGs is complex and it is important that this complexity is understood and considered when developing dietary guidance.

According to scientific consensus, the major driver of climate change is the generation of GHGs primarily from human activity. Much of the energy from the sun that hits the Earth's surface is normally reflected into space, but GHGs put a blanket-like layer above our atmosphere, preventing solar energy from escaping, thus causing warming. A key element of the climate change discussion is the reciprocal relation with production agriculture, and in particular, animal agriculture and resultant GHG emissions. These discussions will significantly affect decisions regarding the role of ASFs in meeting nutritional needs domestically and globally, as well as decisions regarding the sustainability of ASFs in a changing environment.

The 3 primary GHGs are carbon dioxide, methane (CH_4), and nitrous oxide (N_2O). **Box 1** includes some relevant data on primary sources of GHGs (33–36).

Box 1: Relative contributions of industry to GHG emissions (33, 36)

- The transportation, industry, and power sectors combined emit ∼80% of all GHGs in the United States.
- Agriculture (total sector) produces 9% of GHGs.
- Animal agriculture alone contributes 3.9%.
- Total global GHGs from all sources amount to 49 gigatons.
- US fossil fuels contribute 11% to the global total. US ASFs and plant-based foods contribute 0.5% and 0.6%, respectively, to total global emissions.

Most discussion about the differences between these gases pertains to the global warming potential (GWP100), or the potency of the molecules to trap heat from the sun. The GWP100 of $CO_2 = 1$, $CH_4 = 28$, and $N_2O = 265$. However, of critical importance to this discussion is the relative "life span" of these GHGs. Whereas carbon dioxide and N_2O have a very long life span ($\leq$1000 y), CH_4 has a life span of only 1 decade.

The fact that fossil carbon (i.e., oil-, coal-, and gas-using sectors of society) is responsible for the majority of GHGs in the United States is accepted by climate experts and is well documented. In fact, the US Environmental Protection Agency assigns ∼80% of all GHGs to 3 sectors: transportation, industry, and power (36). Because extensive burning of fossil fuels has released carbon into the atmosphere, most climate scientists say fossil fuels are the primary contributors to global warming. However, a significant debate remains about the relative contribution of CH_4 derived from agriculture and in particular ASFs. A recent National Academy of Sciences publication on the global CH_4 budget put much focus on CH_4 from ASFs (37). However, the CH_4 balance, i.e., the balance between CH_4 production and processes that destroy and sequester CH_4, did not receive much attention.

Photosynthesis by plants converts carbon dioxide to carbohydrates. Ruminants (e.g., cattle, sheep), unlike monogastric species (e.g., humans, pigs), are able to eat plants such as grasses and forage, and convert the plant-based carbohydrates (e.g., cellulose) into energy and high-quality protein. CH_4 is a by-product that is emitted either via enteric fermentation (i.e., belching) or from manure. That CH_4 stays in the atmosphere for 10 y, and then is broken down into carbon dioxide and water. This resulting carbon dioxide is recycled (not new) carbon, because it originated from atmospheric carbon dioxide before assimilation by plants. This process is also referred to as the biogenic carbon cycle, which is distinctly different from fossil fuel source–derived carbon emissions (38). Fossil fuel combustion puts new carbon dioxide into the atmosphere at rates far larger than those at which the plants, soils, and oceans can take it on; thus, this combustion is the primary reason for increased concentration of carbon in the atmosphere.

Because of this cycle, if livestock numbers remain constant in a country or region, CH_4 produced is equal to the amount of CH_4 destroyed. A new dairy or beef operation will add new CH_4 to the air over the first 10 y, after which the amount produced equals the amount destroyed. Thus, if ruminant livestock numbers are constant, new CH_4 is not being added to the atmosphere and additional warming does not occur (39, 40). GHGs associated with livestock are going up in developing nations as a function of increasing demand, whereas in developed countries GHGs are reaching a plateau or even decreasing because livestock numbers are staying constant (41).

Human population growth from developed countries is reaching a plateau, but in developing countries it is skyrocketing, with a projected 9.5 billion people worldwide by 2050. The question becomes: how we can satisfy the nutritional needs of the population without depleting our natural resources? It is estimated that by 2050 there will be population increases of 41%, 49%, 7%, and 4% in Southeast Asia, Africa, South America, and North America, respectively. Thus, the primary 2050 challenge is a drastically increasing human population in the 2 "hotspots" of Southeast Asia and Sub-Saharan Africa (42, 43).

A critical consideration is how best to utilize existing resources to meet global demands with existing land. Of all the agricultural land in the world, 70% is marginal and unsuited to crop production (44, 45); it is suitable only for ruminant livestock (e.g., beef, dairy, sheep, or goats) because of their ability to convert low-quality plant material into nutrient-dense food. Removing livestock would effectively eliminate 70% of all the agricultural land on the planet. Only the remaining 30% of land is arable and half of that land is fertilized with manure from animal agriculture (44, 45).

Factors affecting efficiency have a great impact on environmental and economic sustainability. For example, in the United States a cow produces 23,000 pounds of milk per year; in many developing countries the average is only 1–2000 pounds/y (46). Therefore, developing nations need 10–20 cows to produce the same amount of milk as 1 US cow. FAO data show that Southeast Asia and Sub-Saharan Africa—the same regions where population growth is exploding—have the least efficient cows and the highest environmental footprints per unit of meat, milk, and eggs (47). These are also the regions, according to the EAT–*Lancet* report (18), that need to drastically increase their ASF intakes. Clearly, production efficiency will need to improve to meet these demands and avoid compounding an already severe environmental situation in those places.

Currently, the US agricultural enterprise has the lowest carbon footprint per unit of ASF production. This is attributable to greater reproductive efficiency, better veterinary care, advanced breeding (i.e., resulting in more improved feed efficiency and production), and improved feeding strategies (more energy-dense diets). These positives have allowed the United States to shrink livestock and pork herds to historically low levels. For example, the United States has gone from 25 million dairy cows in 1950 to 9 million today with a concomitant 60% increase in milk production and 33% decrease in the carbon footprint (48). The same is true for beef, poultry, and all other ASF production where productivity improvements have drastically shrunk environmental impacts (49).

Conversely, China produces half of the world's pigs (1 billion/y) but they have a preweaning mortality rate of 40% and a death loss of 400 million/y, which is more than the total number of pigs in the United States (50). This is much worse in other regions such as India and Africa. Improved efficiency is essential for their systems to be economically and environmentally sustainable.

Much of the EAT–*Lancet* report is based on 2 embedded assumptions: protein consumption is too high, and there is an inability to improve production of "enough" ASFs, so there must be a reduction of demand. Overall, available data (16) do not suggest over-consumption of protein, which challenges the first assumption. Moreover, in the past 65 y, US agricultural output has tripled without increasing relative production costs (51), which challenges the second assumption.

The EAT–*Lancet* reference diet is widely publicized as having far less environmental impact than the present omnivorous, pescatarian, vegetarian, or vegan diets; however, many have challenged this assumption. In fact, 1 person changing from an omnivore to a vegan diet for 1 y would reduce the carbon footprint by 0.8 tons; by comparison, 1 transatlantic flight per passenger results in 1.6 tons of carbon emissions (52). If we as a nation were to institute a "Meatless Monday" we would reduce our carbon footprint by 0.3%. If we were to go completely vegan, we would reduce our footprint by 2.6% (53).

In summary, the primary drivers of climate change GHGs result from human activity, but the relative contributions of the various GHGs are the product of amount produced and life span. CH_4 from ruminant animals has the shortest life span: 10 y. This short life span and the biogenic carbon cycle lead to a net balance where net production equals net removal (when livestock numbers remain constant).

The main ASF sources, ruminants for beef and dairy, are uniquely suited to utilize resources (land and plant) that would be otherwise unavailable for human use. Global ASF demand is increasing owing to economic development and population growth, and meeting demand will require improved production efficiency, especially in low-resource settings. Evidence-informed global policy will be the critical driver in ensuring our ability to meet demand in an economically and environmentally sustainable manner.

Synthesis: What Research Systems Are Needed to Adequately Integrate the Constraints and Benefits of ASFs?

In the past 2 centuries nutrition has been primarily a reductionist science, answering questions such as "what amount of nutrient *x* is needed to maximize metabolic outcome *y*?" However, the preceding discussion has pointed out that developing sound nutritional guidance for consumption of ASFs is exceedingly complex and requires a multidisciplinary approach with diverse sets of data. New tools and research systems are essential to accomplishing this task (54). The challenge moving forward is how best to utilize these often divergent data sources to support evidence-informed, context-specific programs, policies, and guidance. Tradeoffs are an inherent characteristic of sustainable food systems. These occur in terms of nutrition and health, the environment, economics, and cultural/societal preferences. Life Cycle Assessment (LCA) is a tool for accounting the environmental impact of products and services, focusing on providing a fair comparison of alternate solutions to problems we face. It is a systematic evaluation of a full system, accounting for the inputs and outputs—extractions from nature and emissions back to nature—that is characterized in terms of functional units.

LCA is commonly used in product development, design for environment, innovation, benchmarking, strategic planning, and informing public policy. LCA can be attributional or consequential. An attributional system traces contributing activities backward in time. A consequential system is more valuable for policy decisions because it looks at activities that are expected to change, tracing the consequences of increased demand forward in time.

The first step in LCA is inventory analysis, which accounts for extractions from nature and emissions back to nature. Each activity in the system has a full material and energy balance associated with it, that is, emissions and extractions, and they are linked together in a large diagram. Algorithms are used to calculate and sum all the emissions and proceed to the impact assessment. The Life Cycle Impact Assessment takes the inventory results (i.e., the list of individual emissions) and an environmental cause–effect chain is constructed that converts, for example, the GHG-trapping capacity of each emission into a GWP100 or carbon dioxide equivalent (i.e., the carbon footprint).

In this analysis, the primary focus is on the effects on the systems' endpoints. Specifically, the objective is to assess the climate change impacts on human health, agriculture, coastal area, water, and forest land. Extending the cause–effect chain down to an understanding of what more frequent catastrophic weather events mean for human health and other endpoints is necessary. Much has been learned from LCA, and future analyses will require data availability, geospatial impact assessment, benefit modeling, and metrics.

Several examples exist of the application of LCA to various aspects of agriculture. Good management is more important than the specific farming practices used in production, and LCA shows some things matter more than others. Hotspots are opportunities for innovation, i.e., to provide better technology for certain areas. High-quality data are needed for such analyses. For example, a dairy sector study uncovered a wide variation in environmental impact, revealing not just 1 milk carbon footprint, but hundreds (48). Categorizing various factors showed that feed, manure, and enteric CH_4 were the biggest contributors. Within the same production categories, some farmers were doing things differently from other farmers, which lowered their emissions. This analysis revealed opportunities for sector-level improvement: if high emitters come down, the entire sector will improve.

A National Pork Board swine production project (55) evaluated changes to management practices that would lead to tradeoffs (increases/decreases) in the carbon footprint. The biggest impact was from omitting prophylactic antibiotics, resulting in greater morbidity and mortality in the herd and higher emissions—a clear example of a tradeoff, because reducing antibiotic use in animal agriculture is an important (now regulated) goal, but with other consequences. Another finding was that the use of gestational group pens, rather than individual pens for sows, was associated with slightly lower emissions.

An unpublished National Cattlemen's Beef Association Biodiversity Project report (G. Thoma, University of Arkansas, 2019) aimed to understand the impacts associated with beef production management practices in the United States. The analysis of financial returns for beef production in Illinois indicated that *1*) lower-level practices are very important in the global supply chain; *2*) better supply chain mapping is needed; and *3*) spatially resolved inventory data are required.

With specific regard to nutrition and its incorporation into LCA, many questions emerge. An important starting point is the recognition that nutrition is both an input to and an outcome of health. One approach might be to view nutrition effects similarly to how GHG emissions are evaluated for their effects on climate. In this case, a food, meal, or diet can be used as the functional unit and analyzed for its impact on health.

An example of this approach is the Combined Nutritional and Environmental (CONE) evolution of LCA (56). CONE LCA uses global burden of disease risks associated with food groups, converts those to relevant public health indicators, e.g., disability-adjusted life years (DALYs), and couples those with other human health endpoints associated with pesticides or other supply chain inputs. The structure is the same, i.e., the inventory is captured and then run through the analysis with the appropriate calculations.

LCA offers great potential for supporting efforts to develop evidence-based guidance for healthy and sustainable dietary patterns. For example, a recent analysis compared the impacts of adding a serving of milk to a meal, adding milk but reducing other items isocalorically, or adding milk while taking away sugar and sweetened beverages. This revealed increased environmental impact, but also a health benefit, primarily a DALY reduction from colorectal cancer decline. Removing the sugar and sweetened beverages yielded the greatest health impact and about the same environmental impacts (56).

An ongoing fruits and vegetables (FV) and climate change project (57) is assessing the capacity to meet FV demands in a changing climate/environment. The project involves a transdisciplinary team. Crop, hydrology, economic, and profitability modeling includes LCA and supply chain inputs to generate current and prospective estimates for crops and sectors.

Summary

Micronutrient malnutrition is a significant global problem in many parts of the world, potentially among some populations in more developed countries (5). Several interventions can address this challenge. ASFs provide a unique combination of quality protein and essential vitamins and minerals in a bioavailable matrix that is well suited to meet nutrient requirements. Although ample evidence supports the inclusion of ASFs to meet nutritional needs and prevent adverse birth, developmental, and health outcomes, context-specific guidance for the role of ASFs in healthy eating patterns requires a more robust research agenda that includes well designed and conceptualized clinical trials to better understand the role of whole foods and dietary patterns in health across the life span.

Nutritional issues associated with ASFs combine with the nature and implications of the intersection of current production practices and a changing environment. The current conversation is dominated by questions associated with the "carbon footprint" of ASF agriculture and its contribution to GHG emissions. The polemics associated with these questions distract from the recognition that we live in a changing environment that will demand a multidisciplinary, balanced, and collegial examination of all the evidence to identify solutions.

Assessment of sustainability of ASFs must be built on the premise that future generations will have access to sufficient quality and quantity of culturally appropriate food choices to achieve nutrition security. To do this we need to develop a systems framework that encompasses many disciplines, which allows us to create, develop, and measure the metrics. Production is being constrained by resource limitations, so relevant measures are needed along with metrics to track this and identify hotspots and tradeoffs for informed decisions and policy, involving everyone in the supply chain. A need also exists to increase our understanding of the benefits of ASFs. These approaches will require teams that include social scientists and approaches that utilize extensive linkages and integration of multiple models and tools.

Our ability to meet these challenges of a rapidly growing population in a changing environment demands an inclusive effort that engages the full continuum of expertise involved in the global agricultural/food, nutrition, and health enterprise. This requires the ability to exploit numerous inputs and outputs that are continually being generated by myriad stakeholder groups involved in various aspects of food/nutrition and health. New tools such as LCA offer unique opportunities to engage communities involved in this effort.

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