

Food Security, Food Systems, and Environmental Change

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One of the central sustainability challenges of our time is how to achieve food security for a population anticipated to exceed nine billion by 2050 while minimizing further environmental degradation.¹ Further, food consumption patterns are changing rapidly as average wealth increases (especially for the emerging ‘middle class’ in much of the world), leading to many people consuming more food overall, and particularly more meat.² This needs to be seen in the context of natural resource depletion, stagnating rural economies, significant social and sociocultural changes such as the ‘Westernization’ of diets, and a changing climate.

The world’s food systems are failing many; a billion people do not have access to sufficient calories, and over two billion lack sufficient nutrients.³ On the other hand, over two billion others are overweight or obese, many of whom also suffer from insufficient nutrients.⁴ An increasing global population is only part of the problem—rising affluence for many is leading to shifts in dietary preferences, particularly an increasing appetite for animal products that have concomitant environmental and health consequences.⁵

In addition to health concerns, contemporary food systems contribute significantly to climate change through greenhouse gas emissions, threaten biodiversity, and undermine natural processes upon which food security depends.^{6,7} Conversely, climate change is already affecting crop yields,^{8,9} while supplies of freshwater are reaching their limit in some areas due to over-exploitation, mainly for irrigation.¹⁰ Expected increases in the frequency and intensity of extreme weather events, especially floods and droughts, will not only affect production but also disrupt food storage, distribution, and food safety.^{11,12} These factors will also impact market prices for food.

Given the multiple stresses on food systems, it is a complex challenge to sustainably satisfy current—let alone future—food demand. There is a need to determine how to provide adequate diets equitably while minimizing environmental degradation and without undermining the economies supporting livelihoods of the many actors and viability of the enterprises involved.

A business-as-usual approach is not tenable; current food system activities coupled with increasing demand are unsustainable. New concepts, tools,

In Brief

With limited global resources, and in the face of environmental changes, meeting future food security challenges will first require a shift in thinking from just ‘producing food’ (and other sectoral interests) to ‘food systems.’ Solutions will need to be applied at local and regional levels, but still be interlinked through dialogue and alliances between all food system actors, including producers, processors, retailers and consumers, policy makers, NGOs, and other food system ‘influencers’ such as civil society groups. Though progress is being made, the current level of thinking around cross-sectoral dialogue and solutions is far from adequate. Policy strategies are required at all points in the system—on both the demand and supply side. While constructive engagement with industry and individuals is crucial, change is essentially being left up to voluntary actions. Future solutions should aim to find synergies between climate mitigation and adaptation and between health and environmental goals, with inevitable trade-offs that will need careful management. However, a holistic approach should also create opportunities that may help to smooth the transition from business-as-usual to a more sustainable food system.

and approaches are needed and practical solutions must be found on both the supply and demand ends of food systems. Indeed, it is essential to shift towards a solutions approach that integrates the health, economic, and environmental dimensions of our food systems, so as to achieve sustainable food security going forward.

Farming in a Changing Climate

Climate change is already affecting crop production. There has also been increased volatility in food prices partly associated with weather extremes in key food-producing regions. Wheat yields are projected to drop by up to half if the global temperature is allowed to rise 4°C above the pre-Industrial mean. Models project that direct climate impacts to maize, soybean, wheat, and rice involve losses of eight to 24 percent of present-day totals when carbon dioxide fertilization effects are accounted for, or 24 to 43 percent otherwise.¹³ The globalization of grain markets implies that weather extremes that reduce food harvests in such regions would continue to influence world food prices.¹⁴

While the effects of climate change on production are likely to be complex—varying with time, geography, and other factors—the long-term, global picture is one of declining benefits and increasing costs.¹³ Tropical regions will likely be disproportionately negatively affected, with fewer benefits to crop production and more negative impacts.¹⁵ Variability in crop production is projected to increase, which makes the tasks of maintaining continuity and efficiency in value chains considerably harder. From a farm income perspective, bumper crop production can also lead to farm income losses due to lower prices. Impacts on livestock are less well-studied but broadly follow the same response patterns as crops, with negative impacts in hot and dry climates

and on high-productivity animal systems (e.g., dairy, feedlot, and piggeries) in warm temperate environments, but with some possible production increases in cooler environments.⁸

Key Concepts

- Current food systems are vulnerable to climate change and associated weather extremes. They are also a major factor in causing climate change and many aspects of environmental degradation.
- Transformation of our food system to a sustainable one is needed for environmental, health, and social reasons. This will require new dialogue and alliances between different actors in the value chain, with solutions on both supply and demand sides.
- Adaptation strategies for climate change will be needed on-farm and beyond the farm gate. Strategies will require a mix of smaller changes to farms and fisheries together with wholesale shifts in production landscapes and distribution systems.
- Research is needed urgently into food system links with energy and nutrient flows, and options for changes in policy and practice in different environments.
- Solutions aimed at managing the demand for food are also essential as they can potentially deliver substantial environmental and health benefits via a mix of regulatory, economic, social, and education strategies.
- Better food system management to reduce food loss and waste is needed in the developing world by focusing on technical and logistical strategies to reduce post-harvest losses, and in affluent countries to work with retailers, restaurateurs, and consumers to reduce food waste and to turn what is wasted into a resource.

Adaptive climate change strategies can include changes in crop management, such as new planting, tillage, fertilizer, and irrigation regimes. New varieties better adapted

to future climatic and ecological conditions are likely to emerge, and food systems suited to elevated levels of carbon dioxide will also be needed. Collectively, such measures could raise production by as much as 20 percent, depending on how the climate changes.⁸

For livestock, adaptations include changing breeds, forage management, new diets, housing and shade, husbandry, and changed integration with cropping. More intensive production methods can improve animal health, allowing them to put on weight quicker and emit less methane over a lifetime, but these practices raise animal welfare concerns. Changes in feed, such as the addition of natural oils, can reduce emissions substantially. Where possible, converting manure into energy (as is being done in some piggeries and dairies) saves on fuels and also cuts methane emissions.

Adaptation may also include harnessing traditional knowledge (for instance, to cope with production variations due to weather extremes), and increased use of edible but underutilized “orphan crops” and forest-based or “wild” foods. The conservation of agrobiodiversity is imperative in this regard; a wealth of crop species and genetic diversity provide a bulwark against environmental change as it allows for more possible resilience. However, it must be remembered that diversified production could raise the risk of food wastage due to, for instance, a larger percentage of goods falling below necessary retail standards—this means food reserve, storage, processing, distribution, and retail policies and systems will also need to be ready.¹⁶ Finally, setting aside land for nature conservation, agroforestry, and restoration, together with sustainable soil management practices, also helps to retain carbon in the landscape.

Adaptation strategies often dovetail strongly with rural sustainable development strategies by increasing

market options and/or food system resilience. Effective adaptation to climate change for the betterment of food systems thus requires policy, governance, and institutional reforms that favor investment in new technologies, infrastructure, information, good community engagement, and gender equity. Insurance markets that better reflect changing risk can be powerful drivers of adaptation, and for many rural communities especially, greater clarity and empowerment on property rights are essential.

Even with a few degrees of temperature increase, production landscapes are likely to see large shifts in what food is produced where. The past will be a poor guide to the future under climate change, and so communities need to have the wherewithal to properly consider options for the systemic and transformational change (including shifting livelihoods away from agriculture) and not simply tinker with current farming and food systems.¹⁷

Solutions Beyond the Farm Gate

Much of the climate–food debate focuses on the two-way interactions between climate change and food production. But the food system includes many other activities undertaken to convert materials produced on a farm into consumed food. These are termed “post-farm gate” activities and are also vulnerable to climate change. For example, climate change will likely disrupt food transport (e.g., road flooding, storm risks at ports, buckling of rails during heat waves) and higher temperatures may make it harder to maintain food safety due to potential pathogen increases.^{18,19} Post-farm gate activities also have a significant environmental ‘footprint’ (Table 1); for a typical food product in a high-income country (e.g., a ‘ready meal’), more than half of the direct greenhouse gas emissions can occur in haulage, storage,



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Amundra, a small farmer in Northwest Uganda, is participating in the Northern Ugandan Agriculture Cooperative, a farm employing smallholder farmers, seed experts, and agricultural technology in an effort to increase production and food security in the region.

processing, packaging, cooking, and disposal.²⁰

Note: Once we look beyond the farm gate and take in the whole food system we begin to get a better appreciation for the full impact of food, and can start to tailor solutions to address systemic problems.

Improving post-farm gate activities like storage, transport, and trade can provide both adaptation and mitigation solutions. Since large national inventories tend to raise food prices by restricting market supply and can result in 20 percent or more waste, networks of

IMPACT	PRODUCING FOOD	PROCESSING & PACKAGING FOOD	DISTRIBUTING & RETAILING FOOD	CONSUMING FOOD
Climate change	Greenhouse gas emissions (CO ₂ , methane, N ₂ O) and changes in albedo from land use	Factory emissions	Emissions from transport and cold chain	Emissions of greenhouse gases and smoke from cooking and food waste
Nutrient cycle change (N and P)	Fertilizers	Factory effluent	Nitrous oxides from transport	Food waste
Fresh water use	Irrigation	Washing, heating, cooling	Cleaning food, washing-up in restaurants	Cooking, cleaning
Biodiversity loss	Landuse change, degradation of soil, pesticides, over-fishing.	Biomass for paper/card; aluminum- and iron-ore mining	Invasive species	
Atmospheric aerosols	Dust from land-use change, tillage		Shipping	Smoke from cooking
Chemical pollution	Pesticide run-off	Factory effluent	Transport emissions	Cooking, cleaning

Table 1. Some examples of the environmental impacts of food system activities (adapted from Ingram¹⁰).

warehouses at subnational levels may be a better solution to reduce volatility.²¹ Continued improvements in and better access to information technologies will help to improve the uptake and success of logistical solutions.

Food trade liberalization offers both solutions and challenges. Modeling studies suggest, for example, that regional and global trade can help to offset the price impacts of extreme weather events on irrigation.²² Food freight (food miles) typically

contributes less than other activities (e.g., refrigeration or cooking) to greenhouse gas emissions, ocean acidification, and other environmental impacts.^{23,24}

Nevertheless, evidence suggests trade liberalization can drive up deforestation in areas of high agricultural potential, increasing emissions and biodiversity loss,²⁵ particularly in the Amazon basin. There is also concern that global corporations can evade social and environmental responsibilities where the food is

being grown. Thus, effective trade solutions must also incorporate better governance and regulation to limit unwanted environmental and social impacts.²⁶

Greater attention to supply chain management has the potential to enable adaptation to changing conditions, often delivering efficiency savings, which cuts emissions in turn. However, despite their potential as adaptive and mitigating strategies, these solutions remain under-researched.



Bob Nichols / USDA

A farmer in Texas uses modern technology to harvest grain sorghum.

Towards Sustainable Eating

Much can be done to reduce the environmental impacts of primary production and improve the efficiency of the food system beyond the farm gate. However, if absolute reductions in food-related greenhouse gas emissions and other impacts are to be achieved, then the demand side of the equation must also be addressed.^{27,28}

As the environmental impacts are severe, growing demand for animal products specifically needs to be moderated and, among more intense consumers, reduced. Rearing animals for meat, eggs, and milk generates 14.5 percent of total global greenhouse gas emissions, occupies 70 percent of agricultural land (including a third of arable land for feed crops), is the main agricultural cause of ecosystem degradation, and is also a major source of water

pollution.^{29,30} There are also concerns about the depletion of wild fish stocks and the negative effects of overfishing on aquatic ecosystems. Prolonged and intense overexploitation not only delays population rebuilding but also substantially increases the uncertainty in recovery times, especially for collapsed stocks.³¹

Further, there are significant implications for human health. As incomes rise, so does demand for animal products. Animal products are rich in protein and micronutrients, and hence can form part of a healthy diet. But overconsumption is associated with a range of non-communicable diseases. While specifics vary by context and individual, more sustainable and healthy eating patterns center on a diverse range of tubers, whole grains, legumes, and fruits and vegetables, with animal products eaten

sparingly.^{32,33} These conclusions hold not just at the country level but also globally.⁶ Estimates vary but suggest that dietary changes in high-income countries can achieve per-capita greenhouse gas emissions reductions of 25 to 50 percent without abandoning cultural norms.^{33,34} Transitioning toward more plant-based diets that are in line with standard dietary guidelines could reduce global mortality by six to 10 percent and food-related greenhouse gas emissions by 29 to 70 percent compared with a reference scenario in 2050.³⁵ A few governments, such as those of Sweden and the Netherlands, are already beginning to integrate policies related to this idea to better address health and environmental objectives.^{36,37}

There is, of course, no one-size-fits-all policy fix, and solutions should take account of the important cultural



Ken Hammond / USDA

Oranges are processed at a plant in Florida.

role of producing and consuming meat. While there is scope for synergies between environmental and health outcomes, trade-offs will need to be understood and addressed.

Reshaping eating patterns to minimize environmental and health risks is not easy. There are uncertainties and knowledge gaps, and more research into demand-side strategies is urgently needed, but this is not an excuse for inaction. Indeed, action produces data and there is already a discernible, broad path forward. So far, it seems a mix of direct regulation and market-based interventions will be needed alongside “softer” approaches such as public education and social marketing campaigns. On the other hand, change is unlikely if left up to independent individual action or industry goodwill.³⁸

Cutting Food Loss and Waste

Food loss and waste is estimated to be about one-third of global production.^{39,40} It has recently emerged on political and research agenda as a major issue, and reducing it would help to reduce the food system’s environmental impacts.^{41,42}

Postharvest storage losses are generally more important in Africa, Asia, and Latin America, while in more affluent parts of the world, food waste mainly occurs in supermarkets, eateries, and the home.³⁹ Relatively simple technical and behavioral changes (such as weather-proofing grain stores or thinking more carefully about discarding wholesome food) have high potential to help reduce food loss and waste.

In poorer countries, both technical (e.g., storage, packaging, product stabilization, and communication

infrastructure) and organizational innovations (e.g., access to capital by microfinance, warehouse receipting and inventory credits, and cooperation and mutualizing investments) could reduce postharvest loss.⁴³ In more affluent countries, data sharing, flow monitoring, and smart sensors could enable a more precise matching between supply and demand, and greater efficiency savings.² Innovative manufacturing and packaging technologies and more flexible supply-chain organization could deliver a wider access to food otherwise rejected by the market. New marketing opportunities such as stock clearance, on-site processing, and food donations can also cut waste. Leftover food can be recovered and recycled, for example, as animal feed, anaerobic digestion, and composting.⁴⁴



Patrik Rastenberger / NEFCO

A cattle farm in Oisu, Estonia.

The cold chain—continuous storage of perishable foods at controlled temperatures from farm-gate to consumer—is well established in many parts of the world and is increasingly prevalent in developing countries.⁴⁵ It provides an obvious solution to reducing food waste and improving food safety under global warming. At temperatures below 10°C, each reduction of 1°C approximately halves bacterial growth.⁴⁶ While refrigeration comes at carbon cost, greater attention to precision and other energy-saving techniques can balance the benefits of reduced food waste with the costs of energy use.^{47,48}

However, many efforts over recent decades have shown that solutions are very context-specific and require strong collaboration with local producers, wholesalers, and other stakeholders. This involves taking into account the food systems approach as a whole with its long-term economic benefits and return-on-investment so as to understand the possible incentives and barriers in implementing interventions aimed at improving health and environmental outcomes.⁴⁹ Overall, a mix of regulation, financial tools, and education and training is

required to help all food system actors from producers to consumers move towards less wasteful practices.⁵⁰

Final Thoughts

The impacts of current food systems on climate and other environmental parameters are significant, seriously degrading the natural resource base upon which our food security and other aspects of well-being depend. While positive developments including higher yields per hectare, higher feed efficiencies in livestock and aquaculture production, and higher labor productivity in many areas have helped address food security worldwide, they come at a cost for both health and environment. New policies and practices need to be developed which reduce the environmental impacts while improving health outcomes and maintaining the enterprises and associated livelihoods for the many people working within food systems. The necessary transformations of food systems will need dialogue and new alliances between all actors in the food system, including policy makers, producers, processors, retailers, and consumers ourselves. **S**

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Food loss and waste is estimated to be about one-third of global production.

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Jeremy Brooks



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More sustainable healthy eating habits center on whole grains, fruits, and vegetables, with animal products eaten sparingly.

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Towards Solutions to the Global Nutrient Challenge

by Sarah E. Cornell and Hanna Ahlström

Nitrogen and phosphorus are essential nutrients underpinning the global food system. World agriculture has come to rely on synthetic nitrogen and phosphorus fertilizers (Table 1), enabling dramatic increases in food production but also increasing nutrient leakage into the environment, at a cost to farmers and society alike.

Sustainable nutrient management in the Anthropocene is now a major global challenge.¹ Most of the world's anthropogenically emitted nitrogen is fixed industrially in an energy-intensive process. Combustion, mainly by the power and transport sectors, is also a source. The phosphorus used in agriculture and industrial production comes from rock phosphate, which is a finite resource—although it is managed as if it were not. Moreover, converting the mineral into usable phosphate is also energy expensive.

Nutrient pollution affects air, water, and soil quality, with adverse impacts on ecosystem health. Effects are most obvious locally, but nutrient pollution cascades through Earth systems. Nitrogen fertilizers, for example, are a source of the potent greenhouse gas nitrous oxide.

Everything indicates that nutrient demand and impacts will rise, unless decisions today change global use. The world's fertilizer use is very unequally distributed, with roughly half being applied to just 10 percent of the world's cropland. In other places, food insecurity arises because soils lack nutrients.² For the poorest farmers, synthetic fertilizers are unaffordable.³ Globalized trade means consumers are

disconnected from the consequences of rising nutrient use on farms.

Solutions are needed that lift food production without causing environmental harm, locking people in poverty, or lumbering them with unsustainable dependence. Here we discuss some ways forward in the complex environmental and social landscape of nutrient management.

Respecting Planetary Boundaries

Planetary boundaries are proposed limits to human interference in Earth system processes. Initially, a boundary was proposed for synthetic nitrogen fixation, sharply reducing this new flow into the Earth system. A phosphorus boundary was based on evidence of impacts of land-to-sea flows. Boundaries have since been suggested for other environmental impacts.^{2,4}

If the whole world were to use industrial nitrogen fertilizer to satisfy food demand, applications would be more than six times greater than the original boundary. Sustainable nutrient management therefore needs to square a circle marked out by Earth system dynamics, local environmental impacts, human well-being, and global justice. Is it possible?

The minimum amount of synthetic nitrogen fixation required to sustain humanity is around 50 to 80 million metric tons per year. The maximum amount that can be applied without serious environmental effect is around 60 to 100 million metric tons. So it may be possible, but only with substantial changes to agricultural and industrial practices, policy, and environmental assessment.

Improving Scientific Understanding

We need a concerted research effort on nutrients in the Earth system. Current observations and models only allow for limited investigation of how changing nutrient cycles affect (and are affected by) changes in climate and ecosystems on land and in oceans. Setting boundaries without attention to these links may not be appropriate.

The Global Partnership on Nutrient Management has recently called for a global scientific assessment of nutrient cycling, use, and impacts.¹ A regional example is the 2011 European Nitrogen Assessment.

Strengthening Nutrient Policies

Policies dealing with nutrient-related concerns have been implemented in parts of the world where problems have become acute. An example is the UNECE Convention on Long Range Transboundary Air Pollution (the Air Convention). This initially focused on end-of-pipe technical solutions for polluting emissions. More recently, it shifted its attention to pollution prevention, tackling a wider range of pollutants.

Pollution prevention policies need to attend to all stages of the nutrient use process: processing, transportation, management, application, and recycling. Europe's Water Framework Directive attempts to do this. It aims to achieve 'good status' of all waters, both ecologically and chemically, through better management of whole river basins. Similarly, the Air Convention's Task Force on Reactive Nitrogen now considers the whole nitrogen cycle as it

develops guidance on agricultural practices. For phosphorus, the institutional milieu is more fragmented than for nitrogen, but this means that actors and institutions can be mobilized in ways that can, from the outset, deal with cross-sectoral and cross-scale issues.

Translating Science into On-The-Ground Solutions

Changing farming practices can increase nutrient-use efficiency, including precision agriculture technologies that respond to crop needs, controlled-release fertilizers, and improved cropping systems. These all involve on-farm science, working with people who make daily decisions about nutrient use. One example is dNmark, a Danish-led network that links farmers, land planners, and researchers to test ways to optimize decisions for sustainable nitrogen use.

Elsewhere, old ways of integrating agriculture with sewage and water treatment are being used. Japan's Phosphorus Recycling Promotion Council shows how economic incentives, technical improvements, and

regulatory changes can help close the food-system cycle.⁵

New life-cycle impact assessments translate the science of nutrient pollution into business decision-support tools. These help businesses to internalize nutrient pollution costs and harness the creative energies of the private sector to find solutions.

Towards a Global Solution to a Global Problem

Perturbed nutrient cycles have consequences at all scales, so their management should be everyone's business. However, international governance of nutrient management is patchy. Interests often clash, and power relations of stakeholders are asymmetric. It is difficult to identify knowledge needs, propose options for action, and evaluate implementation.

Forums are emerging to share best practices for tackling the nutrient problem. The Global Partnership for Nutrient Management enables governments, industry, researchers, international agencies, and nongovernmental organizations to write a shared agenda

for redistributing nutrients more fairly. It gives space for dialogue about national responsibility for global concerns.

A global, solutions-focused approach to nutrient management is in its infancy. Key to all solutions is actually recognizing it as a complex global, cross-sectoral, cross-scale problem. From there dialogue, research, and reforms appropriate to the task can begin to take shape. **S**

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	Nitrogen (000 tonnes N)			Phosphorus (000 tonnes P ₂ O ₅ *)		
	1993	2013	% change	1993	2013	% change
Developed countries	30,612	33,358	9	13,528	10,795	-20
Developing countries	41,585	77,145	86	15,423	29,511	91
Global total	72,197	110,493		28,951	40,306	

Table 1. Global N and P fertilizer consumption in 1993 and 2013.

*P₂O₅ (phosphorus pentoxide) is how P concentration in fertilizers is expressed. Data shown are total N and total P₂O₅, including compound fertilizers, in thousands of metric tons of nutrients. Data and country classification from the International Fertilizer Industry Association (ifadata.fertilizer.org).