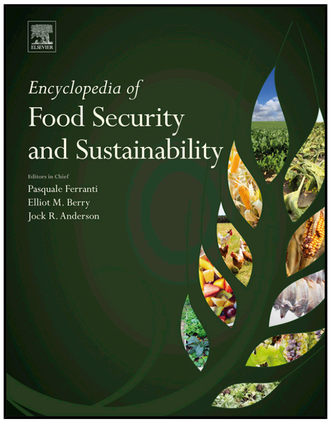

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Sustainable Pathways for Meeting Future Food Demand

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Abstract

Food production has tripled over the past half century and has allowed the world's population to increase by 4.5 billion people. This boom in food supply as a result of the Green Revolution avoided widespread famine but carried with it substantial environmental costs including depletion of freshwater resources, eutrophication from injudicious fertilizer use, greenhouse gas emissions from livestock, rice paddies, mechanization, and fertilizer denitrification, and agricultural expansion into natural systems. Humanity will need to feed several billion more people by mid-century while minimizing the environmental burden of food production and coping with the impacts of a changing climate. This text provides an overview of the key tradeoffs that have historically occurred between food production and the environment and explores solutions that offer promise for enhancing food supply and environmental stewardship together.

Introduction

Global food supply has nearly tripled over the past half century, supporting an additional 4.5 billion people and reducing malnourishment by hundreds of millions during that time period (FAO, 2009a, 2017a; UN DESA, 2015). These increases in production have also allowed for richer diets – through the increased use of crops for animal feed – and supported the expansion of alternative crop-based energy sources. At the same time, 815 million people (or 1 in 9 people) still cope with chronic undernourishment (FAO, 2017b), and the environmental burden of agriculture has grown substantially. Croplands and rangelands now cover a third of the planet's ice-free surface (Ramankutty et al., 2008; Foley et al., 2011). More than half of accessible runoff is withdrawn for human use (Postel et al., 1996), and nearly all of the anthropogenic consumptive water use is for agriculture (Hoekstra and Mekonnen, 2012). Fertilizer production has more than doubled the amount of reactive nitrogen in the environment (Galloway et al., 2008; Schlesinger, 2009), while greenhouse gas emissions from food production (e.g., ruminant digestion, fertilizer denitrification) and land use change contribute 19%–29% of humanity's greenhouse gas emissions (Vermeulen et al., 2012).

There is wide agreement that humanity's rate of resource use exceeds what can be sustainably generated and absorbed by Earth's systems (Wackernagel et al., 2002; Rockström et al., 2009; Hoekstra and Wiedmann, 2014; Galli et al., 2014; Steffen et al., 2015). It is also clear that a continuation of current agricultural practices will enhance the vulnerability of the global food system to economic and environmental shocks (Suweis et al., 2015). A radical transformation of the global food system is therefore required in order to increase nutritious food production while minimizing its environmental impacts and facing uncertainties related to demand and climate impacts (FAO, 2009b; Tilman et al., 2011; Alexandratos and Bruinsma, 2012; Rosenzweig et al., 2014; DeFries et al., 2015). The sections below briefly examine some of the key interactions between the global food system and the environment and explore avenues by which future food demand and environmental sustainability can potentially be achieved in tandem.

Water Demand

The agricultural sector is responsible for 70% of global freshwater withdrawals, with even larger shares in Asia and Africa (FAO, 2011a). In addition, irrigation drives 90% of global freshwater consumption (Hoekstra and Mekonnen, 2012). While mostly

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rainfed (80% of cultivated land in 2009, FAO, 2011a), global food production importantly relies on productive irrigated fields, with 40% of the global food supply produced with irrigation (UN WWAP, 2014), and as much as 80% of food production in Pakistan, 70% in China and over 50% in India. Irrigation water sources, referred to as 'blue water', include surface and groundwater, from river flow to reservoirs and deep aquifers with each type presenting a different opportunity cost, availability over time and space, and renewal rate (Dalin and Rodriguez-Iturbe, 2016). The sustainability of food systems is thus strongly dependent on the source and volume of water resources it consumes.

In particular, non-renewable aquifers are increasingly overexploited for irrigation in large food baskets of the world, such as the California Central Valley, central USA, the North China Plain, Northern India and Pakistan (Wada et al., 2012; Dalin et al., 2017). This means that a significant share of the food supply is produced unsustainably due to overuse of groundwater. In addition, surface water use can also be unsustainable, both in terms of water storage depletion (i.e., via reduced inflows from rivers exploited for irrigation upstream) and in relative terms (i.e., when excessive withdrawals relative to the environmental flow requirements hinder ecosystem functions e.g., Richter et al., 2003).

In places where the timing and amount of water demand exceed what is locally available, water use can lead to water stress or scarcity (Brauman et al., 2016). This can have cascading consequences that include degraded water quality (e.g., increased salinity), land subsidence when aquifers are emptied, loss of livelihoods (e.g., fisheries decline), and impacts on biodiversity (Postel, 2000; Postel and Richter, 2003). While the impacts on water resources occur in the producing regions, agricultural water use is in part driven by remote demand for food and feed and linked to consuming regions through international trade. Dalin et al. (2017) showed that the food demand of most countries is at least in part supported by unsustainable water use (i.e., where the water demand of production exceeds the annual renewable availability) either through the irrigation of local production or through food imports. In particular, food exports from Pakistan, the USA, and India are partially unsustainable because some of these food crops were irrigated from overexploited aquifers.

The United Nations Food and Agriculture Organization (FAO) projects that 60% more food will be required by 2050, and that total global water withdrawals will increase by 50% in developing countries and 18% in developed countries by 2025 (Flammini et al., 2014). In particular, additional demand for irrigation to increase crop yields is expected to enhance water stress in many agricultural baskets (Davis et al., 2017a). In addition, renewable water availability may become more variable under future climate change and may further decrease in already dry areas ('dry get drier'; Stocker et al., 2013). Rising temperatures also mean that some crops will require more water to grow in the future (Urban and Sheffield, 2017).

The combination of widespread unsustainable water use, rising food demand, and anticipated climatic stress requires agricultural solutions that align nutrition, livelihoods, and water sustainability. Wada et al. (2014) have summarised six global strategies to reduce water stress in affected regions. Two of these are directly related to agriculture: improving agricultural productivity and increasing irrigation efficiency. Other proposed strategies include reducing overall water demand (limiting the rate of population growth, improving industrial and domestic water-use efficiency) and increasing availability (via reservoirs and desalination). Improving agricultural productivity can be achieved by using different cultivars or with better nutrient management. Foley et al. (2011) found important yield gaps could be filled by simply adding enough fertilizer to the currently cultivated crops. However, overuse of fertilizers may lead to eutrophication in rivers and deltas and other environmental damages (see next section). Important water savings could also be achieved by increasing irrigation efficiency, for example by reducing leakage in irrigation infrastructure or by switching practices from flood irrigation to sprinkler or drip.

Important water savings can also come from food demand management. Along with population growth control, reducing food waste at each step of the supply chain could significantly reduce agricultural water demand (Kummu et al., 2012) – as about a third of the food produced globally is lost or wasted (FAO, 2011b). Diet changes are also strong levers to reduce the water demand of humanity (Jalava et al., 2014; Gephart et al., 2016). These strategies generally offer advantages across a suite of environmental outcomes.

Nitrogen Use

The proliferation of reactive nitrogen (all forms of N except unreactive N_2) – via the Haber-Bosch process and legume cultivation – has allowed humanity to support a booming population over the past 50 years (Erisman et al., 2008). Most of the N used to produce food is lost to the environment along the food supply chain ($\sim$80%), and much of the remainder ($\sim$20%) is lost after food consumption and trade (Galloway et al., 2014). These losses to the environment have been amplified by rates of nitrogen application that exceed, in many locations, the nitrogen removed from the landscape in harvested products (Mueller et al., 2014), and by diminishing yield returns to nitrogen at higher application rates (Tilman et al., 2002; Lassaletta et al., 2014). Once in the environment, anthropogenic N contributes to smog, acid deposition, air pollution, eutrophication of fresh and marine waters, atmospheric warming, and stratospheric ozone depletion through a phenomenon of the N cascade (Erisman et al., 2013).

This has led to the historical dilemma where humanity must create new reactive N to have enough to produce food, but most of the N is lost to the environment, contributing to degradation at local, regional, and global scales. These unprecedented alterations to the nitrogen cycle mean that humans create three to four times more reactive N than natural terrestrial processes (Fowler et al., 2013), most of which is in support of food production. In 2010 the production and consumption of food utilized $\sim$160 Tg N year^{-1}. By 2050 this reactive N demand is expected to double to 320 Tg N year^{-1} if trends in food production and consumption practices are not changed (Galloway et al., 2017).

Important opportunities exist at each step of the production chain to increase the efficiency of reactive N use while minimizing losses to the environment. These strategies can be implemented through three broad approaches: 1) policy mandates, 2) technological advances, and 3) changes in consumption patterns.

Policy changes could, for example, set limits on reactive N emissions from power plants or set standards of N removal rates at wastewater treatment facilities. These strategies have proven effective in many countries for air quality regulation. For example, in the US, the emission of NOx to the atmosphere has decreased by several fold due to the Clean Air Act and its amendments (Sullivan et al., 2018). N losses from agricultural systems, however, are much more challenging to control as the sources are diffuse and heterogeneous in space and time. Therefore, a multi-phase approach to nitrogen management – that seeks to promote nitrogen use efficiency through improvements in technologies and on-farm management of the timing, rate, and location of fertilizer application – is likely necessary (Zhang et al., 2015).

Technological solutions can improve the efficiency of converting reactive N into the product of interest, such as fertilizer application solutions that improve nitrogen use efficiency of crop production and improve feed conversion ratios in animal protein production. In addition, there are other steps along the food supply chain where food waste (and the associated losses of N) can be decreased, including processing, distribution, and sale. This also provides the opportunity to involve a variety of stakeholders — farmers, processors, distributors, and retailers (Galloway et al., 2015).

A key stakeholder is of course the consumer. Consumers can make dietary choices that have a lower nitrogen footprint, such as choosing more plant protein sources and reducing protein consumption to recommended dietary levels. Footprint tools and environmental footprint labels can also help communicate the environmental impacts of food choices to consumers (e.g., Leach et al., 2012; Leach et al., 2016). Changes in consumption patterns that lead to lower environmental impacts could then drive improvements up the supply chain (Galloway et al., 2017).

Land Use Change

Land use change refers to two major processes. The first process is a change in land cover associated with the expansion or contraction of the area of land used for different purposes (e.g., pasture, cropland, urban). The second process is a change in the type of management on existing land cover (e.g., changes in irrigation, fertilizer use, crop type, harvesting practices, or impermeable surfaces). Land use change related to management can occur without changing the extent of different land covers.

Since the middle of the 20th century, food production has increased dramatically through land use change. The world's cereal supply increased by a factor of 2.2 and outpaced the 1.3-fold increase in population (FAO, 2017a). This increased production is mainly attributable to agricultural intensification – where crop yields and harvesting frequencies are enhanced through the addition of irrigation, fertilizers, pesticides, herbicides, and mechanization. While the expansion of agriculture was relatively small compared with overall agricultural area, more than 80% of agricultural expansion since the 1980s has been at the expense of tropical forests (Gibbs et al., 2010).

Approximately 38% of the Earth's total, ice-free land surface is currently used for agriculture. The majority is used for pasture with the remainder used as cropland (Foley et al., 2011). Urban areas cover only a small fraction of the land surface, but currently contain more than half of the world's population and generate a large proportion of the demand for commercial agricultural production.

With globalization, rising incomes, and trade, land use change is increasingly determined by demands for products distant from where they were produced (Liu et al., 2013). These 'teleconnections' create demands for export-oriented production and ultimately result in land use changes, a prime example of which is the clearing of tropical forests for oil palm production in Southeast Asia to supply other parts of the world with palm oil for cooking and biodiesel. Moreover, the income-driven increase in demand for animal products has also created 'teleconnections' for land use change, a prominent example of which is the linkage between demands for soybeans for animal feed in Europe and Asia and forest clearing in South America.

Land use change is associated with a variety of positive and negative outcomes for society and the environment. From society's point of view, land use change is essential to produce food, feed, and fiber for human use, as well as to provide habitable space for people. Scientists debate whether high-yield, intensive production on a relatively small area (land-sparing) is preferable to lower-yield, more biodiversity-friendly production over a larger area (land-sharing) (Phalan et al., 2011). From an environmental point of view, land use determines a range of environmental outcomes, including carbon emissions and habitat loss for biodiversity with land clearing, and soil degradation and erosion with overgrazing, salinization, and other unsustainable practices.

Reconciling the multiple dimensions of land use change is not straightforward, and a variety of actors have implemented strategies aimed at responsible land use management and the prevention of agricultural expansion. Organizations within the private sector have instituted company-wide policies of sustainable supply chain management, and some have adopted non-binding zero-deforestation commitments (Rueda et al., 2017; Lambin et al., 2018; Thorlakson et al., 2018). Across the globe there have also been a variety of governance-based conservation efforts, the most ubiquitous of which is perhaps the use of protected areas aimed at preserving forested lands and other high biodiversity areas (Leverington et al., 2010; Joppa and Pfaff, 2010). Government agencies have also been vital to monitoring and enforcement efforts (Nolte et al., 2013; Nepstad et al., 2014). Non-governmental organizations have also played a key role in driving sustainable land use initiatives. Examples of these efforts include deforestation moratia (e.g., soybeans in Brazil (Gibbs et al., 2015), oil palm in Indonesia (Busch et al., 2015)), certification protocols (e.g., Fairtrade, Rainforest Alliance) (e.g., DeFries et al., 2017; Carlson et al., 2018), and roundtables for key international commodities (e.g., beef, soy, and oil palm) (see e.g., Garrett et al., 2016).

Climate Change

Climate change poses a dual challenge for agricultural systems. First, agricultural management practices and land clearing for agriculture are substantial contributors to greenhouse gas emissions and can influence regional climate (Smith et al., 2014), meaning that efforts to increase production should be done in ways that help mitigate harmful impacts. Second, agriculture is uniquely vulnerable to changes in climate, and farmers will increasingly need to adapt to changing temperature and precipitation patterns across the globe (Challinor et al., 2014; Myers et al., 2017).

Agriculture jointly influences climate through two mechanisms: biogeochemical and biophysical (Anderson-Teixeira et al., 2012). The biogeochemical pathway occurs when agricultural management practices or land clearing produce greenhouse gas emissions. Agricultural emissions include land clearing and deforestation for agriculture (carbon dioxide - CO_2), peatland drainage and peat fires (CO_2, nitrous oxide - N_2O, and methane - CH_4), enteric fermentation from ruminant livestock (CH_4), rice cultivation (CH_4), manure management (CH_4), and application of both synthetic and organic nitrogen fertilizers (N_2O). Together, these emissions account for nearly a quarter of greenhouse gas emissions (Smith et al., 2014). Greenhouse gas emissions from agricultural management are concentrated in North America, Western Europe, South Asia, and East Asia, with the highest emissions intensity (i.e., emissions per unit of food production) occurring in Asia (Carlson et al., 2017).

Agriculture's biophysical impacts on climate result from how agricultural management practices and vegetation alter the regulation of water and energy. Temperatures can be influenced by energy use to evaporate water from the soil or through the leaves (together termed "evapotranspiration"), as well as by the reflectivity, or albedo, of the surface. Higher albedo and higher rates of evapotranspiration are associated with cooler temperatures, and rates of evapotranspiration can also influence regional rainfall. For example, increasing productivity and evapotranspiration is thought to have cooled summer temperatures and increased rainfall in the US Midwest (Mueller et al., 2017; Alter et al., 2018) and South Asia (Puma and Cook, 2010), adoption of no-till agriculture in Europe across winter croplands could cool temperature extremes (Davin et al., 2014), and deforestation for agriculture in Brazil could lead to warming and drying and subsequent damage to agricultural productivity (Oliveira et al., 2013).

The impacts of climate change on agricultural production will result from the complex interaction of farmer management practices, crop cultivar development, rising CO_2 concentrations, and changing temperature and precipitation patterns (Porter et al., 2014). Some regions, particularly in high latitudes, are expected to see yield benefits from a changing climate, whereas yield damages are expected in lower latitudes (Rosenzweig et al., 2014). Elevated CO_2 concentrations will offset damages to some degree, as CO_2 has a fertilization effect and provides a water savings for many crops (Leakey et al., 2009). At a global level, net declines in productivity are expected for major crops (Porter et al., 2014; Rosenzweig et al., 2014). Productivity shocks from increasing exposure to extreme events are of great concern for food prices and food security, particularly in developing countries (Battisti and Naylor, 2009).

Looking to the future, agriculture will need to reduce greenhouse gas emissions while simultaneously increasing productivity and adapting to a changing climate. Historical increases in crop productivity helped avoid deforestation and greenhouse gas emissions, and further productivity increases are necessary to constrain the agricultural land footprint and minimize deforestation as food demand increases (Burney et al., 2010). More efficient use of fertilizers and soil carbon management are other strategies that can reduce the climate impacts of agriculture (Smith et al., 2014). Farmers will undoubtedly adapt to changes in climate by altering agricultural practices (e.g., planting dates or crop choice) in ways that minimize harm, or, conversely, exploit beneficial opportunities (Porter et al., 2014).

Towards Food System Sustainability on a Globalizing Planet

The dilemma between increasing both food supply and the environmental burden of production is a feature of historical agricultural approaches, and a large body of literature focuses on identifying strategies for its resolution (e.g., Godfray et al., 2010; Foley et al., 2011; Tilman et al., 2011). These potential solutions include enhancing crop yields on current croplands, improving resource use efficiency, reducing food waste, and shifting to less resource-intensive diets – all of which can offer benefits across the environmental impacts explored here. Indeed, recent work has shown that employing a suite of these solutions can achieve food security and environmental co-benefits in the coming decades (Tilman and Clark, 2014; Davis et al., 2016; Jägermeyr et al., 2017). Other work has shown that – by better aligning food security and environmental goals – it is possible to substantially reduce resource demand while also producing more food (e.g., Bajželj et al., 2014; Mueller et al., 2014; Davis et al., 2017b). While all of this research is a cause for optimism, the major challenge that remains in actualizing food system sustainability is in adapting these solutions to specific locations in ways that incorporate local priorities and that engender local buy-in.

One key to addressing these challenges is to better understand the 'wedges' – be they policy-based, cultural, infrastructural, or economic – that have produced discrepancies between current patterns of food production and those that optimize outcomes along the dimensions of nutrition, environmental sustainability, climate resilience, and livelihoods (e.g., Wada et al., 2014). Identifying and prioritizing certain 'wedges' for intervention will require interdisciplinary approaches that link a global perspective with direct stakeholder engagement. In addition, understanding how local and distant policy and consumption decisions influence specific production choices – and acknowledging the growing role of international food trade in redistributing food (MacDonald et al., 2015; Wood et al., 2018) and its impacts of production – will be essential for effectively addressing sustainability challenges within food systems. Countries can complement these efforts through awareness initiatives and educational programs that inform the public of the environmental consequences of their dietary choices, including through the use of footprint tools (e.g., Leach et al., 2012), sustainability food labels (e.g., Leach et al., 2016), and guidelines for healthy eating (e.g., Tilman and Clark, 2014) among other strategies. It is clear that any solution aimed at achieving sustainable food systems must be tailored to a specific place, taking into account nutritional, cultural, political, economic, and environmental factors. The approaches that will offer the most promise for achieving increased food production and environmental sustainability together will be those that best identify and minimize potential tradeoffs and that seek ways to realize multiple co-benefits.

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