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Key Points:
- We investigate the trade-offs of water use for food or energy production and the nexus among water, food, and energy
- We investigate the broader issue of feeding the planet with limited resources while ensuring sustainability, resilience, and equity
- We analyze a number of approaches to future food and energy security

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The Global Food-Energy-Water Nexus

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Abstract Water availability is a major factor constraining humanity's ability to meet the future food and energy needs of a growing and increasingly affluent human population. Water plays an important role in the production of energy, including renewable energy sources and the extraction of unconventional fossil fuels that are expected to become important players in future energy security. The emergent competition for water between the food and energy systems is increasingly recognized in the concept of the "food-energy-water nexus." The nexus between food and water is made even more complex by the globalization of agriculture and rapid growth in food trade, which results in a massive virtual transfer of water among regions and plays an important role in the food and water security of some regions. This review explores multiple components of the food-energy-water nexus and highlights possible approaches that could be used to meet food and energy security with the limited renewable water resources of the planet. Despite clear tensions inherent in meeting the growing and changing demand for food and energy in the 21st century, the inherent linkages among food, water, and energy systems can offer an opportunity for synergistic strategies aimed at resilient food, water, and energy security, such as the circular economy.

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"Earth provides enough to satisfy every man's need but not every man's greed."

Mahatma Gandhi (1869–1948)

1. Introduction

Humanity is in a historical moment in which the capacity to live without irreversibly compromising the environmental and biophysical conditions on which it depends is dramatically questioned (Rockström et al., 2009). Anthropogenic pressure on the Earth system has reached a point where abrupt environmental change is feared with global sustainability becoming a mere utopia. Despite the adoption of governance initiatives, such as the 2030 Agenda for Sustainable Development and the related 17 Sustainable Development Goals (SDGs; UN, 2016; Biermann et al., 2017), there are significant challenges and intrinsic trade-offs that arise from the interaction of social and environmental systems (Dell'Angelo, D'Odorico, & Rulli, 2017; Pradhan et al., 2017). In particular, the interdependencies among the food, energy, and water systems are central to the global sustainability question (e.g., Nerini et al., 2017).

During the second half of the twentieth century, unprecedented growth in global crop production fueled in part by the recent availability of nitrogen fertilizers (Erisman et al., 2008) occurred side by side with unprecedented population growth. Because of their reliance on trade, some countries have sustained high rates of demographic growth despite their low agricultural yields (van Ittersum et al., 2016); however, globally, both crop production and population have dramatically increased in the last century. The degree to which humanity is susceptible to a severe global food crisis in the 21st century is a matter of much debate and growing uncertainty. Global population is projected to continue to rise this century, with median estimates from the UN of 9.6 billion people by 2050 and 10.9 billion by 2100 (Gerland et al., 2014; Lee, 2011). At the same time, the consumption of animal products and other resource-intensive foods is likely to grow (Tilman & Clark, 2014). Water is a vital part of this story, as an important limiting factor controlling food production (e.g., Falkenmark & Rockström, 2006; Porkka et al., 2017). The ability to maintain adequate food supplies with limited water resources has therefore become a pressing concern (Falkenmark & Rockström, 2004). In fact, despite the development of new technology (e.g., new cultivars, irrigation techniques, and water reuse methods), the human pressure on global water resources has been increasing at alarming rates in response to population growth and changes in diet, raising new concerns about the planet's ability to feed humanity within the limited renewable freshwater resources (Carr et al., 2013; Falkenmark & Rockström, 2006; Gleick, 1993; Hoekstra & Chapagain, 2008; Rockström et al., 2012; Varis et al., 2017).

An often overlooked aspect of the water crisis is the emergent competition for water resources between the food and energy industries, which is expected to dominate the water security debate in the next few decades (Rosa et al., 2017, 2018; Scanlon et al., 2017). Until recently, most of the energy needs of industrial societies have been met with the use of conventional fossil fuels that require relatively low water costs for their extraction. In addition to renewable energy, such as hydropower, the near future will see an increasing reliance on unconventional fossil fuel deposits, such as oil sands, shale oil, and shale gas, which require greater amounts of water (Rosa et al., 2017, 2018). These deposits account for most of the proven fossil fuels on Earth, and their extraction might be limited by water availability, especially in arid and semiarid regions where stronger competition is expected to emerge between water uses for food and energy (Rosa et al., 2018). The growth in demand for renewable energy is also likely to substantially increase dam development, which can have numerous social and environmental consequences in river basins; for example, Zarfl et al. (2015) recently estimated that about 3,700 large hydropower dams were planned or under construction globally. At the same time, recent bioenergy policies (European Union (EU) Parliament, 2009; U.S. Congress, 2007) have mandated a certain degree of reliance on renewable energy, stimulating the development of the biofuel industry with a direct competition between food and energy uses of crops and embodied water (Farrell et al., 2006; Hermele, 2014; Ravi et al., 2014; Rulli et al., 2016).

Competition in water use for food and energy security constitutes the core of an emerging debate on the food-energy-water (FEW) nexus: the growing societal needs for food and energy rely on the same pool of limited freshwater resources, a situation that is generating new questions on the environmental, ethical, economics, and policy implications of human appropriation of water resources. The FEW nexus is an emerging research focus for natural and social scientists who are exploring the impact of water limitations on the production of energy and food (Jones et al., 2017; Rulli et al., 2016; Scanlon et al., 2017), and the extent to which the human pressure on the global freshwater system is expected to increase in response to the growing demand for food and energy (Chiarelli et al., 2018; Grafton et al., 2017). Although advancements have been made in terms of understanding linkages among FEW systems (e.g., Biggs et al., 2015; Jones et al., 2017; Liu et al., 2017; Ringler et al., 2013; Smajgl et al., 2016) and working toward integrated modeling (Bazilian et al., 2011; McCarl et al., 2017), the highly interdisciplinary nature of FEW research has resulted in somewhat disparate clusters of FEW studies. This article seeks to review and synthesize a broad set of issues related to each FEW system individually (see sections 2–4), then outline a range of intersections among each system—"nexus" points—relevant to scholars in environmental sciences, engineering, economics, political ecology, and other social sciences and analyze their pairwise interactions (i.e., food-water, water-energy, and food-energy; Figure 1). We extend the FEW nexus concepts to consider linkages between biophysical and social impacts (e.g., human rights), governance, globalization, and resilience and look toward the future to ask what issues are on the horizon for each FEW system and their intersection in terms of food, energy, and water security. We also discuss the challenges emerging from the analysis of FEW dynamics and the associated "trilemma" of using natural resources, such as water for food, energy, or environmental needs. This review provides a global perspective on FEW trade-offs through an analysis of globalization of patterns, international investments, and global resilience. The article ends with a review of possible new approaches to a more sustainable management of the FEW system through new advanced technologies, low technological methods, and reduced consumption.

2. The Food System

Food systems encompass the different production, distribution, and consumption activities that link people to the food they eat, as well as the system outcomes for society and the environment (e.g., Ingram, 2011; Schipanski et al., 2016). Food system activities include the use of natural resources and labor in the production, processing, and transport of food, as well as individual food consumption decisions (e.g., diets and waste). Food systems are therefore shaped by policies related to agriculture, trade, and food, as well as other institutional arrangements, alongside the cultural, educational, and economic dimensions of food consumers (Ingram, 2011).

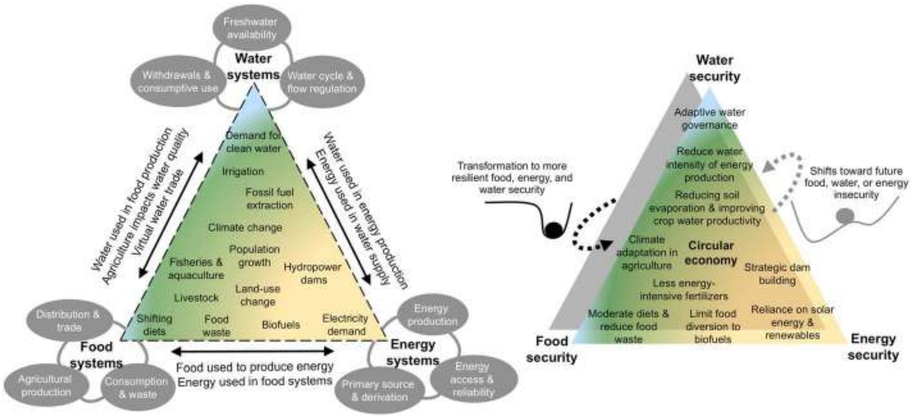

Figure 1. The food-energy-water nexus highlights the inherent linkages between individual food, energy, and water systems, including the competition in demand for water between food and energy production (adapted from UN Water, 2013). The right panel shows a conceptual depiction of resilience in the food-energy-water nexus, which is discussed in section 10.1.

2.1. Trends in Food Production and Demand

Global crop supply has more than tripled, and animal production has increased 2.5-fold over the past 50 years (Food and Agriculture Organization (FAO), 2013) and by 50% since the mid-1980s (Figure 2; D'Odorico et al., 2014). Currently, only five countries—Brazil, China, India, Indonesia, and the United States—produce more than one half (52%) of the world's crops. In addition, just four crops—wheat, rice, maize, and soybeans—constitute more than one half (57% by calorie or 61% by protein content) of current food production. Food systems have become increasingly globalized; 23% of food calories currently are traded internationally, and about 85% of countries rely on food imports to meet domestic demand (D'Odorico et al., 2014).

Recent global increases in food demand have been largely driven by demographic growth and improvements in income (Alexandratos & Bruinsma, 2012; FAO, 2011; Tilman et al., 2011). Since World War II, population has more than tripled (Box 1) from 2.4 billion (1945) to 7.3 billion people (2015); South and East Asia experienced the most substantial increases (UN Department of Economic and Social Affairs, 2015). Rising incomes have allowed households to afford richer diets with higher calorie and protein intake per capita (Di Paola et al., 2017; Tilman et al., 2011) but often with stronger burdens on natural resources and the environment (Box 2). A typical trend observed in countries undergoing economic development is that, as the average income increases, there is a growth in the consumption of nonstarchy food such as vegetables, dairy,

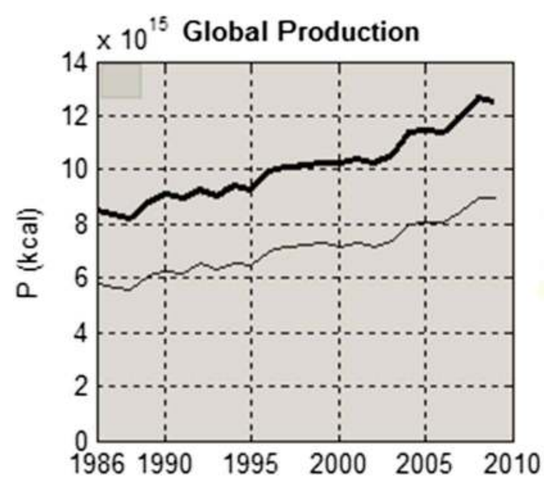

Figure 2. Global production (in kilocalories) of food for direct human consumption (thin line) compared to total agricultural production (food + livestock feed + other agricultural products; thick line; from D'Odorico et al., 2014).

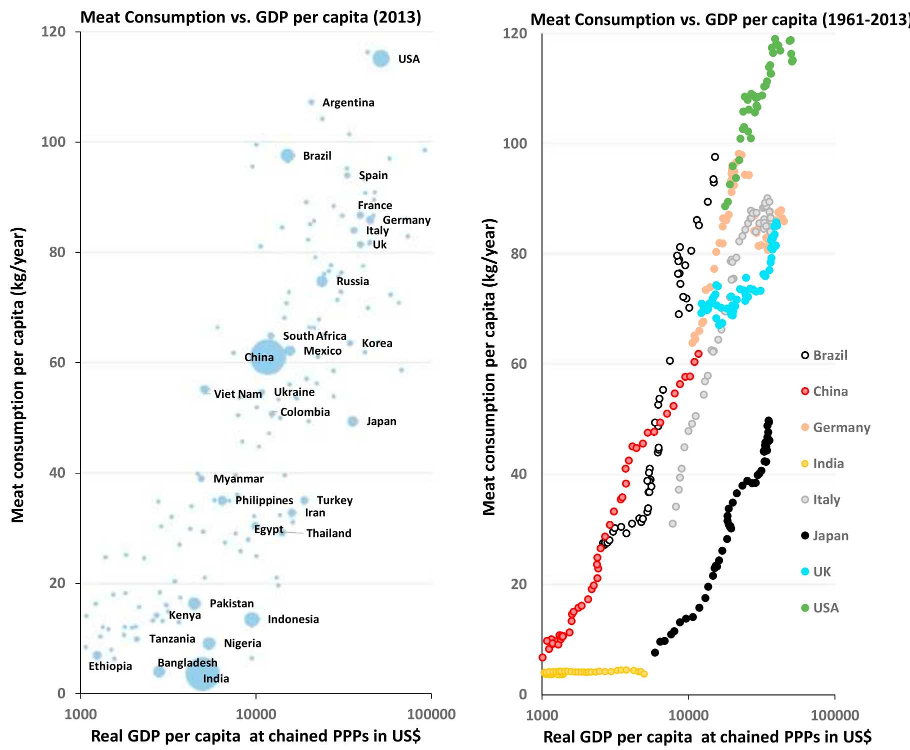

Figure 3. Meat consumption as a function of income levels. Income is expressed in terms of gross domestic product (GDP) per capita at chained purchasing power parity (PPP), which is a metric typically used to compare relative income and living standards across countries and over time (Feenstra et al., 2015). Meat consumption data are from FAOSTAT (2017).

meat, and consumable oil (Figure 3), a pattern that is also known as "Bennett's law" (Bennett, 1941). Indeed, per capita consumption of animal food has been increasing in the last few decades (Tilman et al., 2011). Dairy and meat production are expected to increase by 65% and 76%, respectively, by 2050 (Bailey et al., 2014). Such an increase in the consumption of animal products can impede humanity's ability to meet greenhouse gas (GHG) emission targets (e.g., Wellesley et al., 2015). The general improvement in household economic status has meant that 123 million people in developing countries were able to escape undernourishment between 1990 and 2015 alone (Alexandratos & Bruinsma, 2012). Yet substantial nutrition deficiencies (Box 3) persist with roughly one in seven people receiving inadequate protein and calories and still more lacking access to important micronutrients (FAO, 2009b; Godfray et al., 2010).

Box 1. Population Growth and Food Availability: The Four Food Revolutions and Food Security

The food security debate often starts from the analysis of whether and for how long humanity will be able to produce enough food to feed every human being with the limited resources existing on the planet (e.g., Cohen, 1995). This question dates back to Malthus (1798) who argued that human population grows faster than humanity's ability to increase food availability. Thus, food production would not be able to keep up with demographic growth, and the population size will eventually exceed the ability of the planet to feed everyone. Moreover, population growth can lead to unsustainable use of natural resources (Ehrlich & Holdren, 1971). However, to date, there is no conclusive evidence that, globally, population growth is constrained by resource availability. Therefore, demographers typically do not account for the effect of resource limitation, but they do model population growth as the result of an unbalance between fertility and mortality rates, which are related to social factors such as health care and women's education, employment, and empowerment (Lee, 2011). In recent decades, it has been argued that Malthus's prophecy missed something because it did not account for humanity's ability to develop new technologies that could allow for an increase in food production. The last few centuries have seen major

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technological revolutions that have increased humanity's ability to produce crops. The *industrial revolution* with modern machineries for farming, processing, storage, and transportation, and the *green revolution* with industrial fertilizers, irrigation systems, and new cultivars, occurred after the publication of Malthus's theory. On the other hand, it is widely recognized that the acceleration in demographic growth that occurred after World War II (Table B1) would have not been possible without the invention of industrial nitrogen fixation (the *Haber-Bosch process*) and its application to fertilizer synthesis (Erisman et al., 2008), which greatly contributed to the tenfold increase in crop production during the twentieth century (e.g., Warren, 2015). Although this interpretation would suggest that resource availability does constrain population growth (consistent with Malthus's theory), in the 1980s (i.e., on the wake of the green revolution), Boserup (1981) suggested the opposite: that population growth drives technological innovations, including the development of new advancements that are crucial to the intensification of agricultural production. Boserup's theory, which was probably motivated by the effects of the green revolution with the unprecedented increase in crop yields that occurred in those decades, did not account for the finite resources of the planet: If population growth favors the emergence of technological innovations that enhance food production, a positive feedback could lead to infinite growth. This paradox was previously highlighted by von Foerster and Pask (1960) in a thought-provoking paper in which population growth was modeled as a logistic equation with carrying capacity expressed as a (nonlinear) increasing function of the population size. Foerster's model showed that these assumptions can lead to the "explosion" of the "population bomb" by 2026, an apocalyptic result that conceptually demonstrates the weakness of some of the early non-Malthusian claims (Kaack & Katul, 2013; Parolari et al, 2015).

Malthus's theory has also been challenged by other scholars from different viewpoints. As noted earlier, demographic models (including UN's population projections) do not account for resource limitation (Lee, 2011), an aspect that is troublesome because it ignores the fact that it is agriculture (and not health care or education) that feeds the world (e.g., Warren, 2015). On the other hand, in his seminal work on poverty and famines, Sen (1982) noted that major famines are not attributable to food scarcity but to lack of access to food, including economic access. This research partly contributed to modern definitions of *food security* adopted by the UN (FAO, 2013), which are based not only on *availability* (i.e., food production and supply) but also on *economic and physical access* to food and its utilization (i.e., nutritional value of healthy food). The *stability* of these components over time is critical to maintain food security because food needs to be available at all times despite shocks in production and prices (FAO, 2013).

The reduced emphasis on availability was also consistent with decades of sustained increase in crop yields, driven initially by increased nutrient inputs and irrigation (Tilman et al., 2002) and by massive private research and development (Fuglie et al., 2012). However, starting in the 1990s, there have been reductions in crop yield growth for some key crops (Fuglie et al., 2012) and, in many regions, crop yields are reaching a plateau (Ray et al., 2012). At the same time, most of the world's prime arable lands are already in use, so opportunity for expansion is limited (Foley et al., 2011), and food production comes at major environmental costs (Godfray et al., 2010). Given that the demand for food commodities is increasing as a result of population growth and changes in diets (see section 2.1), new concerns about the role of crop utilization in ensuring global food availability are emerging (e.g., Cassidy et al., 2013; Davis et al., 2016; see section 11.3). A number of recent studies have quantified the global carrying capacity for human population to stress the finite magnitude of the agricultural resources available locally and globally (e.g., Davis et al., 2016; Fader et al., 2013; Porkka et al., 2017), including water resources (Falkenmark & Rockström, 2006; Suweis et al., 2013). After the industrial and green revolutions, another major dimension of food availability has emerged from the globalization of food through trade and the growing role of imports (see section 9; D'Odorico et al., 2014; MacDonald et al., 2015; Porkka et al., 2013). Global trade allows food-scarce regions to rely on excess in production existing elsewhere around the world. This "trade revolution" has reduced local food deficits by increasing global interdependencies in the food system without really increasing the carrying capacity of the planet. As agricultural yields are stagnating in many regions and the safety margins associated with local redundancies in production are eroded, humanity has started to face (again, after decades of abundance) major food crises with global-scale repercussions (e.g., in 2008 and 2011). For example, there was an 83% increase in food prices from 2005 to 2008, which was estimated to have pushed about 40 million people into hunger (Mittal, 2009). Such trends raise serious concerns for global food security. Of course, it is still possible to improve crop production by bringing modern

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technology to areas of the developing world where the yield gaps are still big because of a lack of adequate investment. This "fourth food revolution" (D'Odorico & Rulli, 2013) that has been taking place in recent years (since 2005), however, may have negative impacts on rural communities (sections 9.3 and 11.1) and will only delay the emergence of an unavoidable food crisis (section 9.2). Solutions to such a crisis that aim at curbing the demand instead of increasing production (e.g., by reducing waste, using resources more efficiently, adopting less demanding diets, or containing population growth) appear to be a more forward-looking and responsible approach to sustainable food security (section 11.3).

Table B1
Toward Peak Population

Population year	Year	Time to 1 billion+	Key global trends or events
1 billion	1804	—	Industrial revolution
2 billion	1927	(123 years later)	Green revolution follows WW2
3 billion	1960	(33 years later)	Green revolution in developing world
4 billion	1974	(14 years later)	—
5 billion	1987	(13 years later)	Global trade intensification
6 billion	1999	(12 years later)	China enters World Trade Organization (2001)
7 billion	2011	(13 years later)	Global food crises (2007–2008 and 2011)
8 billion	2025 (projection)	(14 years later)	—

Note. How quickly did we become 7 billion? Following the industrial revolution, human population doubled in about 120 years from the beginning of the nineteenth century to the 1920s. The green revolution coincided with a doubling of the global population every 50 years and with a 1 billion increase every 12–14 years since 1960 (data from UN, 1999, and *UN Population Division*).

Box 2. Environmental Impacts of Diets

Sustainable diets not only have low environmental impacts but also contribute to food and nutrition security for a healthy life for present and future generations (FAO, 2010). Within the context of the FEW nexus, sustainable diet research must account for the water and energy production of the food items as well as the nutritional value of the foods (e.g., Pimentel & Pimentel, 2007). This means that although a food item may require little water or energy input for production, if it has low nutritional content, it may not contribute to a sustainable diet. Put another way, although the water or energy footprint may be low on a per kilogram of product basis, the footprint may be high in terms of calories, grams of protein, or micronutrients for nutritionally poor foods (i.e., a low nutritional density; Gustafson et al., 2016). One approach to study both the environmental and nutritional dimensions of sustainable diets is to examine the environmental footprints of diet scenarios derived from variations of observed diets (Figure B2). For example, Davis et al. (2016) project the changes in water and carbon footprints associated with business-as-usual, Mediterranean, pescetarian (i.e., relying on seafood for protein intake), and vegetarian diet scenarios. The per capita water footprints improved under the vegetarian and pescetarian scenarios, and the per capita carbon footprint improved in those two diet scenarios, as well as the Mediterranean diet scenario (Davis et al., 2016). A systematic review of the impact of diet scenarios on GHG emissions found the largest GHG reductions in vegan and vegetarian diets, although the authors point out that this result is sensitive to the foods that substitute for meat or animal products in the diet (Hallström et al., 2015). Another approach taken is to use recommended minimum levels of nutrient intake as constraints in an optimization context to identify diets that minimize environmental footprints. For example, Gephart, Davis, et al. (2016) identify diets minimizing water and carbon footprints while meeting 19 micronutrient and macronutrient requirements. The authors found that optimal diet for a small carbon footprint consists of about two-thirds vegetables, one-third nuts, and small amounts of seafood and milk, whereas the optimal diet for the water footprint consists of about four-fifths vegetables, one-fifth starchy roots, and small amounts of seafood (Gephart, Davis, et al., 2016). While optimization can produce unrealistically homogenous diets, it can provide insight into which foods are more efficient when environmental impacts and nutritional quality are simultaneously considered. Identifying sustainable diets is difficult owing to the vast number of food products that vary in terms of their environmental footprints and nutritional content, based on the details of the production methods, where the food is produced, and how the food is prepared. In addition to the difficulty of choosing metrics, it is difficult to generalize which production or dietary options are most relevant to a diversity of sociocultural and economic contexts (Jones et al., 2016). As a result, there is much room for future research on identifying sustainable diets. Despite this variability, previous studies generally found that sustainable diets consist of less meat, particularly less beef and more vegetables, and tend to be similar to vegetarian, pescetarian, or Mediterranean diets (Hallström et al., 2015; Perignon et al., 2016, 2017). These findings indicate that there are options to improve environmental and nutritional sustainability through diets (Tilman & Clark, 2014).

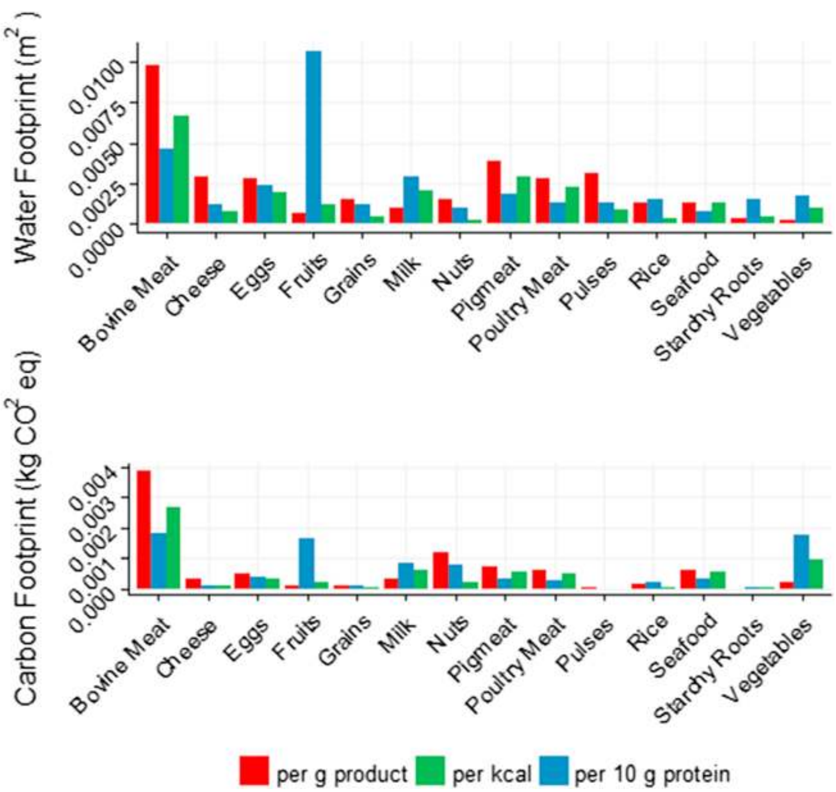

Figure B2. The water and carbon footprints of food products (based on Gephart, Davis, et al., 2016).

Box 3. Malnourishment and Diet Transitions

Food security requires the *availability* of, and *access* to, a sufficient amount of food (in terms of energy content, typically expressed in calories) with adequate nutritional properties (see Box 1 and FAO (2011)). **Malnourishment**, refers to conditions in which *caloric and nutrient intake* does not meet or exceeds per capita requirements. **Undernourishment** is a condition in which the caloric intake is not sufficient to conduct a healthy and productive life. In contrast, **overnourishment** is the case of excessive nutrient intake to the point of causing obesity, diabetes, hypertension, or other chronic diseases. **Undernutrition** can be caused either by not eating enough food (i.e., undernourishment, in terms of energy, protein, or other nutrient intake) or rapid nutrient loss and poor absorption owing to illness (e.g., as a result of repeated diarrheal infections, a problem typically resulting from low water quality and poor sanitation) FAO (2011; WFP, 2012). It has been estimated that undernourishment (i.e., calorie deficiency) affects about 800 million people in the world, whereas micronutrient malnutrition affects 2 billion people (so-called hidden hunger) (IFPRI, 2016). About 60% of the global population suffers from iron deficiency (Misselhorn et al., 2012). Undernutrition may affect children by causing low weight at birth, stunting, wasting, and micronutrient deficiencies. **Wasting** refers to the condition of losing weight or not being able to gain weight. It is a typical symptom of *acute malnutrition* and is typically assessed through direct measurements of the weight-to-height ratio. Recent cases of wasting could be reversed through adequate food intake. A major risk factor for child mortality, wasting affects about 8% of children under 5 years old worldwide, which corresponds to 52 million people (based on 2011 data, FAO, 2011). **Stunting** refers to insufficient growth in height with respect to age. It affects about 165 million children worldwide, mostly (90%) in Africa and Asia (based on 2011 data, FAO, 2011). A typical symptom of *chronic malnutrition*, stunting is often associated with cognitive impairment, as well as high mortality and morbidity rates. These deficits in mental and physical development can only be prevented, not cured. Stunting typically results from insufficient nourishment and inadequate protein intake in the first 1,000 days: from pregnancy to the second birthday of the child. It can also result from undernutrition in childbearing women, infections, and illness. Unlike wasting, stunting initially can be difficult to recognize. Therefore, a *positive feedback of undernutrition* seems to exist, whereby poorer mothers have less access to food, which exposes their children to the risk of stunting and cognitive deficits, thereby limiting educational achievements and access to better jobs (WFP, 2012)While undernutrition remains a shameful societal and institutional failure, overnutrition and the consumption of nutritionally inadequate diets is also becoming a major concern for public health and the environment. The rapid rural-to-urban transition that is occurring around the world affects where and how people have access to food and what they eat. The typical outcome of urbanization is a nutrient shift, whereby potentially unhealthy food products such as fats, sugar, meat, and processed foods become more readily available and economically more accessible— largely as a result of the intensification and industrialization of agriculture—while fresh vegetables and fruit become relatively more costly and less accessible (e.g., in food deserts). Known as the *nutrition transition*, this major shift in the global diet, which is reflected in Bennett's law (see Section 2.1), is having major impacts on human health, with an increase in the incidence of obesity and cardiovascular diseases (Popkin and Gordon-Larsen, 2004), and anthropogenic pressure on the environment (Section 2.2).

Despite massive increases in crop production over the past 50 years, a growing share of this output is not being used for direct human consumption. The growth in demand for animal products (Box 2), combined with a shift toward a more crop-dependent livestock sector, has substantially increased competition for crop use between direct human consumption and feed to support livestock (Thornton, 2010). Indeed, the excess in crop production afforded by the technological advances of the green revolution has allowed for the use of crops as feed, thereby dramatically increasing the rates of livestock production, a phenomenon known as the "livestock revolution" (Delgado et al., 1999). This new system of livestock production has increasingly relied on concentrated animal feed operations as an alternative to rangeland production (Figure 4). Owing in large part to the usage of energy-rich oil cakes (i.e., what is left of oil seeds after pressing) as feed, 51% of the world's crop calories are currently devoted to animal production (Davis & D'Odorico, 2015; FAOSTAT, 2017). This trend has meant that countries with emerging economies and a rising middle class (e.g., China) have had to depend more heavily on feed imports, mainly from the United States, Brazil, and Argentina, in order to support domestic animal production (Davis, Yu, Herrero, et al., 2015). Likewise, the global demand for seafood has increased and has been met by increased fish and seafood production in aquaculture operations, while increasing the pressure on wild fisheries (see Box 4).

In addition to demographic and dietary drivers, there has been a rapid increase in demand for crop-based biofuels since the start of the 21st century (Organisation for Economic Co-operation and Development/FAO, 2016), driven in part by clean energy mandates in the United States (U.S. Congress, 2007) and the EU Parliament (2009). This has led to the growing diversion of crop supply, mainly maize in the United States, sugarcane in Brazil, rapeseed in Europe, and oil palm in Indonesia and Malaysia, toward the production of bioethanol and biodiesel (e.g., Rulli et al., 2016). Although in 2000 only about 3% (or less) of crop supply was used for biofuel production, diversion of human-edible calories to crop-based biofuels increased

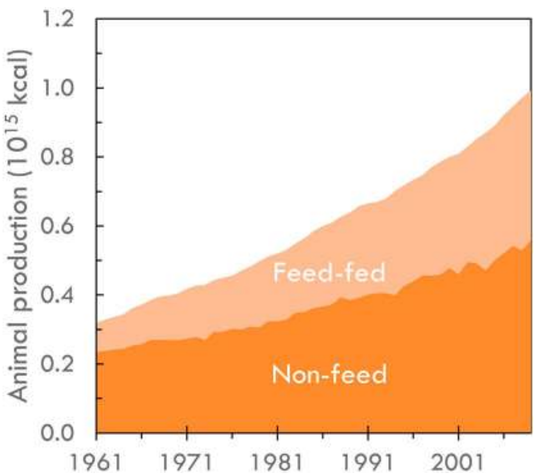

Figure 4. Recent trends in feed-fed and non-feed-fed livestock production (taken from Davis & D'Odorico, 2015).

dramatically during 2000–2010 (Cassidy et al., 2013; West et al., 2014). Rulli et al. (2016) estimate that the crops diverted to biofuel use could feed nearly 300 million people if they were used as food. In addition, the rise in biofuel demand has had an important influence on food commodity markets; several studies provide evidence that biofuels have contributed substantially to higher food prices, as well as increased market volatility (e.g., Hochman et al., 2012, 2014; IFPRI, 2016; Von Braun et al., 2008). Thus, it is clear that these first-generation biofuels have served to further increase competition for crop use and the resources to support food production.

Another key component in the fate of global crop production is that of food waste. Roughly one-quarter of food production is lost or wasted at various steps along the food supply chain, from losses during production to uneaten food on a person's plate, with distinct regional patterns (Gustavsson et al., 2011). In Asia and sub-Saharan Africa, the vast majority of food losses occur during the early stages of the supply chain as a result of large production losses from dry spells, flooding, and tropical disease, as well as inadequate storage. In contrast, for Europe and North America, approximately one third of food waste occurs at either the retailer level or the consumer level (Gustavsson et al., 2011).

2.2. Environmental Pressures of Food Production

The wide diffusion of fertilizers and high-yielding crop varieties has led to much of the tripling in food supply, which to some degree has likely avoided even greater expansion of croplands. However, this intensification of agriculture to prevent the widespread conversion of natural systems has come with important trade-offs (Foley et al., 2005), promoting cultivation practices with extensive environmental consequences that were often inadvertently supported by policies and subsidies (Pingali, 2012). For instance, overapplication of fertilizers, pesticides, and herbicides is a major contributor to nonpoint source pollution, eutrophication of water bodies, loss of soil biodiversity, GHG emissions, and acid rain (e.g., Galloway et al., 2004; Matson et al., 1997; Tilman et al., 2002).

As a result, the global food system has become one of the most extensive ways by which humanity has modified the environment (Ramankutty et al., 2008). Croplands and rangelands now cover approximately 38% of

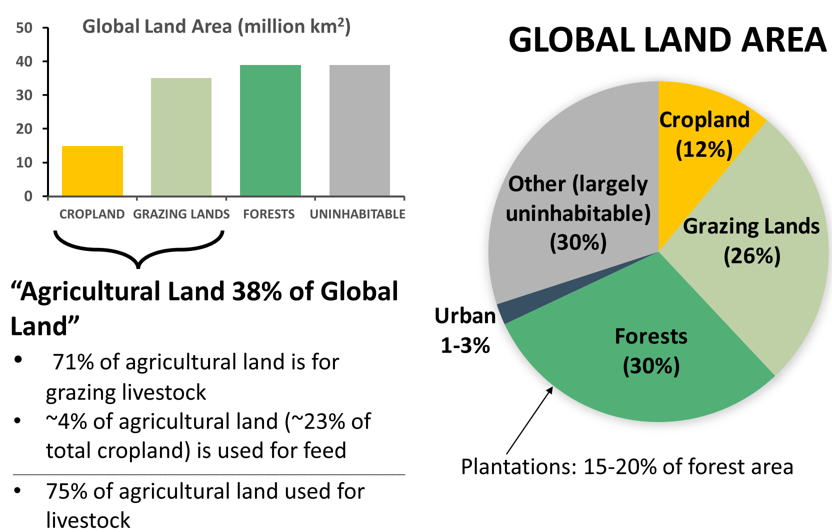

Figure 5. Global land area and its uses. Land area estimates are from Sachs (2015); the livestock contribution estimates are from Foley et al. (2011); the urban extent is a range from Potere and Schneider (2007) with <1% of land area in built-up urban areas.

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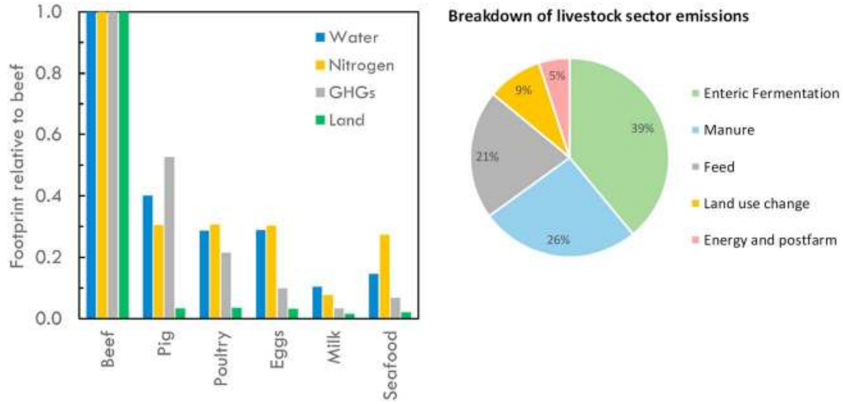

Figure 6. (left) Land, carbon, nitrogen, and water footprints of animal products relative to the case of beef (based on data in Davis et al., 2016). (right) Breakdown of livestock emissions by source (based on Wellesley et al., 2015). GHG = greenhouse gases.

the planet's ice-free surface (Foley et al., 2011; Figure 5). More than one half of the accessible runoff is withdrawn for human use (Richter, 2014), and nearly all of the anthropogenic consumptive water use (i.e., water loss to the atmosphere) is for agriculture (Hoekstra & Mekonnen, 2012). The mechanization of agricultural production has allowed for intensified soil tillage, thereby increasing the rates of soil loss, which by far exceed those of soil formation (Montgomery, 2007). Fertilizer production has more than doubled the amount of reactive nitrogen (N) in the environment (Schlesinger, 2009), and GHG emissions from food production (e.g., ruminant digestion and fertilizer denitrification) and land use change (e.g., deforestation) contribute 19–30% of humanity's GHG emissions (Tubiello et al., 2013; Vermeulen et al., 2012). GHG emissions from agricultural activities increased annually by 1.1% from year 2000 to 2010 (Tubiello et al., 2013).

The livestock sector contributes disproportionately to the environmental burden of food production (Eshel et al., 2014; Herrero et al., 2013; Kastner et al., 2012; West et al., 2014). Although animal production makes up 25% of the world's food supply by weight, 18% of dietary calories, and 39% of protein (FAOSTAT, 2013), it accounts for approximately 75% of agricultural land area (Foley et al., 2011), 29–43% of the total agricultural water footprint (Davis et al., 2016; Mekonnen & Hoekstra, 2012), 46–74% of agricultural GHG emissions (Davis et al., 2016; FAOSTAT, 2013; Herrero et al., 2013), and 34–58% of total nitrogen use (Davis, Yu, Herrero, et al., 2015; Davis et al., 2016). The overall greater footprint of livestock production is in large part attributable to the inefficiencies by which plant biomass can be incorporated into animal tissue, particularly for cattle (Figure 6; e.g., Mekonnen & Hoekstra, 2012; West et al., 2014). Owing in large part to the efficient feed conversion ratios of monogastric (i.e., nonruminant) digestion, as well as the inherent variability in rangeland biomass production (FAO, 2010; Steinfeld et al., 2006), the world's livestock systems have been transitioning (Figure 7) from an extensive, beef-dominated system toward a focus on concentrated, feed-reliant pig and chicken production (Davis & D'Odorico, 2015). This trend has led to important environmental trade-offs that have occurred

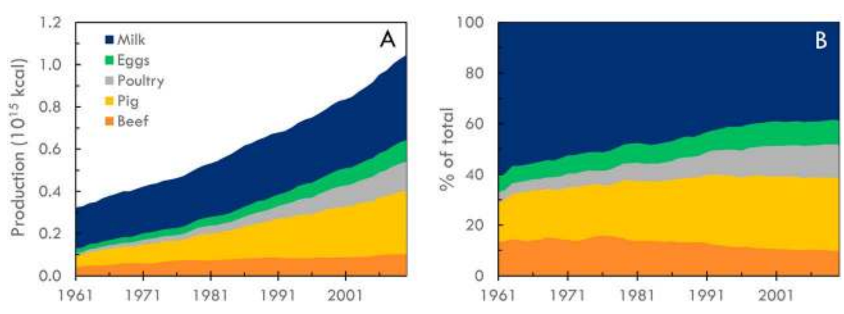

Figure 7. Recent trends in beef, pig, poultry, eggs, and milk production (based on data in Davis & D'Odorico, 2015). The increase in pig and poultry production by far exceeds that of beef leading to an increasing reliance on these less resource-intensive resources ("livestock transition").

within the livestock sector, where improvements in land use efficiency and GHG emissions per unit of animal production have been offset by the increasing water and nitrogen requirements of feed production (Davis, Yu, Herrero, et al., 2015).

Animal agriculture is a major source of GHG emissions, land use, and water consumption. Interestingly, pets such as dogs and cats are also major contributors to the demand for animal products. A recent study for the United States has shown that dogs and cats account for roughly 25–30% of the land, water, and phosphate footprint of animal production (Okin, 2017). A decrease in the reliance on animal-derived products can reduce environmental impacts and increase food security. A recent study, which modeled the U.S. agricultural system without farmed animals, found that, without animal food production, the total food production of the United States would increase by 23% and total agricultural GHG emissions would decrease by 28% (White & Hall, 2017). However, in this system modeled without farmed animals, population diet of the United States resulted in the absence of essential nutrients (e.g., vitamin B12 and fatty acids) that are present only in animal products (White & Hall, 2017).

2.3. Environmental and Climate Constraints on Food Production

Global food production is facing mounting constraints to its continued growth. These limitations fall into two broad categories related to changing climate and bounds imposed by plant physiology and production decisions. Regarding the first, there is evidence of reductions in food production resulting from climate change in recent decades, though overall production gains have been able to overcome these reductions so far (Vermeulen et al., 2012). Early work on this topic showed that between 1981 and 2002 the combined production of three major crops—barley, maize, and wheat—was reduced by 40 Mt/year, compared to a case with no climate effect (Lobell & Field, 2007). From 1980 to 2008, global wheat and maize production fell 4% and 6%, respectively, below what would be expected without climate trends; these effects varied widely across crops and countries (Backlund et al., 2008; Lobell et al., 2011). It has been estimated that, without accounting for the effect of CO_2 fertilization, each degree Celsius of mean global temperature increase is expected to induce a 6.0% drop in the global yield of wheat, 3.2% of rice, 7.4% of maize, and 3.1% of soybean (Zhao et al., 2017). Other work has shown that as much of one third of global crop yield variability can be explained by interannual fluctuations in temperature or precipitation, with climate variability explaining as much as 60% of yield variability in certain breadbasket areas (e.g., maize in the U.S. Midwest and China's Corn Belt; wheat in western Europe and Australia; Ray et al., 2015). Moreover, extreme droughts and heat waves, which are expected to intensify under climate change, can strongly reduce crop production (Lesk et al., 2016). Recent modeling efforts created an ensemble of models that consider a different configuration of carbon dioxide (CO_2) under most recent climate projections (McSweeney & Jones, 2016; Mistry et al., 2017). Regarding livestock, there has been substantial investigation of the effects of heat stress on animal production (e.g., Aggarwal & Upadhyay, 2013; St-Pierre et al., 2003), but to date, no studies have examined the relation between animal productivity and interannual climate variability. Even though historical effects of climate trends on food systems have been modest and masked by overall gains in production from specific regions, it is expected that climate change impacts on food production will become more pronounced in the coming decades, depending on the GHG emissions trajectory considered (Wheeler & Von Braun, 2013).

The second set of constraints to production, which are related to crop physiology and production decisions, play an important role as well. Many places around the world—23–37% of maize, rice, soybean, and wheat areas—are experiencing a plateau or collapse of major crop yields from a combination of biophysical and socioeconomic factors (Grassini et al., 2013; Ray & Foley, 2013). In areas that continue to realize overall yield gains, there are emerging indications that these improvements are being disproportionately contributed by a small fraction of highly productive cropland, whereas yields in other cultivated areas have increased more slowly. Pointing to this, a recent study focused on maize in the U.S. Midwest showed that the greatest yield improvements are being provided by a narrowing area of cropland (Lobell & Azzari, 2017). Along with these features of yield trends, the efficient use of fertilizers for cereal production has also plateaued, as the highest returns on nutrient inputs occur when yields are low (Tilman et al., 2002).

The nutritional quality of global cereal production has declined steadily with time, as nutrient-rich cereals have been supplanted by high-yielding rice, wheat, and maize varieties (DeFries et al., 2016; Medek et al., 2017). This increase in high-yielding crop production has been in part driven by the increasing prevalence of large farms, which generally produce a less nutritionally diverse set of crops (Herrero, et al., 2017), and has resulted in dwindling amounts of key nutrients, such as protein, iron, and zinc per tons of cereal crop (DeFries et al., 2016). Enhancements of atmospheric CO_2 concentrations are expected to exacerbate these declines by adversely affecting crop nutrient content in plant tissue, especially in C3 crops (e.g., rice and wheat; Myers et al., 2014). Though food supply remains largely nutritionally adequate at the global scale, the persisting challenges of food access, widespread malnourishment, and nutrient deficiencies amplify these trends of declining nutritional quality.

Though not explored in depth here, other important factors also serve to curtail food production. For instance, desertification and soil salinization have rendered large amounts of arable land and grazing areas unusable (D'Odorico et al., 2013). Urbanization has removed a fraction of fertile cropland from active production (D'Amour et al., 2017). Excess surface ozone has further led to relative yield decreases of between 3% and 16% for maize, rice, soybeans, and wheat (Van Dingenen et al., 2009).

Box 4. The state of global fisheries

Global production of fish and other aquatic animals (seafood) reached nearly 170 million tonnes in 2015 (FISHSTAT, 2016). Up until the early 1990s, the vast majority of seafood production was from wild capture fisheries (Figure B4). During the 1990s, capture fishery production stagnated, leading to an active debate about the status and future of global capture fisheries (Worm et al., 2009). The analysis by the Food and Agriculture Organization of the U.N. of assessed commercial fish stocks found the share of overfished stocks increased from 10% in 1974 to 31.4% in 2013 (FAO, 2016). Although management has been improving in many fisheries and there are efforts to rebuild fisheries (Worm et al., 2009), it is unlikely wild catch will meet the increasing global demand for seafood. To date (2018), global seafood production has kept pace with increasing populations as a result of the rapid growth in aquaculture production (Figure B4). Today, aquaculture supplies approximately one-half of all seafood production. Aquaculture production is unevenly distributed globally, with 89% of aquaculture produced for human consumption occurring in Asia (FAO, 2016). During the recent period of rapid aquaculture growth, seafood trade has become increasingly globalized, with a 58% increase in traded quantity and an 85% increase in real value from 1994 to 2012 (Gephart and Pace, 2015). Globally, seafood provides 17 % of animal protein and is an important source of essential fats, vitamins, and minerals (FAO, 2016). The contribution of seafood to nutrition varies around the world, with the highest reliance in coastal and island developing nations. Globally, per capita seafood supply has increased in recent decades and is expected to continue to rise with growing gross domestic product in developing nations (Figure B4; Food and Agriculture Organization, 2016; Delgado, 2003; Tilman et al., 2011). The existing or potential role of aquaculture, and marine and inland capture fisheries, in food security, especially in nutritionally vulnerable small-scale fishing/farming communities, is increasingly being recognized and evaluated (Golden et al., 2016; McIntyre et al., 2016). The ability of fisheries and aquaculture to meet or improve nutrition depends on improved management, appropriate market structures, and mitigation of the impacts of climate change and environmental variability on seafood production (Gephart et al., 2017; Worm et al., 2009).

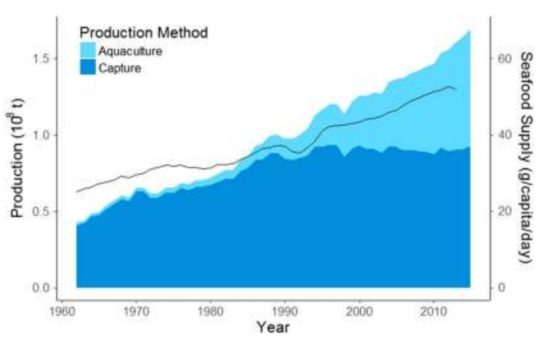

Figure B4. Recent trends in seafood production through aquaculture and capture (left axis) and per capita seafood supply (black line, right axis) (Based on data from the FAO FISHSTAT Database, 2016).

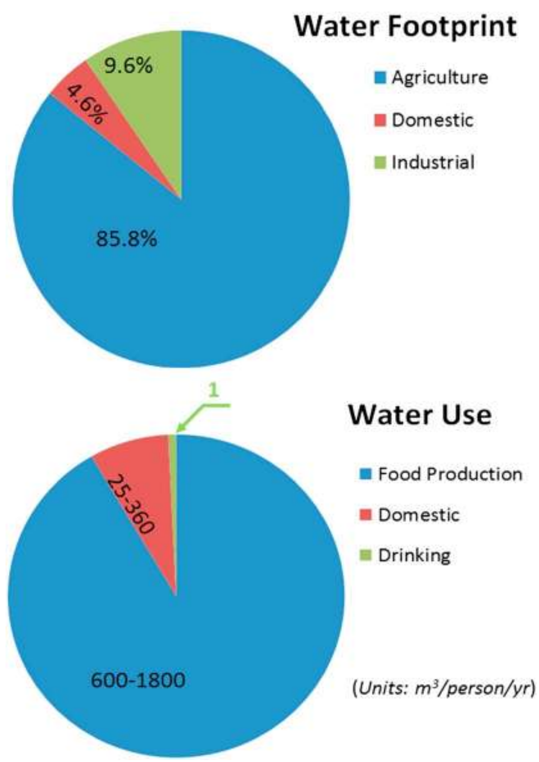

Figure 8. The water footprint of human activities. Based on data from Hoekstra and Chapagain (2008) and Falkenmark and Rockström (2004).

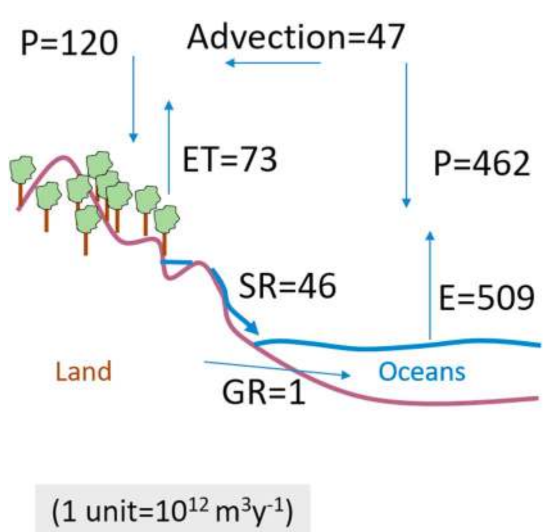

Figure 9. A schematic representation of the global water cycle with separate precipitation (*P*) and evaporation (*E*) or evapotranspiration (ET) amounts for land masses and oceans. Water leaves land masses either as evapotranspiration (ET or green water flow) or surface-water (SR) and groundwater (GR) runoff (blue water flows; based on values reported in Chow et al., 1988).

3. The Water System

Human societies rely on freshwater resources for a variety of activities, including drinking, household usage, and industrial and agricultural production (Figure 8). Agricultural uses, however, by far exceed any other form of human appropriation of freshwater resources (e.g., Gleick, 1993; Hoekstra & Chapagain, 2008; Oki & Kanae, 2006; Rosegrant et al., 2009). Water consumption for food production, including crops and livestock, accounts for about 86% of the total societal water consumption, though, locally, household and industrial uses can be predominant, particularly in major urban areas. Thus, securing water resources for agriculture, while reconciling the competing water needs of growing cities and surrounding rural areas, is a major challenge of our time. Climate change is expected to further enhance local water scarcity, especially in the subtropics (Arnell, 2004). In fact, while climate warming is slightly increasing global precipitation (about 2–3%, see, e.g., Katul et al. (2012)), the global patterns of rainfall distribution are expected to become more uneven with an intensification of aridity in the dry subtropics, and an increase in precipitation in the wet tropics and the midlatitude temperate zone (Held & Soden, 2006). The temporal variability of precipitation will likely increase, thereby enhancing the probability of drought and flood occurrences (Easterling et al., 2000; Intergovernmental Panel on Climate Change, 2013).

3.1. Freshwater Use

Despite recent developments in desalinization technology (e.g., International Energy Agency (IEA), 2016), most human activities related to food and energy production rely on the consumptive use of freshwater. Desalinization remains limited to specific uses that require relatively small amounts of water (e.g., drinking water) and to societies that can sustain the associated costs (Karagiannis & Soldatos, 2008). The freshwater available for human activities is stored in continental land masses either in (unsaturated) soils or in surface-water bodies and groundwater aquifers. Often referred to as "green water," soil moisture is retained in the ground by capillary forces and can be extracted only when it is subjected to a suction that overcomes the action of capillarity. Plants exert such suction through root uptake. Although most of terrestrial vegetation in natural ecosystems relies on green water (except for phreatophytes, which have access to the groundwater), soil moisture remains for most part unavailable to direct human use because it is difficult to extract. In contrast, water stored in surface-water bodies and aquifers, referred to as "blue water," is more mobile and contributes to surface-water and groundwater runoff. Thus, green water leaves land masses in the water vapor phase as evapotranspiration (or green water flows), whereas blue water flows to the ocean in the liquid phase as runoff (blue water flows; Figure 9).

Since antiquity, human societies have engineered systems to withdraw blue water from rivers, lakes, and aquifers and have transported it through channels and pipes to meet the needs of a variety of human activities. Today, the main consumptive use of blue water (i.e., liquid water returned to the atmosphere as water vapor) is for irrigation (92%; Richter, 2014), which strongly increases green water flows at the expense of blue water flows. Irrigation is a major human

Table 1
Global Water Flows and Demands, and Sources of Data

Process	Annual flow (m^3/year)	Year	Source
Precipitation over land	120×10^{12}		Chow et al. (1988)
Evapotranspiration from land (Green water flows)	72×10^{12}		"
Global runoff (Blue water flows)	48×10^{12}		"
Planetary boundaries of Blue Water	4.0×10^{12}		Rockström et al. (2009)
Total water withdrawal	3.8×10^{12}		Oki & Kanae (2006)
Water withdrawal for irrigation	2.56×10^{12}	2000	Sacks et al. (2009)
	2.41×10^{12}	1980–2009	Jägermeyr et al. (2017)
Water consumption for irrigation	0.90×10^{12}	1996–2005	Hoekstra and Mekonnen (2012)
	1.28×10^{12}	2000–2010	Siebert and Döll (2010)
Groundwater consumption for irrigation	0.54×10^{12}	2000–2010	Siebert and Döll (2010)
Groundwater withdrawals	0.73×10^{12}	2000	Wada et al. (2010)
Groundwater Depletion	0.14×10^{12}	2001–2008	Konikow (2011)
	0.28×10^{12}	2000	Wada et al. (2010)
Water consumption for food production	6.67×10^{12}	1996–2005	Hoekstra and Mekonnen (2012)
	7.6×10^{12}		Oki and Kanae (2006)
Green water consumption for food	5.77×10^{12}	1996–2005	Mekonnen and Hoekstra (2010)
Blue water consumption for food	0.90×10^{12}	1996–2005	Mekonnen and Hoekstra (2010)
Freshwater for agricultural production		1996–2005	Mekonnen and Hoekstra (2011b)
All crops (food, feed, fiber, and biofuel crops)	7.40×10^{12}		"
Rangelands and pastures	0.91×10^{12}		"
Water for livestock (blue and green)	2.26×10^{12}	1996–2005	Hoekstra and Mekonnen (2012)
Blue water for feed crops	0.10×10^{12}		"
Blue water from direct livestock consumption	0.05×10^{12}		"
Green water for feed crops and grazing	2.11×10^{12}		"
Freshwater used for biofuel production	0.18×10^{12}	2013	Rulli et al. (2016)
Green water for biofuel crops	0.17×10^{12}		"
Blue water for biofuel crop	0.11×10^{11}		"
Total artificial storage capacity (reservoirs from dams)	7.2×10^{12}	1998	Oki & Kanae (2006)
Evapotranspiration losses from artificial storages	0.275×10^{12}	1996	Postel et al. (1996)
Water cost of present energy demand ("ancient" water)	7.35×10^{13}	2013	D'Odorico, Natyzak et al. (2017)
Virtual water trade (food only)	2.81×10^{12}	2010	Carr et al. (2013)
Water cost of fossil fuel extraction	1.80×10^{10}	2013	International Energy Agency (IEA, 2016)
Freshwater withdrawals for energy production	0.40×10^{12}	2016	IEA (2016)
Primary energy source extraction	0.05×10^{12}		"
Power generation	0.35×10^{12}		"
Freshwater consumption for energy production	0.05×10^{12}	2016	IEA (2016)
Primary energy source extraction	0.034×10^{12}		"
Power generation	0.016×10^{12}		"

Note. The "Year" column denotes the period considered in each study (see D'Odorico, Natyzak, et al., 2017; D'Odorico & Rulli, 2013).

disruption of the water cycle (e.g., Jägermeyr et al., 2017); indeed, many rivers are so strongly depleted that they no longer reach the ocean (e.g., the Colorado and the Rio Grande in North America), while lakes in basins with internal drainage (e.g., Lake Chad and the Aral Sea) are drying out (e.g., Richter, 2014). Irrigation can modify the local climate, possibly by increasing evapotranspiration and effectively cooling the near-surface atmosphere (e.g., Mueller et al., 2015, 2017; Sacks et al., 2009). Irrigation may also moderately enhance precipitation downwind of irrigated areas (Puma & Cook, 2010) and induce mesoscale circulations (land breezes) driven by the contrast between irrigated areas and the surrounding drylands (Segal et al., 1998; Segal & Arritt, 1992).

Table 2
Global and Continental Groundwater Depletion

Region	Groundwater depletion (10^9 m^3/year; Wada et al., 2012)	Groundwater depletion (10^9 m^3/year; Konikow, 2011)
World	204 ± 30	145 ± 39
Asia	150 ± 25	111 ± 30
Africa	5.0 ± 1.5	5.5 ± 1.5
North America	40 ± 10	26 ± 7
South America	1.5 ± 0.5	0.9 ± 0.5
Australia	0.5 ± 0.2	0.4 ± 0.2
Europe	7 ± 2	1.3 ± 0.7

Note. From Taylor et al. (2013).

It has been estimated that globally, irrigation uses a water volume that is roughly 2.56×10^{12} m^3/year (Table 1), which accounts for about 2% of the precipitation (Sacks et al., 2009). Although water is a renewable resource that is conserved in the Earth system, freshwater stocks can be depleted when their use exceeds the rates of natural replenishment. A typical example is groundwater that is often used for agriculture (Table 1) and

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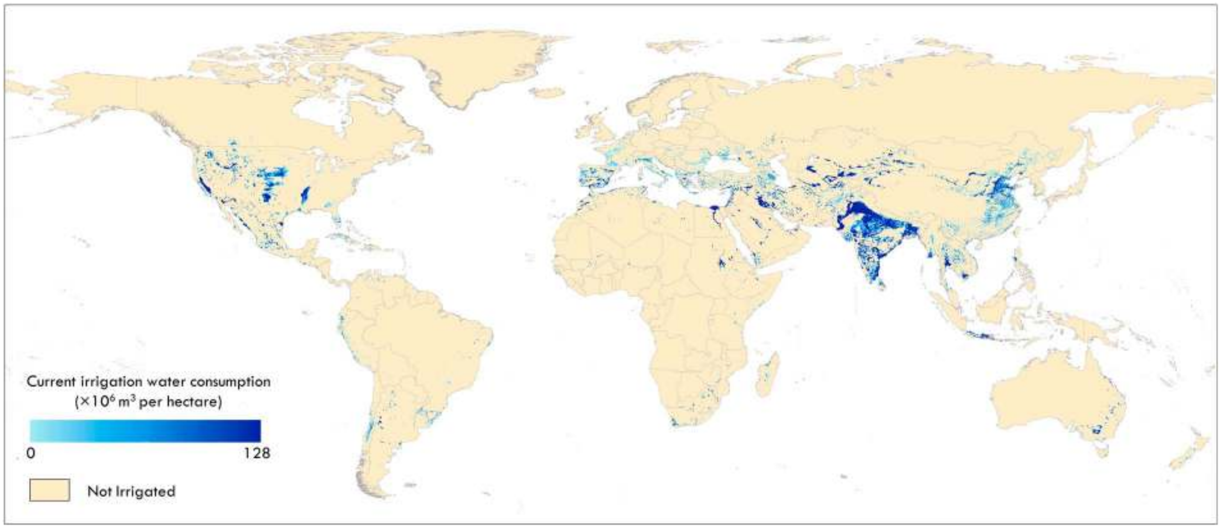


Figure 10. Current irrigated areas of the world. Irrigated areas are here defined as areas that are more than 5% equipped for irrigation (using data from Siebert et al., 2013) and where the ratio between blue water and the total crop water consumption is greater than 0.10 (i.e., Blue Water/(Blue Water + Green Water) $>$ 0.10). For smaller values of this ratio, the increment of production afforded by irrigation is likely too limited to justify investments in irrigation because the local climate is sufficiently wet to sustain relatively high rates of rainfed production (Dell'Angelo et al., 2018). According to these criteria, irrigated areas account for irrigated lands (2.5×10^6 km^2), which is about 20% of global cultivated land (13.1×10^6 km^2) (FAOSTAT, 2017).

is being depleted in many regions of the world (Table 2), including the North American Southwest, Northern Africa, the Arabian Peninsula, and India (Konikow, 2011; Wada et al., 2012). In some cases, groundwater use is depleting water stocks that accumulated in epochs with a wetter climate. In these aquifers "overpumping" leads to a permanent extraction of water resources, a phenomenon that is known as "groundwater mining" to better stress its unsustainability and the irreversible loss of resources that will not be available to future generations. However, even when the depletion of water resources is reversible, its environmental impacts may not be. Excessive water withdrawals from rivers and streams destroy the aquatic habitat and lead to extinction of riparian species. Interestingly, freshwater ecosystems are particularly vulnerable because the extinction rate of freshwater aquatic species is much greater (about 5 times) than that of terrestrial organisms (Postel & Richter, 2003). Thus, sustainable use of water resources should prevent not only their permanent depletion but also the irreversible damage of downstream ecosystems. A rich body of literature has discussed criteria to define minimum flow requirements and minimum flow variability required to conserve the aquatic habitat (Pastor et al., 2014; Richter et al., 2012). A reevaluation of those efforts within the context of water sustainability has led to the formulation of the concepts of "planetary boundaries" and "safe operating space" that define a cap for sustainable water use (Rockström et al., 2009). Such a cap is typically expressed as a fraction of the natural (i.e., undisturbed) river flow, ranging from 20% (Mekonnen & Hoekstra, 2016; Richter et al., 2012) to 60% (Pastor et al., 2014), though recent studies have suggested referring to season-dependent fractions (25% in low-flow conditions and 55% in high-flow condition; Pastor et al., 2014; Steffen et al., 2015). Although globally, the current use of water for irrigation is smaller than the planetary boundary for blue water and accounts for only 5.4% of the global blue water flows (Table 1), in many regions of the world those boundaries are locally exceeded, thereby causing habitat loss (Jägermeyr et al., 2017; Richter, 2014).

Overall, irrigation is critical to sustaining the present rates of agricultural production. Although only 20% of the global agricultural land is irrigated (Figure 10), it sustains about 40% of the global crop production owing to the typically much higher yields in irrigated systems (e.g., Molden et al., 2010; Siebert & Döll, 2010). Collectively, irrigated and rainfed agriculture accounts for about 10% of global precipitation over land, with green water flows from agroecosystems contributing to roughly 16% of the global evapotranspiration from terrestrial ecosystems (Table 1). These figures give us a sense of the proportion of the water cycle that has been appropriated by agriculture. Moreover, other economic activities, such as mining, manufacturing, and energy production further increase the human demand for freshwater.

3.2. Hydrological Impacts of Land Use Change

Food production affects the water system also indirectly through land use change. Since the onset of civilization, agriculture has claimed land (and water resources) from natural ecosystems, such as forests, savannas, and grasslands. By converting these landscapes into agricultural land, humankind has profoundly altered the water and biogeochemical cycles (e.g., Bonan, 2008; Davidson et al., 2012; Runyan & D'Odorico, 2016). Decades of research on deforestation have highlighted the profound hydroclimatic impacts of land use and land cover change (Perugini et al., 2017). Compared to forests, rainfed farmland sustains lower evapotranspiration rates because of the smaller leaf area index, surface roughness, and root depth, and the greater albedo (Bonan, 2008; Perugini et al., 2017). The infiltration rates are also smaller because agricultural soils are often more compacted, typically from leaving the land fallow for part of the year and cultivated with heavy machinery. Smaller evapotranspiration and infiltration rates are expected to lead to higher runoff (e.g., Runyan & D'Odorico, 2016). However, in areas where agriculture is irrigated, water withdrawals for crop production deplete surface-water bodies and aquifers (Jägermeyr et al., 2017).

Land use change also has an impact on the regional climate. Land use change alters the surface energy balance and land-atmosphere interaction; these changes modify near-surface temperature, boundary layer stability, and the triggering of convection and convective precipitation (Bonan, 2008; Perugini et al., 2017). Some of these effects can alter the rainfall regime within the same region in which land cover change occurs, though it has been suggested that the impact also can be on adjacent ecosystems (Ray et al., 2006). Moreover, land cover change may modify the rate of emission of biological aerosols, thereby affecting cloud microphysics and cloud processes (Pöschl et al., 2010). The reduced evapotranspiration has the effect of reducing precipitation recycling, which is the fraction of regional precipitation contributed by atmospheric moisture from regional evapotransporation (Eltahir & Bras, 1996), a phenomenon that is relevant to policies and therefore is receiving the attention of social scientists (Keys et al., 2017), despite the great uncertainties with which it can be evaluated (Dirmeyer & Brubaker, 2007; Salati et al., 1979; Van der Ent et al., 2010). Overall, forest or woodland conversion to cropland over large regions (e.g., $>$100 km) is expected to reduce precipitation (particularly rainfall frequency) and increase diurnal temperatures (Bonan, 2008), though these effects depend on the size of the cleared area (e.g., Lawrence & Vandekar, 2015). The direct and indirect impacts of human activities on freshwater resources may strongly affect their availability to meet the competing needs of food or energy production and the environment, raising questions on the type of institutional arrangements that could improve water governance.

3.3. Water Governance and the Commodification of Water

Water is by its own nature fluid, renewable, and difficult to quantify (Rodríguez-Labajos & Martínez-Alier, 2015), and its biophysical characteristics, such as the fact that it is a key input into biological processes and that is relatively plentiful and widely distributed (compared to oil), make the political economy of this resource very different from other similarly important strategic natural resources (Selby, 2005). From early human history, water use has led to complex dynamics of competition and cooperation (Wolf, 1998). In a world with increasing societal pressure over scarce water resources and aggravating hydroclimatic change, water governance is fundamental in the policy and development dimensions of water management. Even though access to safe water and sanitation is recognized as one of the UN-SDGs (Goal #6, UN, 2015, 2016), about 4 billion people face water scarcity at least 1 month per year (Mekonnen & Hoekstra, 2016). Water availability may be affected by water quality, particularly in the case of drinking water, as the cost of treatment may become prohibitive in some locations, creating physical water scarcity of costly water resources.

The reliance on water markets historically has been, and still is, strongly influenced by neoliberal governance approaches based on privatization, liberalization, and extension of property rights. The core principle behind these approaches is that water markets provide the correct economic incentives to promote the reallocation of water to higher valued uses and improve efficiency. These approaches treat water as a commodity and thus require the recognition of property rights that define the use, management, and trade of water resources (Rosegrant & Binswanger, 1994). Easter et al. (1999) describe a strong legal system as the main institutional condition necessary for water markets to function properly. The creation of water markets in the Western United States and in Chile (see Box 5) have been used as exemplary policy and governance models that could be exported and promoted in developing countries (Bauer, 2012). Since the 1980s, the World Bank has been the main promoter of water markets in developing countries, while also supporting the development of lucrative transnational opportunities in the water sector for private investors (Goldman, 2007). In the context of the FEW nexus debate, however, a water market economy may lead to water resources previously used to produce food being transferred to other (more profitable) uses, such as industrial production (e.g., fossil fuel extraction) or household needs in urban areas. In fact, the economic yield of food commodities (per cubic meter of water consumption) may typically be orders of magnitude lower than that of the energy and water utility sectors (Debaere et al., 2014).

Food as a basic human need (and right, see section 5.5) means that market approaches to water governance also can be evaluated in the context of their impacts on food security, particularly for the poor. For example, water markets could be structured with special consideration for certain industries, including agriculture, to avoid losing water allocations for production of food. A counterargument in favor of water markets stresses their positive environmental outcomes such as when water is partly acquired to reestablish environmental flows and improve aquatic habitat, or if the market sets a cap on the amount of water that can be withdrawn for human uses (Richter, 2016).

The contemporary neoliberal trends of water commodification, that is, the multidimensional process through which goods that traditionally are not priced enter the world of money and markets (Bakker, 2005; Polanyi, 1944), could be in stark contrast with the principle that access to water is a fundamental human right (Gleick, 1998). Ostrom (1990) describes water resources as an iconic example of common-pool resources, which often have been successfully governed through diverse community and communal-property institutional arrangements. The multiple characterizations of freshwater by different cultures and societies make it difficult for freshwater to be reduced to a monetized commodity. Water can be perceived as a sacred commodity, a human right (see section 5.5), a political good, an ecosystem medium, and a security asset (Gupta & Pahl-Wostl, 2013). Moreover, the water sector has intrinsic characteristics that can be associated with structural market failures, with large externalities, and interconnectedness that make the level of individual and collective interdependence particularly critical (Meinzen-Dick, 2007). From a social and environmental justice perspective, the idea that water is not treated as a “common good” but as a commodity has generated criticism around the perpetuation of inequality and violation of fundamental human rights (Bakker, 2005; Goldman, 2007; Swyngedouw et al., 2002).

Different narratives and political perceptions about the value, the meaning, and the function of water in society make a clear and uniform definition of “good water governance” difficult. As described by Meinzen-Dick (2007), rather than considering single solutions for water governance, it may be more productive to have multiple institutions work together in an adaptive learning process. The complexity of sociohydrological dynamics, the variability of institutional settings, and the interdependencies of water with other key dimensions, such as food and energy, could benefit from innovative adaptive governance approaches (Huitema et al., 2009; Konar, Evans, et al., 2016).

Box 5. What is ‘Water Governance’?

The term “water governance” encompasses a variety of meanings in the policy, politics, and development fields (e.g., Tropp, 2007). The influence of political agendas on a critical resource such as water is strong. Therefore, the normative element of the concept can vary hugely, depending on different political perspectives and societal scales. In other words, the vision of ideal “good water governance” directly depends on the narratives and models that are affirmed by a powerful coalition of actors that have an interest in maintaining certain policy and political paradigms (Molle, 2008). Woodhouse and Muller (2017), in reviewing the current debates in the field, point to different aspects of water accessibility, such as how water governance is intertwined with historical-political dynamics, how different priorities associated with the politics of water depend on the political-economic and development status of different countries, and how the scale of the phenomenon (local vs. transnational problems) matters. From a historical perspective, water governance evolved through different phases of water-management paradigms. Different historical phases can describe the vision of society for water development, or what has also been defined as the hydraulic mission. A pattern observed in the 20th century has been the societal tendency to move from an emphasis on infrastructures and engineering to an emphasis on the economic dimension of water allocation (see Section 3.3). In a linear account of water development, the focus eventually moves towards management and governance dynamics (Allan, 2006; Molle, 2008; Molle et al., 2009). Different water-governance paradigms have prevailed in different historical moments. A synthetic representation describes a movement from old to new forms of water governance that produced a shift from top-down management, hierarchical control, centralization, and emphasis on government and bureaucracy to a new era where distributed forms of governance with inclusive, multistakeholders, bottom-up negotiation, and participation processes of water management are implemented (Tropp, 2007. The search for panaceas for water governance can be observed in three overlapping trends: the focus on the role of the State, the focus on users' management organization, and the focus on market institutions (Meinzen-Dick, 2007). Nevertheless, the attractiveness of the simplicity of exporting or expanding models of governance from places where they succeeded to other places where there is a need often produced negative outcomes (Meinzen-Dick, 2007). For instance, the neoliberal approach is particularly influential in key economic and development international organizations and has impacted some of the core prescriptions of good water governance, invoking neoliberal principles such as privatization, market-based regulation, efficiency, and cost effectiveness (Bakker, 2010; Bauer, 2012; Swyngedouw, 2005). The archetype of the neoliberal water reform was implemented in Chile during the Pinochet military regime on the guidance of the "Los Chicago Boys," a group of Chilean economists aligned with the regime that were trained in the Economics Department of the University of Chicago. This group of economists had the mission to promote a United States centered political economy agenda once they were back in Chile; water reform was one of the first key strategic sectors where this transformation was implemented (Bauer, 2012; Harvey, 2007). More recently, alternative approaches, based on theories of polycentricity that go beyond markets and states and that integrate institutional systems on multiple scales, have been discussed and applied to water governance (McCord et al., 2016; Neef, 2009; Ostrom, 2007, 2010a, 2010b; Pahl-Wostl et al., 2012). Overall, complex systems, such as socio-environmental and socio-hydrological systems, could benefit by being co-managed in an adaptive fashion that includes collaboration, public participation, experimentation, and focus on the bioregional scale (Huitema et al., 2009).

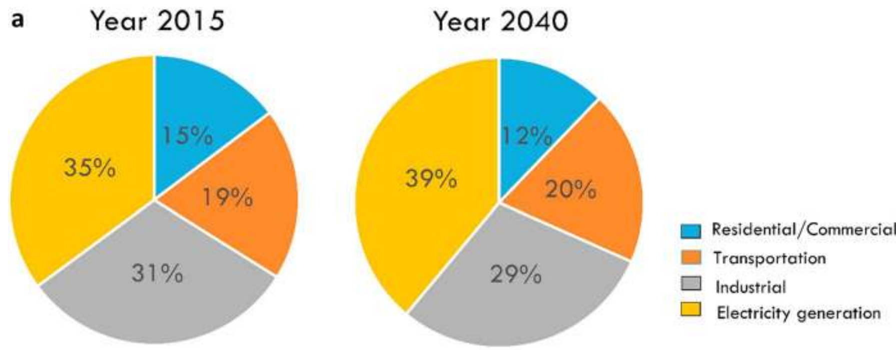
3.4. Water Infrastructures: Water and Economic Development

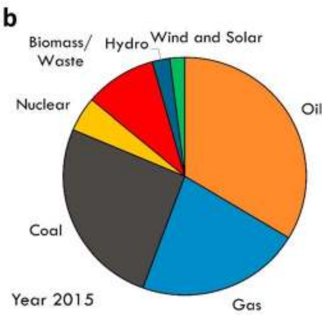
The idea that the development of water infrastructure is important to economic development has often been considered as a corollary to classical models of economic development postulating the need for "growth" in the agricultural sector, followed by the development of industry and services (e.g., Distefano & Kelly, 2017; Hanjra et al., 2009). The rationale for this growth model is that investments in water infrastructure are required to develop irrigation systems that would lead to higher crop yields (see section 11.1). It has been argued that in some developing countries, economic development has been impeded by strong intra-annual and interannual variability in hydrologic conditions that expose crops to often unpredictable water stress; therefore, investments in water infrastructures are urgently needed across the developing world (Grey & Sadoff, 2007). Even though these claims have not been conclusively supported by data, they are often invoked to advocate for new investments in dams and other "gray" infrastructures, such as canals, pipelines, or other hydraulic structures (Muller et al., 2015). This model of economic development, however, remains controversial because such infrastructures could cause irreversible environmental damage and often serve the needs of large-scale commercial agribusinesses rather than subsistence farmers, whereas green approaches, based on water harvesting, small farm-scale ponds, and new crop water management techniques with low evaporative losses of water are likely more effective and less costly (Palmer et al., 2015). Recent research on this topic has highlighted the benefit of building small decentralized water harvestings and storage facilities as a sounder and economically more viable alternative to large dams (Blanc et al., 2014; Blanc & Strobl, 2013; Dile et al., 2013). Indeed, farm-scale reservoirs and small retention ponds better suited for decentralized approaches to water management (Box 5) are more likely to serve small-scale farmers and reduce the cost of conveyance and distribution systems (Blanc et al., 2014; Burney et al., 2013; Strobl & Strobl, 2011; Van der Zaag & Gupta, 2008; Wisser et al., 2010).

4. The Energy System

Human activities require energy to power systems of production, transportation, heating, and cooling (Figure 11). In preindustrial societies energy options were relatively limited and mainly consisted of wood

10.1029/2017RG000591





Source of Energy	Share of Primary Energy (%) in year 2015	Share of Primary Energy (%) in year 2040
Oil	34	32
Gas	22	25
Coal	26	20
Nuclear	5	7
Hydro	2	3
Waste and Biomass	10	8
Solar and Wind	2	4

Figure 11. (a) Primary energy consumption by sector and (b) share of primary energy by fuel or other primary energy sources (based on data from ExxonMobil, 2017).

burning and draft animals (The power of flowing water and wind was used to power mills and for navigation.), which in turn required land and water for the production of fuelwood or fodder. Thus, land and water availability constrained energy production in the preindustrial world (e.g., Hermele, 2014). The industrial revolution provided unprecedented access to power with engines fueled by fossil materials (particularly coal) that required almost no land or water (Scheidel & Sorman, 2012). After 1950, there was a massive energy transition in the “Great Acceleration” period, with particularly large increases in fossil fuel-based energy systems (coal, oil, and gas; Steffen et al., 2007). This transition toward a high-energy society after 1950 coincided with dramatic socioeconomic changes, including increased agricultural production (along with innovation from the subsequent green revolution), as well as an increased rate of manufacturing, economic growth, urbanization, and demographic growth (Box 1; Steffen et al., 2007). Such trends occurred along with a reduction in the amount of labor effort needed by the societal metabolism, that is, the way materials and energy are exchanged within societies, among societies, and between societies and nature (Giampietro & Mayumi, 2000). The benefits of the increasing reliance on fossil fuels, however, came at the cost of burning, in just a few decades, much of the readily available oil and gas, thereby depriving future generations of these energy options. At the same time, fossil fuel consumption increased atmospheric CO_2 concentrations with important impacts on the global climate (Page, 2008).

Today the energy system suffers from major problems that are a legacy from the twentieth century: energy consumption mostly (80%) relies on nonrenewable (fossil) sources and increases (about 2% per year) as a result of population and economic growth, while about 3 billion people have no access to safe and reliable energy sources. In year 2017, 2.8 billion people relied on biomass, coal, or kerosene for cooking (IEA, 2017). Household air pollution from these sources is linked to millions of premature deaths, along with health and environmental impacts on local communities (Kammen, 1995; Kammen & Dove, 1997). Moreover, across the developing world several billion hours are spent every year collecting firewood for cooking, mostly by women. This time could be put to more productive uses such as education (Bailis et al., 2005). The ongoing continued reliance on fossil fuels is a major contributor to GHG emissions, air pollution, and associated health and environmental problems (Johansson et al., 2012). In recent years, there has been a big push for the development of more efficient systems of energy production from renewable sources, such as solar and wind power (Herzog et al., 2010; Kammen, 2006). Societies will likely increasingly rely on renewable energy and gradually reduce dependence on fossil fuels (Riahi & Roehrl, 2000).

In the meantime, however, humanity needs to deal with the challenge of curbing CO_2 emissions, while removing inequalities in the access to energy. To date, one in five people still lack access to modern electricity in their homes; three billion people use wood, coal, charcoal, or animal waste for heating and cooking (IEA, 2016). Access to affordable, clean, and reliable energy, which is listed as one of the UN's SDGs (UN, 2016), is a major challenge of our time. Achieving this goal and, more generally, enhancing energy security—defined as "the uninterrupted availability of energy sources at an affordable price" (IEA, 2012) —requires improvements to the systems of energy production and distribution that may ultimately exacerbate competition for water with agriculture, as explained in sections 7 and 8.

5. Food-Water Nexus

5.1. Water and Crop Production

Meeting the demand for food can depend either directly or indirectly on local water availability. Directly, in terrestrial ecosystems all primary production (i.e., plant growth) requires water. Indirectly, all secondary (i.e., animal) production (except fisheries; see section 5.3) ultimately requires water to produce grass, fodder, or feed. Thus, a strong nexus exists between food production and water availability. Such a nexus is central to the food and water security debate because (1) in many regions of the world, crop production is limited by water availability; (2) an increase crop yields depends on water withdrawn from surface-water and groundwater bodies and used for irrigation; and (3) overall, such agricultural water withdrawals by far exceed any other form of human appropriation of water resources worldwide (e.g., Falkenmark & Rockström, 2004; Hoekstra & Chapagain, 2008).

The water footprint of crops varies by food product, location, and time. For example, wheat has a global average total water footprint of 1,826 m^3/t; rice, 1,674 m^3/t; and maize, 1,222 m^3/t (Mekonnen & Hoekstra, 2011a). Different studies have developed hydrological models to assess water footprints of crops in different climate conditions, geographic locations, and growing periods (Hanasaki et al., 2010; Mekonnen & Hoekstra, 2011a; Rost et al., 2008; Siebert & Döll, 2010; Tuninetti et al., 2015). These models compute the green water (rainwater) and the blue water (irrigation water) footprints at global scale with relatively high resolution (5×5 arc min) for different major crops. In general, the water footprint of crops depends on their yields and actual evapotranspiration, which in turn is a function of climate and hydrologic drivers. It has been shown that the spatial variability of the water footprint of crops is contributed primarily by variability in yields rather than evapotranspiration (Tuninetti et al., 2015). The water footprint of animal products by far exceeds that of crop-based food and varies with the type of meat, egg, or dairy product (e.g., Figure B2). For example, the global average water footprint of beef is 15,400 m^3/t; pork, 6,000 m^3/t; and chicken, 4,300 m^3/t. The average water footprint of meat is also greater than that of crops on a per calorie (Figure B2 in Box 2) and per protein basis. For instance, on a per gram of protein basis, the water footprint of milk, eggs, or chicken is about 1.5 times larger than that of pulses (Mekonnen & Hoekstra, 2010).

On average, a water volume of 1,200 m^3/year per person is consumptively used for food production (Box 6). This value, which is also known as the water footprint of an individual, typically ranges between 600 and 1,800 m^3/year per person, depending on the diet (Box 6). The percentage of kilocalorie intake from animal products varies from 1% to15% in Asian and African countries to about 35% in North America and Europe. A balanced diet is expected to have about 20% of caloric intake from animal products (Falkenmark & Rockström, 2004). Thus, if the role of fish in our diets is neglected (see section 5.3), the water footprint, WF_{bd}, of a balanced diet of, say, D = 3,000 kcal per person per day with q = 20% reliance on animal products should be on average

$$\mathrm{WF_{bd}} = D\times(1-q)\times\mathrm{WF}_v + D\times q\times\mathrm{WF}_a = 3.6\ \mathrm{m}^3/\mathrm{day} = 1,314\ \mathrm{m}^3/\mathrm{year},$$

where $WF_v = 0.5 \times 10^{-3}$ m^3/kcal and $WF_a = 4.0 \times 10^{-3}$ m^3/kcal are the average water footprints of plant and animal foods, respectively (Falkenmark & Rockström, 2004). Notice that the relatively high daily rate of food calorie consumption used in this analysis (3,000 kcal/day) exceeds the typically recommended values of calorie intake because it accounts for unavoidable losses owing to food waste. It has been estimated that about

24% of food production, 23% of cropland area, and 24% of the water used for crop production for human consumption are lost in the food supply chain (Kummu et al., 2012).

Box 6. The water Footprint of Food Production

The water footprint of a commodity is defined as the amount of water evapotranspired in the production of that commodity (Hoekstra & Chapagain, 2008). The classic notion of water footprint refers to a *consumptive use* of water, which corresponds to a loss of water to the atmosphere as water vapor through the processes of evaporation and plant transpiration. Thus, consumptive uses mean that (liquid) water cannot be reused downstream. To be sure, water is a renewable resource that is conserved in the Earth System and even the water lost in water vapor fluxes from agroecosystems can be eventually reused (once it contributes again to precipitation). But the fact that it is a renewable resource does not exclude that water is available only in limited amounts and the rate of the hydrologic cycle limits our ability to reuse water right away after it has been evapotranspired. This is the reason why water footprint analyses refer to consumptive water uses.The water footprint of agriculture (including both crops and livestock production) has been estimated in the range 6.75×10^{12} m^3/year for the 1995–2005 period (Mekonnen & Hoekstra, 2010) and 11.8×10^{12} m^3/year for 2010 (Carr et al., 2013). Roughly 78% of the water footprint of agriculture is contributed by green water and 22% by blue water (i.e., evapotranspiration of irrigation water). Thus, globally, the consumptive use of blue water for irrigation accounts for $0.90–1.28 \times 10^{12}$ m^3/year (Table 1), which is less than the global water withdrawals for agriculture ($2.41–2.56 \times 10^{12}$ m^3/year) because part of this water is not evapotranspired and can be reused downstream.The water footprint of food strongly varies with the type of diet and depends not only on the total caloric intake but also on how it is partitioned between plant food and animal products (eggs, dairy, and meat). In fact, the water footprint of plant food is about 8 times smaller ($\approx 0.5 \times 10^{-3}$ m^3/kcal) than that of animal food ($\approx 4.0 \times 10^{-3}$ m^3/kcal; Falkenmark and Rockström, 2004). It takes several (on average about eight) calories of feed or fodder to produce 1 cal of animal food (Davis et al., 2014b; Pimentel & Pimentel, 2007).

5.2. Water Quality and the Food-Water Nexus

Agriculture is a major source of water-quality impairment in the food-water nexus, primarily through the increased use and diffuse (nonpoint) mobilization of reactive forms of nitrogen (N) and phosphorus (P; e.g., Carpenter et al., 1998; Galloway et al., 2003; Heathwaite, 2010; Jarvie et al., 2015). In general, P and N are the key nutrients that limit or colimit primary productivity in most freshwater and coastal systems, respectively, making these nutrients primary drivers of eutrophication, or nutrient enrichment (Conley et al., 2009; Elser et al., 2007). Degraded water quality resulting from N and P loading can often manifest through the development or increased persistence of harmful algal blooms (Heisler et al., 2008). Key examples of water-quality impacts downstream from agricultural production are hypoxia in the Gulf of Mexico and a growing number of coastal “dead zones” worldwide (Diaz & Rosenberg, 2008). Although increased use of N and P fertilizers between the 1960s and 2000s (approximately 5.6-fold increase for N and 2.5-fold increase for P) have been integral to improving yields (Foley et al., 2011; Schipanski et al., 2016), these inputs have been concentrated in certain regions, such as parts of the United States and Europe, and have contributed to persistent water-quality problems (Vitousek et al., 2009). One of the most profound recent shifts in food production has been the rise of fertilizer use accompanying agricultural intensification in China and other rapidly emerging economies (West et al., 2014). The increase in fertilizer use has led to problems of excess nutrient inputs (Huang et al., 2017; Sattari et al., 2014) that have contributed to recent widespread eutrophication in China, such as in the Lake Taihu Region (Hai et al., 2010; Xu et al., 2010) and the East China Sea (Li et al., 2009).

There is compelling evidence that contemporary use of reactive forms of N and P is beyond a “safe-operating space” needed to avoid widespread impacts, such as eutrophication, or to avoid other unexpected, nonlinear change in the Earth system (Carpenter & Bennett, 2011; Steffen et al., 2015). The use of N fertilizer derived from the Haber-Bosch process (Erisman et al., 2008; Box 1), as well as biological N fixation associated with crop cultivation, has dramatically altered the global N budget (Battye et al., 2017; Galloway et al., 2004). In addition to the negative effects of excess N on water quality, reactive N can “cascade” through the environment, carrying major social costs in the form of degraded air quality, acidification, depletion of stratospheric ozone, and contributions to climate change (Galloway et al., 2003; Keeler et al., 2016; Sobota et al., 2015). In the case of P, the mining of highly geopolitically concentrated deposits of phosphate rock—about 90% of which is used in food production, predominantly as agricultural fertilizers or feed additives (Cordell & White, 2014)—potentially mobilizes an even greater amount of new P inputs to the biosphere annually than "natural" chemical weathering of P (Bennett et al., 2001; Bennett & Schipanski, 2013). Excess agricultural P use has particularly strong impacts on ecosystem services that are related to water quality (Jarvie et al., 2015; MacDonald et al., 2016). In addition, P has a tendency to accumulate in soils where this "legacy P" can contribute to water-quality problems for extensive periods (Rowe et al., 2015, 2016).

Climate change is likely to compound the challenges of sustainable management of N and P for regulation of water quality by contributing to factors that can drive coastal hypoxia and increase the incidence of harmful algal blooms (Michalak, 2016; Rabalais et al., 2010). A primary concern in agriculture is the effect of increased precipitation intensity on N and P loading to surface waters (Ockenden et al., 2017), particularly in Asia (Sinha et al., 2017). Furthermore, there is evidence that elevated atmospheric temperature, in combination with nutrient loading from land use, may be increasing the dominance of cyanobacteria in lakes (e.g., Taranu et al., 2015).

5.3. The Increasing Role of Fish Consumption in the Food-Water Nexus

Seafood production includes a wide range of species groups (e.g., finfish, shellfish, and crustaceans), production environments (fresh, brackish, and marine waters), and production methods (wild capture and aquaculture). Since seafood species are, by definition, aquatic organisms, seafood production is intimately related to water resources. However, water-resource requirements for seafood production are as varied as the species produced and the production methods used (for a full review of water use for seafood, see Gephart et al., 2017).

Aquaculture is currently the fastest growing production component in the global food system (Troell et al., 2014), and as much as one half of seafood consumption is now derived from farmed fish (Box 4). Water use for aquaculture is similar to that for terrestrial food production, such as water use for feeds, but water use for aquaculture differs owing to its large water storage requirements. Aquaculture feed (aquafeed) dependence varies by species, with some species requiring essentially no aquafeeds (e.g., bivalves) and others relying almost completely on feeds (e.g., salmon, trout, and shrimp; Tacon et al., 2011). The water footprint of aquafeeds varies depending on feed composition, which varies by species and time on the basis of the prices of different ingredients (Tacon et al., 2011). Recently, efforts have been made to replace fishmeal and fish oil in aquafeeds with crop-based ingredients in order to improve the sustainability of aquaculture by supplanting the use of capture fisheries for the production of aquafeed based on fishmeal and fish oil (Bell & Waagbø, 2008; Beveridge et al., 2013; Fry et al., 2016). While a shift toward crop-based aquafeeds may reduce pressures on wild fisheries, it also increasingly links seafood consumption to terrestrial agriculture. This shift in feed source may have a trade-off with water use though because production of crop-based feeds typically uses more water than the production of fishmeal and fish oil (Gephart et al., 2014; Pahlow et al., 2015; Troell et al., 2014).

Large water storage requirements for aquaculture differentiates the water use types and processes that are most relevant for aquaculture from those relevant for agriculture or livestock farming (Gephart et al., 2017). Water storage creates a competitive use for water resources, alters the rates and timing of evaporation and seepage, and can involve large quantities of in situ water use (e.g., nonconsumptive water use for cage aquaculture). In situ water use is essential for providing habitat for inland capture fisheries, and minimum environmental flows are needed to maintain appropriate salinity levels in brackish water ecosystems. Although crucial for these capture fisheries and some forms of aquaculture, in situ water use can be difficult to quantify and cannot be directly compared to consumptive water use in agriculture systems. Despite these methodological challenges, as the seafood sector grows (Box 4), it is increasingly important to consider water use for seafood production.

5.4. Water Solutions for Future Food Security

The problem of food security is often related to the availability of water resources to meet the growing needs of human societies (Falkenmark & Rockström, 2004; Gleick, 1993; Suweis et al., 2013). Falkenmark and Rockström (2006) developed one of the early assessments of the global water resources required to meet the needs of the growing human population while eradicating malnourishment. On the basis of their analysis, humanity's water use for food production was roughly 6.8×10^{12} m^3/year, including 1.8×10^{12} m^3/year of irrigation water and 5.0×10^{12} m^3/year of green water (i.e., root zone soil moisture). To eradicate malnourishment by 2030 and meet the needs of the growing human population (roughly 2 billion more people between 2006 and 2030) for a balanced diet (see section 5.1), it would be necessary to increase the water use for agriculture by roughly 4.2×10^{12} m^3/year. Falkenmark and Rockström (2006) suggest using a mix of strategies to meet future water needs. Because many aquifers and most rivers flowing through agricultural areas are already strongly depleted (e.g., Jägermeyr et al., 2017), only a small fraction (0.5×10^{12} m^3/year) of the additional water demand for food production could be met by an increase in irrigation. The rest should come from improvements in soil water management that reduce soil evaporation (e.g., Jägermeyr et al., 2016) and the implementation of "more-crop-per-drop" approaches that use or engineer crops with higher water use efficiency. This analysis (Falkenmark & Rockström, 2006) did not entirely account for the increasing water demand associated with dietary transitions or growing biofuel demand. Nevertheless, it stressed the important constraints placed by water resources on global food security and the need for approaches that conserve water or use it more efficiently (Davis, Rulli, Garrassino, et al., 2017; Davis, Rulli, Seveso, et al., 2017; Davis, Seveso, et al., 2017; Jägermeyr et al., 2016; MacDonald et al., 2016) instead of increasing human appropriation of water resources by expanding agriculture (i.e., green water use) or increasing withdrawals for irrigation (i.e., blue water use).

5.5. Nexus Between Human Rights to Food and Water

In the 1948 Universal Declaration on Human Rights (Article 25), the UN (1948) recognized the right to food as a human right, which is a right that every person has just by the virtue of being human. This right was subsequently restated as the right "to be free from hunger" by the International Covenant on Economic, Social and Cultural Rights (Article 11), which is part of the International Bill of Human Rights (UN, 1966). The International Covenant on Economic, Social and Cultural Rights defines responsibilities for the States (internationally recognized sovereign territories) that shall take "*the measures, which are needed: (a) To improve methods of production, conservation and distribution of food … (b) Taking into account the problems of both food-importing and food-exporting countries, to ensure an equitable distribution of world food supplies in relation to need.*" (UN, 1966). Thus, the right to food recognizes both the entitlements of individuals to have access to adequate food and the legal obligations for States to provide conditions that eradicate hunger and malnutrition. More specifically, governments should respect existing access to food, protect it against third parties, and fulfill the human right to food (e.g., Narula, 2010). Interestingly, such obligations go beyond countries' boundaries through international cooperation and trade agreements that respect, protect, and fulfill food rights. Subsequent UN documents have clarified that the right to food does not necessarily imply a right to be fed but a requirement that States create favorable conditions for people to provide food for themselves (UN Fact Sheet No. 34).

More recently, the UN has also recognized a human right to "*safe, clean, accessible and affordable drinking water and sanitation*" (UN, 2010). Such a right to water, however, focuses on drinking water and sanitation and therefore is only marginally relevant to the right to food, though, as noted in Box 2, good sanitation reduces the risk of intestinal infections that could cause undernutrition. In the context of the water-food nexus, the right to food implies that every individual should have access to enough "virtual" water, that is, water used for the production of enough food commodities to be free from hunger.

6. Water-Energy Nexus

Water and energy are interconnected, largely in terms of the water use involved in power generation but also indirectly as a result of hydrological alterations associated with hydropower development (e.g., U.S. Department of Energy, 2014). Fuel production and power generation rely on water availability, and the supply of water requires energy (King et al., 2008). Both water and energy are finite resources that, in a rapidly changing world, are set to be placed under increasing stress. New energy technologies implemented to "decarbonize" the economy of industrial societies are increasing our reliance on water-intensive fuels (IEA, 2016; Mielke et al., 2010), further exacerbating the interconnection between energy production and water resources. For example, biofuel production, concentrating solar power (CSP), and carbon capture and storage require large amounts of water. Thus, water availability may challenge existing energy operations and is increasingly recognized as a factor determining the physical, economic, and environmental viability of energy production projects.

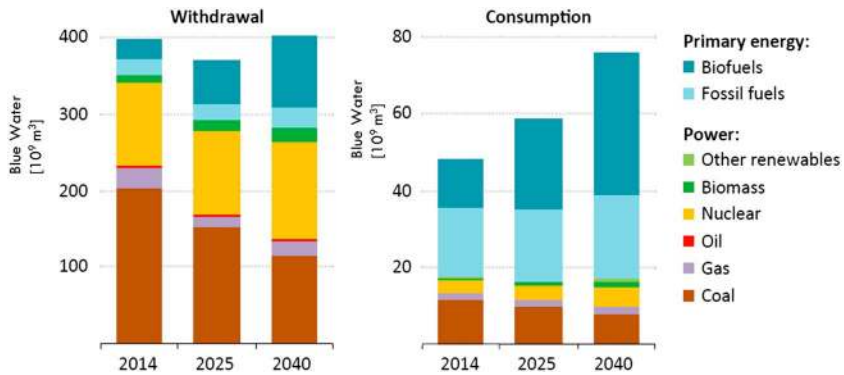


Figure 12. Water withdrawals and consumption for energy production (date source: International Energy Agency, 2016).

The rising importance of the water-energy nexus has been recognized by the IEA's *World Energy Outlook* (IEA, 2012, 2016). Moreover, the energy sector is increasingly concerned about the effects of climate change on the water cycle. More than three quarters of the world's top energy companies indicate that uncertainty in water availability is a major source of risk for their business operations (CDP, 2016). Water shortages have already caused the shutdown of coal-fired power plants in India (IEA, 2015) and are affecting the choice of location and technology used for energy projects in China (IEA, 2015). In south Texas, shale oil and gas extraction using hydraulic fracturing has competed for water with agriculture through a water market, thereby increasing water prices in the region (Rosa et al., 2018). Years of drought in the State of California have reduced the hydropower share of total energy production from 30% to 5% (Garthwaite, 2014).

Dam construction is another rapidly evolving nexus issue for the food-water nexus (i.e., reservoirs built for irrigation purposes) and the energy-water nexus (i.e., dams built for hydropower). On the one hand, dam construction can have significant economic benefits in addition to supplying renewable energy (Winemiller et al., 2016). However, these benefits can come at substantial social and environmental costs in some river basins (see section 11.1). Dam construction alters natural flow regimes (Poff et al., 1997) and the connectivity of river systems, which can disrupt the movement of organisms and sediment, whereas water storage associated with dam operations regulates river flow, which can alter geomorphic processes and disrupt ecological functions both upstream and downstream (e.g., Grill et al., 2015; Nilsson et al., 2005). Hydropower generation is influenced by the year-to-year variations in rainfall that increase the risk of climate-related electricity supply disruption in dry years (Conway et al., 2017). While thousands of hydropower dams are planned or currently under construction globally (Zarfl et al., 2012), three large river basins (Amazon, Congo, and Mekong) have particularly large numbers of hydropower dam projects and collectively hold about one third of freshwater fish species (Winemiller et al., 2016). The Mekong contains the world's largest inland fisheries, which are an important source of food for local populations. These fisheries are particularly sensitive to dam construction because of disruptions of migratory fish stocks (Ziv et al., 2012).

6.1. Water for Energy

In 2014 the energy sector accounted for 10% of total worldwide water withdrawals and around 3% of total water consumption (IEA, 2016). About 12% of these withdrawals and 64% of the consumption were used for energy source extraction (IEA, 2016), and the remaining water was used for power generation (Figure 12).

6.1.1. Crude Oil Production

Water use for crude oil production (i.e., extraction and processing) greatly varies, depending on technology used, local geology of the reservoir, and operational factors (Rosa et al., 2017; Wu et al., 2009). Relatively large amounts of "fossil" water, corresponding to roughly 7 times the volume of oil produced, are extracted with the oil (e.g., Mielke et al., 2010). The produced water is injected into disposal wells, reinjected into the reservoir to improve oil recovery efficiencies, or treated with energy-intensive technologies and added to the water cycle.

Conventional oil can be extracted using three recovery techniques. Primary oil recovery, that is, the natural flow of oil into production wells, has a small water footprint of extraction. However, primary recovery usually extracts less than one third of the hydrocarbons stored in the geologic formation from which they are extracted. To maximize reservoir production, more expensive and advanced technologies, such as secondary and tertiary oil recovery, are implemented. Secondary recovery via water injection uses large amounts of water to improve oil production. Water allocations can come from different sources; for example, in Russia, water is withdrawn from freshwater resources, and in Saudi Arabia, the water used is typically either brackish water or seawater (Wu et al., 2009). Tertiary oil recovery or enhanced oil recovery via thermal recovery is even more costly and energy demanding. In this case, high-pressure steam is injected into the hydrocarbon reservoir to reduce heavy oil viscosity and increase the production flux. Another water-intensive enhanced oil recovery technique is tertiary recovery via CO_2 injection. CO_2 is captured from the "flue" gas emitted using water-based technologies, such as absorption through amine scrubbing (in this process an amine solvent is used to remove carbon dioxide from the flue gas; Bui et al., 2018). Carbon dioxide is subsequently stripped from the solvent by heating and transported and injected into the hydrocarbon reservoir to enhance oil production (Smit et al., 2014).

In recent years unconventional fossil fuels have received increased attention as important energy sources (Farrell & Brandt, 2006; Rosa et al., 2017, 2018). Shale oil and oil sands are expected to contribute to a growing share of our future energy needs (BP, 2017; ExxonMobil, 2017; IEA, 2016). Depending on the depth of the deposit, oil sands are extracted using two different methods—surface mining (i.e., digging into shallow deposits) and in situ drilling (i.e., pumping from recovery wells after injecting high temperature steam to reduce heavy oil's viscosity). In situ technology requires less water than surface mining (Rosa et al., 2017). Bitumen from mined oil sands is a low-quality product that needs to be upgraded through a water-demanding process into synthetic crude oil before being delivered to refineries (Rosa et al., 2017).

Shale oil and gas extraction is performed through horizontal drilling and hydraulic fracturing, technologies that require a lower amount of water than other fossil fuels. However, shale oil extraction requires a large upfront use of water (i.e., during the process of well drilling) over a few days, after which oil is produced over several months (Mielke et al., 2010; Scanlon et al., 2014b). Thus, intensive water withdrawals over a short period of time can induce or enhance local water stress. By adopting a hydrologic perspective that considers water availability and demand together, Rosa et al., 2018 presented a global analysis of the impact of shale oil and gas extraction on water resources, particularly on irrigated crop production. Using a water balance analysis, Rosa et al., 2018 found that 31–44% of the world's shale deposits are located in areas where water stress would either emerge or be exacerbated as a result of unconventional oil and gas extraction from shale rocks. This analysis is an example of how research can analyze all the three dimensions of the FEW nexus using geospatial data-driven analyses. Results from these studies can be used by decision makers and local communities to better understand the water and food security implications of energy systems.

6.1.2. Natural Gas Production

Conventional gas production has a negligible water footprint. A small volume of water is required during the drilling and cementing phases. Interestingly, unconventional gas production from shale gas requires the same amount of water as shale oil wells drilled in the same area (Scanlon et al., 2014a). However, energy production from shale oil has a lower water footprint than energy from shale gas because of the higher energetic content of oil.

Unconventional gas can also be produced from coal bed methane. In this case, deep coal seams undevelopable for mining operations are drilled to extract the natural gas that is absorbed by the organic material in the coal formation. Coal bed methane has a low water footprint and releases substantial volumes of produced water (U.S. Geological Survey, 2000) that, if treated, can be recirculated into the water cycle.

6.1.3. Coal

Coal has not only high GHG emissions per unit of energy produced but also a high water cost (Table 2). The amount of water used for coal mining varies between underground and surface mines. Water requirements increase as the coal mine operations move deeper underground. An increasing trend in coal mining operations is to wash coal, a process that requires about 3.79–7.58 L/GJ (Mielke et al., 2010). Coal washing is accomplished by density separation or froth floatation to separate mined coal ore from a mixture of materials (e.g., rocks, minerals, and sand). This process aims to improve combustion efficiency to meet environmental standards by reducing sulfur and particulate emission during combustion (IEA, 2012). Water can also be used to transport coal as a slurry through pipelines (Mielke et al., 2010).

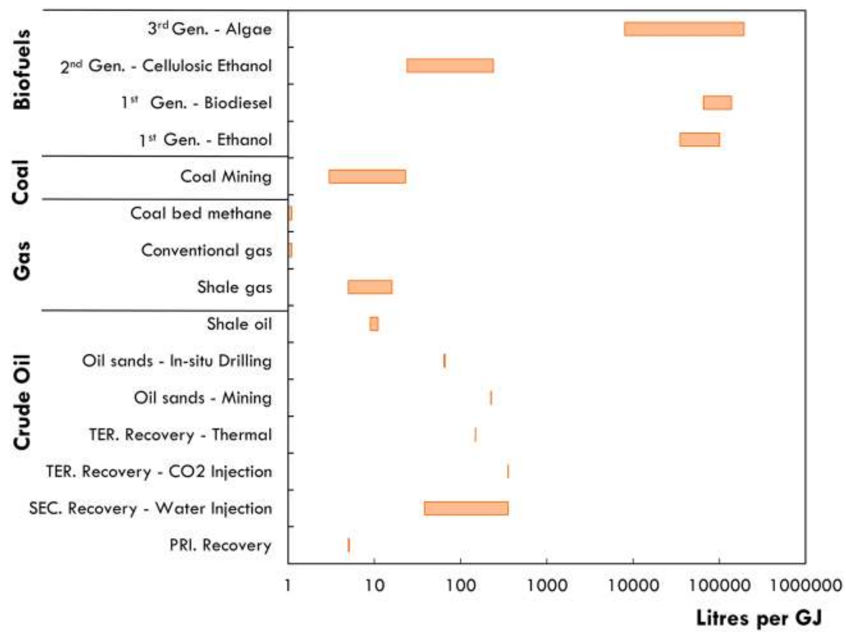


Figure 13. The water footprint of fossil fuel and biofuel production. For fossil fuels, only blue water is used for extraction and processing without accounting for "ancient water" (section 6.1.5). For biofuels, the water footprints account for green water consumption, and the variability results from the dependence on climate and geographic conditions (based on data in Table 3). Biofuels are classified as first, second, and third generation.

6.1.4. Biofuels

In an attempt to curb the increasing atmospheric CO_2 concentrations, recent energy policies have mandated a certain degree of reliance on renewable energy sources as alternatives to fossil fuels (EU, 2009; U.S. Congress, 2007). Thus, gasoline and diesel are now commonly blended with bioethanol and biodiesel. These biofuels can be obtained from a variety of crops, including food crops (first-generation biofuels), cellulose-rich crop residues (second generation), and algae (third generation; Figure 13). To date (2018), the biofuels that are commonly used are of the first generation. Bioethanol is mainly made with maize in the United States and sugarcane in Brazil, whereas biodiesel is produced using vegetable oil (e.g., soybean oil, rapeseed oil, and palm oil; Figure 14). Bioethanol consumption is for most part domestic, and at least

Table 3
Water Footprint Fossil Fuel Extraction and Biofuel Production

Process or method	L/GJ	Source
Crude oil primary recovery	5	Mielke et al. (2010)
Crude oil secondary recovery via water injection-Saudi Arabia	38–125	Mielke et al. (2010)
Crude oil secondary recovery via water injection-U.S.	235	Mielke et al. (2010)
Crude oil tertiary recovery via CO_2 injection	356	Mielke et al. (2010)
Crude oil tertiary recovery thermal recovery	148	Mielke et al. (2010)
Oil sands mining	224	Rosa et al. (2017)
Oil sands in situ drilling	64	Rosa et al. (2017)
Shale oil	9–11	Scanlon et al. (2014a)
Shale gas	5–16	Scanlon et al. (2014a)
Conventional gas	0	U.S. Department of Energy (2006); Mielke et al. (2010)
Coal bed methane	0	International Energy Agency (2016)
Coal mining	3–23	Mielke et al. (2010)
Biofuels first generation: ethanol	41,800–124,800	Rulli et al. (2016)
Biofuels first generation: biodiesel	68,250–137,820	Rulli et al. (2016)
Biofuels second generation: cellulosic ethanol	24–239	International Energy Agency (2016)
Biofuels third generation: algae	8,000–193,000	Gerbens-Leenes et al. (2014)

Note. Values may vary as a function of the calculation methods and the underlying assumptions.

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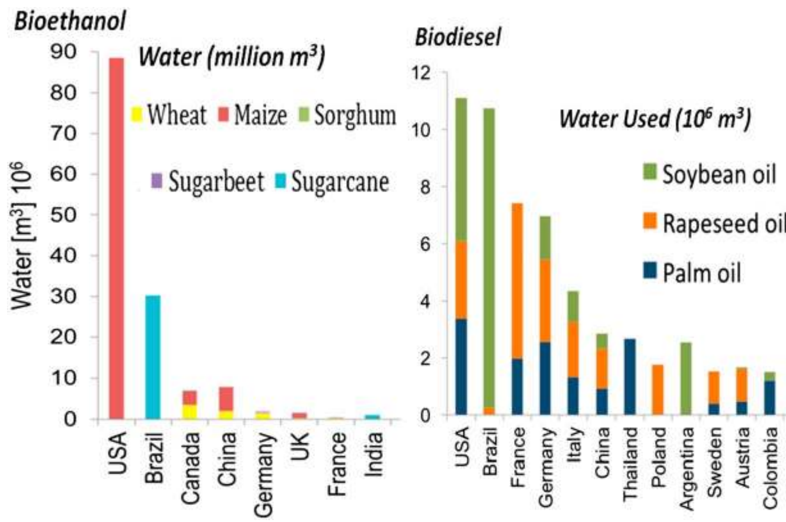

Figure 14. The water footprint of bioethanol and biodiesel fuels in major biofuel consumer countries (from Rulli et al., 2016).

one third of the global biodiesel is available through international trade, mostly associated with palm oil from Indonesia and Malaysia (Rulli et al., 2016).

The water used for biofuels strongly varies with crop type, geographic location, climate, and soil (Fingerman et al., 2010; Gerbens-Leenes et al., 2014; Wu et al., 2009). First-generation biofuels have a much higher water footprint than fossil fuels (Table 2; see also the discussion on "ancient water" in the following sections) and therefore compete with the food system directly (biofuel crops can be directly used as food) and indirectly (blue water used for biofuel crops can be used for food production). The competition of biofuels with food production explains the heated debate on how bioenergy production competes with the food system and the appropriateness of using food crops to fill fuel tanks instead of feeding the poor (e.g., Brown, 2015). Rulli et al. (2016) found, however, that to date, only about 4% of the global energy consumption by the transport sector and 0.2% of global energy use in all sectors is utilized for biofuels. For the year 2000, biofuel production accounted for about 2–3% of the global land and water used for agriculture (Cassidy et al., 2013; Rulli et al., 2016). In 2007, biofuel production accounted for about 2% of the global production of inorganic phosphorus fertilizer (Hein & Leemans, 2012). Second- and third-generation biofuels do not compete with food production because they do not rely on biomass that could otherwise be used for food, and they consume relatively small amounts of water (Gerbens-Leenes et al., 2014; Wu et al., 2009).

6.1.5. Ancient Water and the Water Footprint of Fossil Fuels

The water footprint of fossil fuels is typically calculated (e.g., Figure 13) by accounting only for the water used for oil or gas extraction and processing without considering the fact that these hydrocarbons result from the transformation (i.e., fossilization) of ancient plant biomass over geological time (D'Odorico, Natyzak, et al., 2017). Millions of years ago the growth of that biomass was associated with the transpiration of ancient water, similar to the way today's biofuel production entails the consumptive use of the huge amounts of water (discussed in the previous section). For any agricultural commodity (e.g., cereals, fruit, and fibers), the water consumed in transpiration is the major contributor to the water footprint of fossil fuels. The main difference, in this case, is that the water used for transpiration is ancient water. The omission of ancient water from the calculation of the water footprint of fossil fuels explains the big gap between the water footprint of fossil fuels and biofuels (Table 2). The ancient water component of the water footprint of fossil fuels is difficult to estimate because that water was transpired millions of years ago by plant species and under climate conditions that do not exist anymore and are not known to us. It is possible, however, to estimate the amount of water that it would take today to replace the "burning" of ancient water with present water by shifting from fossil fuels to present biomass (i.e., biofuels). To meet today's fossil energy need (4.69×10^8 TJ/year in 2013 for natural gas, crude oil, and coal), a consumptive use of water would be close to 7.39×10^{13} m^3 year, which is order of magnitude greater than the water used for extraction and processing (4.64×10^8 m^3/year) that is usually accounted for in water footprint calculations of fossil fuels (D'Odorico, Natyzak, et al., 2017). Thus,

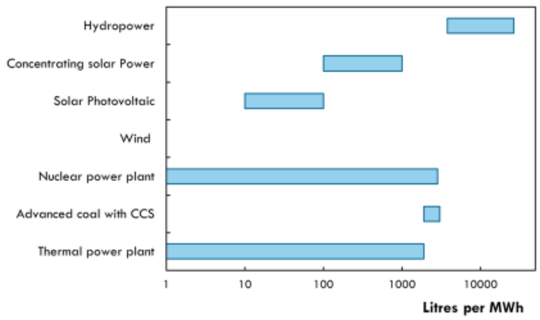

Figure 15. The water footprint of power generation expressed in terms of evaporation losses or "consumptive use" (based on data reported in Table 4). CCS = carbon capture system; MWh = megawatt hour.

to meet its energy needs, humanity is using an amount of ancient water of the same order of magnitude as the annual evapotranspiration from all terrestrial ecosystems (Figure 9). In other words, the energy that is powering industrial societies relies on water from a geological past (D'Odorico, Natyzak, et al., 2017). Likewise, the use of fossil fuels is relying on past sunlight (Hartmann, 2004) and land (Hermele, 2014), allowing industrial societies to have access to an unprecedented amount of energy that cannot be replaced with present-day biomass because of constraints imposed by the water cycle (D'Odorico, Natyzak, et al., 2017) and land availability (Rulli et al., 2016). These findings highlight the need for nonfuel-based sources of renewable energy as future substitutes for fossil fuels.

6.1.6. Integrating Geographic Constraints in Water Footprint Calculations

The discussion of ancient water presented in the previous section highlights some limitations in the calculations of the water footprint of fossil fuels. Although the water footprint of biofuels and food products accounts for the water used their production, for fossil fuels, the water footprint accounts for the actual water needed in extraction and processing, neglecting the ancient water used millions of years ago (D'Odorico, Natyzak, et al., 2017).

Moreover, previous works have assessed the water footprint of energy production and power generation from the life cycle analysis (LCA) perspective without considering the impacts on local water resources (e.g., Scown et al., 2011). In analyses of the hydrologic impacts of fossil fuel production, an approach that looks at the total water used for extraction and processing may be misleading because these two water needs are typically met with water resources available in two different locations (i.e., close to the extraction wells and processing plants, respectively). LCA scientists typically focus on a comprehensive accounting of all water costs associated with production and processing, regardless of where the water comes from. Therefore, there is the need for a more hydrologic-based approach as an alternative to classic LCA calculations of the water footprint (Rosa et al., 2018).

6.1.7. Water Use for Power Generation

Power generation accounts for 88% and 36% of the water withdrawals and consumption in the energy sector, respectively (IEA, 2016). The other major share of water for energy is allocated to energy resource extraction (see previous sections). The water footprint of power generation is calculated in terms of consumptive use (i.e., evaporation losses), similar to the calculation for agricultural products (Figure 15).

6.1.7.1. Thermoelectric Power Generation

Thermal power generation accounts for 70% of world power generation (IEA, 2016). Current technologies used for thermoelectric power plants are based on a steam Rankine cycle and heavily rely on water. In these systems, a cooling fluid is needed to cool and condensate the outlet steam of the expanders. In a thermoelectric power plant, water is heated to produce the steam needed to spin the turbines that generate electricity. Thermodynamic limits require cooling the steam into water before it can be reheated to produce steam again. Surface water from a nearby water body (river, lake, or sea) typically is used as a refrigerating fluid because of its availability and efficient heat transfer properties. For this reason, thermoelectric power plants are built close to rivers, lakes, and seas.

The volumes of water withdrawn for thermal power generation are staggering. For example, in the United States thermoelectric power plants account for 40% of total freshwater withdrawals and 4% of freshwater consumption (U.S. Department of Energy, 2006). Power plants built along the coast can reduce the use of freshwater and limit the exposure to water stress. However, seawater is more corrosive and requires more resistant materials and higher capital costs (IEA, 2015).

Nuclear power has the highest water consumption among thermoelectric technologies (Table 4). Water is needed not only to cool the exhaust steam but also to control the temperature of the fission process of uranium. Additionally, uranium mining and processing requires substantial amounts of water (Mielke et al., 2010).

Coal and natural gas-fired power plants, as well as refineries, can be retrofitted with a carbon capture unit (Bui et al., 2018). Although carbon capture and storage is a promising technology to limit the climate change

Table 4
Water Footprint for Power Production (in Liters per Megawatt Hour)

	L/MWh	Source
Thermal power plant	0–1,895	Mielke et al. (2010)
Advanced coal with CCS	1,895–3,032	Mielke et al. (2010)
Nuclear power plant	0–2,843	Mielke et al. (2010)
Wind	0	Mielke et al. (2010); International Energy Agency (IEA, 2016)
Solar photovoltaic	10–1,00	IEA (2016)
Concentrating solar power	100–1,000	IEA (2016)
Hydropower	3,790–26,530	Mielke et al. (2010)

Note. CCS = carbon capture system.

impacts of energy production by reducing CO_2 emissions from fossil fuels, the actual technology is based on absorption capture units, which rely on large volumes of water to separate CO_2 from the flue gas (Smit et al., 2014).

6.1.7.2. Power Generation From Renewable Energy

Renewable energies differ in their rates of water consumption (Table 4). Wind turbines are not water intensive (Mielke et al., 2010). Solar photovoltaic energy production requires water to clean solar panels of dust deposits (Ravi et al., 2014). Concentrating solar power (CSP), which relies on a Rankine cycle and steam turbines, has water consumption levels similar to those of thermoelectric power plants. Both photovoltaic and CSP plants are usually located in arid regions where solar radiation is high enough to ensure the maximum operating load throughout the year and where there are no constraints on the availability of land for such spatially extensive projects. However, site selection needs to take into account water availability. Interestingly, solar technologies could be paired with biofuels cultivation to reduce the competition for land with food production and optimize water use for energy (to clean solar panels) and crops (Ravi et al., 2014).

Hydropower produces power while providing a source of global energy storage (Hoes et al., 2017). Most of the water stored is returned to the environment. The major contributor to water consumption in hydropower plant is evaporative loss from the reservoir (Bakken et al., 2017). Such losses are site specific and vary with reservoir size and climate and are minimal in the case of flowing water systems with no reservoirs (Bakken et al., 2013; Scherer & Pfister, 2016). (See section 3.4 for impacts of dams on ecosystems.)

6.2. Energy for Water

Access to modern energy is essential for the provision of clean water supply, sanitation, and healthcare. Only recently, attention has been given to the amount of energy required for irrigation (Vora et al., 2017) and clean water supply and treatment (IEA, 2016; King et al., 2008). In 2014, the global water sector used the equivalent of Australia's entire energy demands for water supply and treatment (IEA, 2016). Depending on the quality of water, different energy-intensive processes, such as desalinization and wastewater treatment, need to be implemented to ensure access to clean and potable water. The treatment of brackish and saline water, which is growing in importance in Saudi Arabia and Saharan African countries (IEA, 2016), requires at least 10–12 times more energy than freshwater treatment (King et al., 2008).

Depending on the depth, groundwater pumping is more energy intensive than surface-water withdrawals. Additional energy is required to convey surface water when gravity flow is not an option. For example, the State Water Project in California uses 3% of the State's electric energy to transport water across a 1,100-km distance (Webber, 2016). Likewise, China is developing a massive water transfer project to transport 45 Gm^3/year from the wet south to the dry north (IEA, 2015).

6.3. Future Projections

A recent report by the IEA has quantified the amount of water that will be needed to meet our future energy needs (IEA, 2016). Even though the global energy demand is projected to rise by 30% by 2040 (BP, 2017; ExxonMobil, 2017; IEA, 2016), water withdrawals for energy production are not expected to increase because of the adoption of more advanced water-saving technology (Table 5). However, the increase of nuclear

Table 5
Actual and Projected World Water Withdrawals and Water Consumption From the Energy Sector

	Year 2014 (Gm^3)	Year 2040 (Gm^3)
Water withdrawals	398	400
Water consumption	48	75

Note. International Energy Agency (2016).

power, biofuel production, and unconventional fossil fuels extraction will increase water consumption in the energy sector by more than 60%.

As noted earlier, one of the UN's social development goals (SDGs) is to ensure access to water for all. To reach this goal, more energy will be required to treat wastewater and saline or brackish water. In the next 25 years there will be a shift toward energy-intensive water projects, doubling the energy use for water (IEA, 2016), mostly because of desalinization projects and large-scale water transfer. At the same time, energy intensity in the water sector will increase from 0.2 to 0.3 kWh/m^3 (IEA, 2016).

7. Food-Energy Nexus

Energy is used for multiple food system activities, including the operation of farm machinery and the processing, packaging, transporting, refrigerating, and preparing of food (Ingram, 2011). As one example, the U.S. Department of Agriculture estimated that overall food-related energy use in the United States represented 16% of the Nation's total energy budget (Canning et al., 2010). The energy use involved in the food system therefore to some degree links food systems to GHG emissions. Food systems contribute between 19% and 29% of total global anthropogenic GHG emissions, but direct emissions from agricultural production (e.g., nitrous oxide emissions from excess N fertilizer application and methane emissions from enteric fermentation) and indirect emissions resulting from land use change contribute much more to total emissions than other food system activities (Vermeulen et al., 2012). Even before the food production stage, energy use is required in the production of fertilizers and pesticides; for example, industrial ammonia synthesis using the Haber-Bosch process for N fertilizer manufacturing uses greater than 1% of energy production worldwide because of its reliance on high temperature and high pressure (Smil, 2004). Although food is increasingly transported across vast distances, a life cycle assessment of U.S. foods by Weber and Matthews (2008) found that transportation represented just 11% of total food-related GHG emissions, meaning that food choice (e.g., choosing lower emissions intensity chicken instead of higher emissions intensity red meat) had a higher relative impact on the reduction of overall emissions than the sourcing of local foods to reduce transportation emissions.

One of the most obvious ways in which food is linked to energy is the use of food crops as feedstock for biofuel production (further detailed in section 6.1.4). There is a myriad of cases where the water needs of the energy and food sectors strongly interact with one another through their competition for land and water (section 7). As a result, energy prices can also be linked to food prices because of the increased cost of agricultural production and transportation (e.g., Headey, 2011; Headey & Fan, 2008), which was observed particularly with the growing demand for first-generation biofuels as a result of higher oil prices in the 2000s (Anderson, 2010; Naylor et al., 2007). The links between food and first-generation biofuels are further discussed in the following section.

8. Interactions Underlying the FEW Nexus

The food and energy sectors compete with one another either directly (see section 7) or indirectly through their reliance on the same water resources. In this section, three major examples of strong interactions among the water, energy, and food systems, namely, biofuels, reservoir operation, and unconventional fossil fuel extraction, are discussed.

8.1. First-Generation Biofuels

Perhaps the clearest nexus issue between food, energy, and water is that of first-generation biofuels (section 6.1.4). First-generation biofuels are for the most part produced utilizing crops that could also be used as food (or flex crops). In this case, the interaction between energy and food is a direct competition for these crops or the land and water resources they use (e.g., Naylor et al., 2007). Brown (2013) suggests that the consumption of one 25-gal. tank of fuel (e.g., for a sport utility vehicle) roughly corresponds to the food needed to feed one person for a year. Furthermore, Headey and Fan (2008) and Headey (2011) argue that a surge in demand for biofuels in confluence with other factors (e.g., rising oil prices, depreciation of the U.S. dollar, export restrictions, and trade shocks) was at the root of the 2007/2008 global food crisis because of its impacts on elevating prices for key crops. Such characteristics help to explain why the competition between energy and food production has been at the center of heated debates about the ethical implications of sacrificing food crops to reduce societal reliance on fossil fuels.

The production of biofuels is one of the more prominent examples of connections between food and energy markets that has raised concerns about diverting resources from one product (food) to the production of another product (biofuel), which can generate higher returns. These dynamics are further complicated by agricultural subsidies, tariffs, incentives for renewable energy, and opportunities associated with international land investments for agribusiness corporations. At the same time, biofuel production has a strong impact on the water system, particularly in water-limited regions, where the same water resources could be used for food (e.g., Rulli et al., 2016).

The environmental effects of expanding first-generation biofuel production have led to substantial criticism and debate. Tilman et al. (2009) described this as a "food, energy, and environment trilemma" since first-generation biofuels carry risks to food security and GHG emissions. The increasing demand for ethanol led to a sharp increase in demand for crops such as maize in the United States and sugarcane in Brazil, raising concerns over land use change (Harvey & Pilgrim, 2011). In Brazil, the demand for sugarcane is expected to result in forest loss and land use changes (e.g., Lapola et al., 2010). The effects can be direct and indirect, with biofuel crop plantations displacing pastures, and new pastures replacing forested areas (e.g., Hermele, 2014). Similarly, the use of maize-based ethanol to replace gasoline in the United States could substantially increase CO_2 emissions as land conversion, domestically and abroad, responds to meet this increased demand (Hertel et al., 2010; Searchinger et al., 2008). The boom in biofuel demand in the United States during the late 2000s resulted in substantial increases in maize production for ethanol, which was linked to the expansion of crop production nationally, particularly on more marginal lands, including grasslands and wetlands (Lark et al., 2015). Likewise, the boom of oil palm plantations in Southeast Asia in response to biofuel and oil crop markets has come at the cost of high biodiversity old-growth forests, including substantial emissions of GHGs from cleared forests and particularly drainage of carbon-dense tropical peatlands (Carlson et al., 2012, 2013). Depending on the previous land cover and its capacity for carbon storage, negative net GHG emissions, often touted as the potential advantage of biofuels over conventional fossil fuels, may not be realized for decades after the land conversion when the "carbon debt" from the increased GHG emissions caused by forest clearing has been paid off (Fajardy & Mac Dowell, 2017; Fargione et al., 2008). Using current agricultural lands for biofuel crops may offset the "carbon debt" of land use change but can lead to a displacement of food crops and substantial water use (Rulli et al., 2016). The following sections discuss some examples of more indirect forms of competition between energy and food that can have impacts on the food system but have remained more unnoticed.

8.2. Reservoir Management

Dams are typically built to create reservoirs and store water in rainy seasons or wet years for use in dry periods, when streams and rivers exhibit low flows. Possible uses of reservoir water include irrigation, environment for aquaculture, water supply, and hydropower. Dams can be built to protect downstream areas from floods and to mitigate flood waves by storing part of the flood water in reservoirs. It is not uncommon to see dams that are built for multiple purposes, such as hydropower generation and irrigation. In this case, strong water-related interactions emerge between the energy and food sectors, particularly in regions affected by water limitations for at least part of the year. Water utilized for hydropower production can still be used for irrigation after it has passed through the turbines of a power plant, suggesting that no real competition exists between these two water uses. Nevertheless, competition does exist because hydropower generation and irrigation often require different reservoir management criteria: irrigation water is needed during the growing season, whereas hydropower is typically used during periods of peak demand, which do not necessarily coincide with the growing season. Moreover, after its use in a power plant, water has undergone a major loss in its gravitational potential energy, thereby limiting its ability to be transported to the so-called dam command area (i.e., the area downstream from the dam that can be irrigated with water from the dam's reservoir) by gravity flow. Criteria for multiple-objective reservoir management have been the subject of research in the last 40 years (Cohon & Marks, 1973, 1975; Croley et al., 1979; Yeh, 1982, 1985) and will not be reviewed here. What recent research on the FEW nexus is adding to the analysis of multipurpose reservoir operation is the need for new models of water governance (Box 5) that can define the objectives for optimal reservoir operation. In addition to balancing irrigation and hydropower, dam operation can be redesigned for flow regimes that support existing capture fisheries (Poff et al., 2016).

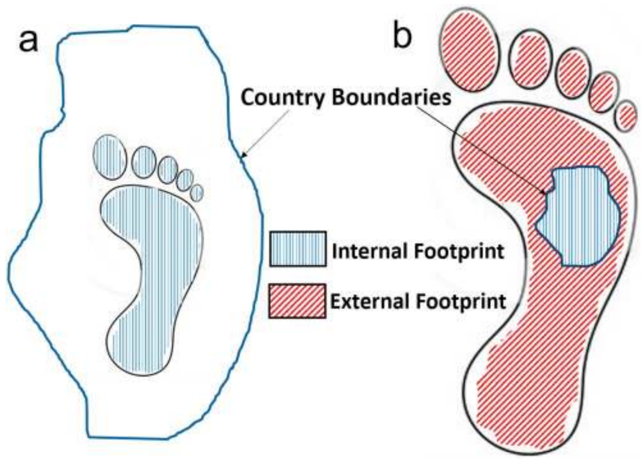

Figure 16. A representation of a country's footprint in conditions of self-sufficiency (a) and trade dependency (b). In the right diagram, there is spillover of the footprint of that country outside its boundaries (or external footprint, shaded in red), whereas in the left diagram of a self-sufficient country (a), the footprint is entirely contained within the country's boundary.

8.3. Fossil Fuel Extraction

As noted in previous sections, the extraction of unconventional oil and natural gas requires water (section 6.1). For example, bitumen is extracted from oil sands in a water-intensive process that can challenge the maintenance of environmental flows even in "water-rich" regions such as Alberta, Canada (Rosa et al., 2017). Shale oil and shale gas are usually extracted using hydraulic fracturing, a water-intensive technology. The required water can be diverted from the agricultural sector toward the more profitable energy sector, thereby leading to the emergence of competition with agriculture. As with the previously described competition for water resources between food production and biofuels, when water management relies on water markets, water is allocated to the sector that can generate higher incomes (e.g., Debaere et al., 2014), which is typically the energy sector.

9. Globalization of Food and Water

With the growth of global trade in agricultural commodities, food, energy, and water systems are now connected across vast distances and in increasingly complex ways (Hoekstra & Chapagain, 2008; Liu et al., 2015; Meyfroidt & Lambin, 2011). International land investments (Rulli et al., 2013) and human migration (e.g., Davis et al., 2013) further contribute to the globalization of land, water, and food (Carr et al., 2013; Lambin & Meyfroidt, 2011; MacDonald, 2013; Porkka et al., 2013; Tuninetti et al., 2017). These processes can be both causes and effects of local food deficits. In fact on the one hand, local food scarcity increases the demand for external (i.e., nonlocal) production, thereby stimulating imports or foreign land acquisitions. On the other hand, reliance on areas with surplus production further sustains population growth in regions with local food deficit (Porkka et al., 2017; Suweis et al., 2013), thereby further increasing the dependence on non-local production. The dynamics of globalization result in a disconnect between consumers and the environment that supports them, which can at least theoretically reduce the sustainable management of agricultural landscapes (e.g., Clapp, 2014, 2015; Cumming et al., 2014). Likewise, agricultural trade acts as a mechanism for the displacement of environmental impacts such as land use change (Meyfroidt et al., 2013; Meyfroidt & Lambin, 2011), N and P pollution (Galloway et al., 2007; O'Bannon et al., 2014; Schipanski & Bennett, 2012; Schipanski & Drinkwater, 2012), and depletion of water resources (e.g., Dalin et al., 2017) toward export-producing nations.

The degree of reliance on these external resources can be effectively pictured through the notion of water footprint (Hoekstra & Chapagain, 2008; see also Box 6) and embodied land. A related concept, the "ecological footprint" is defined in more abstract terms (i.e., not tied to any given place) as the "areas necessary to continuously provide for people's resource supplies and the absorption of their wastes," or more in general the "biological capacity" that is appropriated by a society to meet its needs (Wackernagel et al., 1999). The ecological and water footprints of a given country may fall partly outside its boundaries. In other words, the water and land footprint of each country could have internal and external components (Figure 16). Likewise, the external footprints of other countries may fall within the boundaries of the country in question. This is possible because the globalization dynamics associated with trade and international investments allow for a displacement of land use to other countries (Lambin & Meyfroidt, 2011). Weinzettel et al. (2013) and Kastner et al. (2014) estimate that 24% of the global total land footprint is displaced through international trade. Interestingly, about 25% of this displacement (i.e., 6% of the global total land footprint) is associated with trade from low-income to high-income countries; moreover, the recent increase in the external footprints (i.e., imports) appears to be positively related to income (Weinzettel et al., 2013).

9.1. Global Food Trade

The globalization of food through international trade has more than doubled since the mid-1980s (D'Odorico et al., 2014). A variety of global economic drivers have contributed to this recent growth in global food and agricultural trade, including changes in trade policy, structural changes in the agricultural sector, increased financialization in the food sector, productivity growth, and changing demand (e.g., Anderson, 2010;

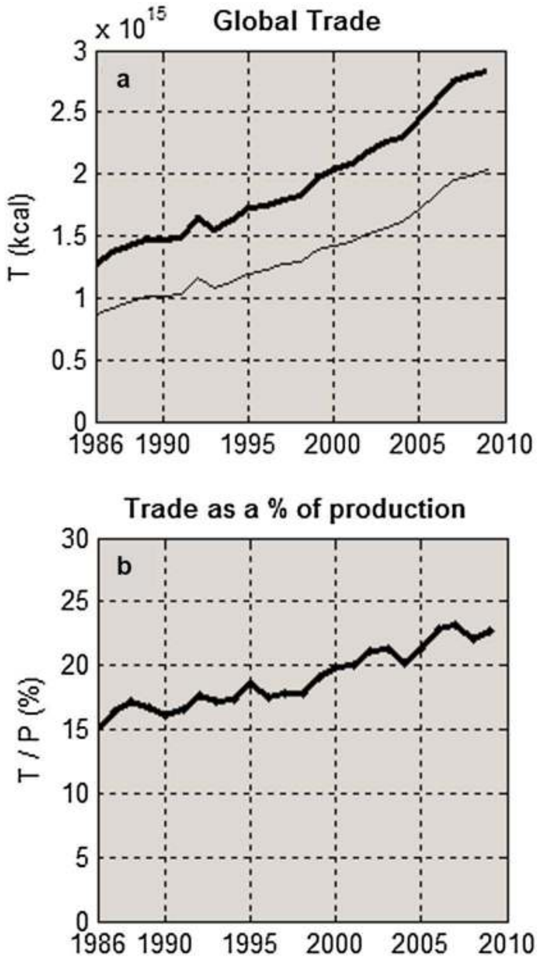

Figure 17. Global trade of food (thin line) and food + feed and other agricultural products (thick line) but excluding secondary food products (a); and share of the global production that is traded (b; from D'Odorico et al., 2014).

Clapp, 2015; Headey, 2008). Trade has consequently increased at a rate that has exceeded the rate of food production, thereby resulting in an increase in the percentage of food production that is traded internationally (Figure 17). The intensification of food trade is observed not only in an increase in the amount of food calories that are imported and exported through existing trade links (Figure 18) but also in the growing number of trade links, which has doubled since the mid-1980s (Carr, D'Odorico, Laio, & Ridolfi, 2012). Although trade can be crucial for food commodities not grown domestically (e.g., Kastner et al., 2014), trade liberalization can also have negative impacts on nutrition and public health, for example, through increased access to unhealthy foods (e.g., Hawkes, 2006; Rayner et al., 2006). At the global scale, there is evidence that food supplies are becoming increasingly homogenous and that the growth of trade in energy-dense foods may be a driving factor (Khoury et al., 2014).

Important changes are taking place in the geography of trade patterns (Figure 18): South America and Southeast Asia have become increasingly integrated in the global food trade, particularly as a result of rising foreign demand for commodity crops such as soybean and palm oil, respectively (Henders et al., 2015; MacDonald et al., 2015). In particular, China has become a major importer of soybeans with the rise of extremely large trade flows from Brazil and Argentina since the year 2000 (e.g., Dalin et al., 2012; Figure 18). Overall, the world has become much more interconnected (or globalized), though the African continent has remained comparatively less integrated in the global network of food trade (e.g., Carr et al., 2013).

One of the fastest growing components of global agricultural trade has been trade in livestock feed (Lassaletta et al., 2014), which has tripled since the mid-1980s (Figure 19) and accounts for roughly 7.6% of the global land area used for livestock production (Davis, Yu, Herrero, et al., 2015). Thus, trade establishes important teleconnections between consumers and the land and water resources that sustain them (Liu et al., 2015).

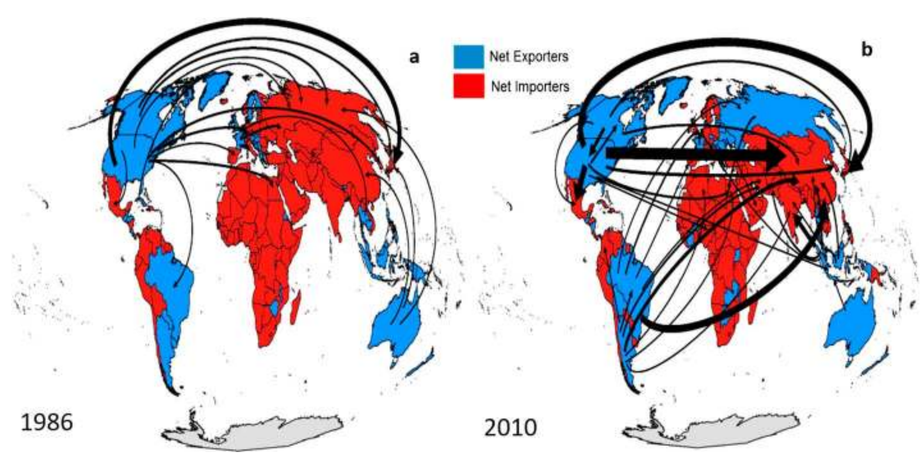

Figure 18. Global patterns of food trade in 1986 (a) and 2010 (b) (from D'Odorico et al., 2014). There has been a major shift in the geographic structure of global food trade in the 2000s, particularly with the growth of exports from South America and the growth of imports to China.

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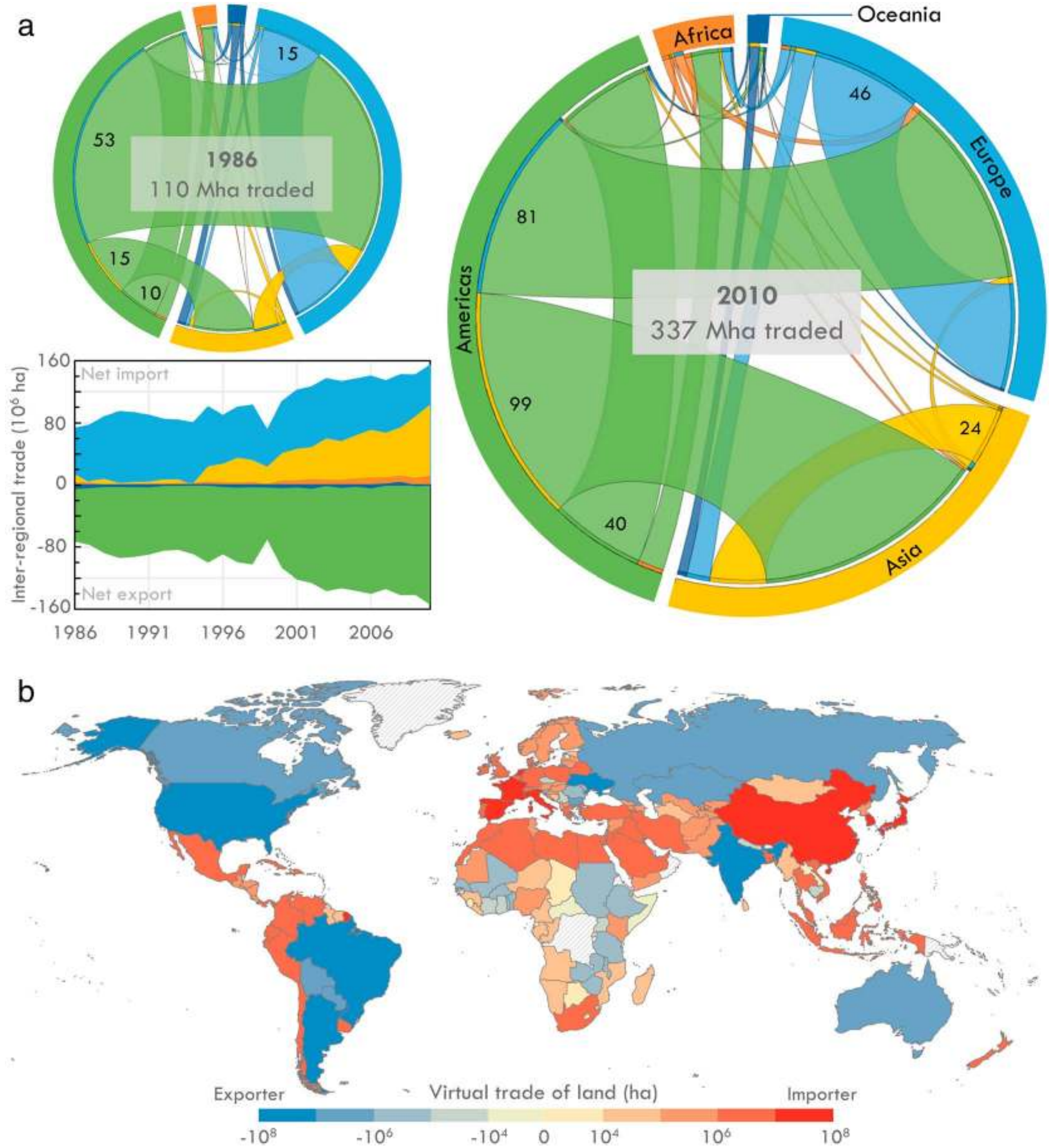

Figure 19. Virtual land trade associated with imports and exports of feed (Davis, Yu, Herrero, et al., 2015). Circles show interregional flows of virtual land via feed trade. The color of each band corresponds to the exporting region, while the numbers within major bands represent the magnitude of the virtual flow of land (in Mha) along the link. Circle areas are scaled to the total virtual land traded in 1986 and 2010. Inset plot shows the steady transition of virtual land's destination, from almost entirely to Europe in 1986 to roughly equals parts Europe and Asia in 2010. Map shows the net virtual trade of land for feed by country (year 2000–2009 average).

9.1.1. Implications of Food Trade for Land and Water Resources

The growing reliance on food trade has had differential effects on natural systems within producer and consumer countries. Food trade is associated with a virtual transfer of water (Allan, 1998), including green and blue water (Konar et al., 2012), and land (Kastner et al., 2014) that are embodied in the production of traded commodities. Most of the new agricultural land use at the global scale has been linked to the increased production of export-oriented commodities (Kastner et al., 2014), particularly the growing foreign demand for oilseeds and corresponding increased production, especially in tropical countries (Byerlee et al., 2016). The growth of global trade therefore has particularly important implications for understanding land use change across countries (Henders et al., 2015; Meyfroidt & Lambin, 2011) and its relation to environmental impacts, such as biodiversity loss (Chaudary & Kastner, 2016; Kastner et al., 2011; Lenzen et al., 2012). Importantly, the growth of food and feed trade has driven large changes in fertilizer use that has altered the biogeochemical

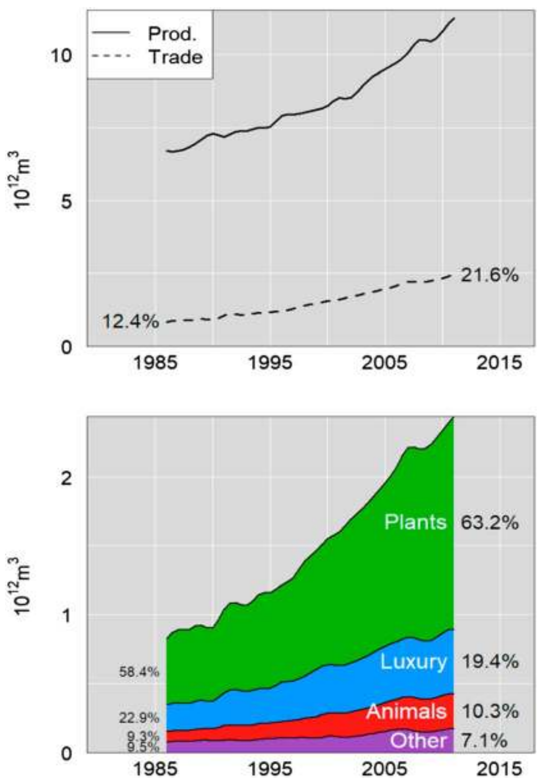

Figure 20. Virtual water trade associated with (top) food commodities and (bottom) agricultural commodities (after Carr, D'Odorico, Laio, & Ridolfi, 2012).

cycles of N (Galloway et al., 2007; Lassaletta et al., 2014) and P (Schipanski & Bennett, 2012) at different scales. The case of P is particularly unique because of the importance of trade in the physical transfer of P across national borders, given the relatively minor atmospheric component in the global P cycle (Grote et al., 2005; Smil, 2000): relatively large quantities of P are traded in phosphate rock (a nonrenewable and geopolitically concentrated resource) and manufactured fertilizers, as well as in agricultural commodities (Cordell & White, 2014; MacDonald et al., 2012). Policies of the EU aimed at a reduction in fertilizer use in the EU has resulted in an increase in agricultural imports, with the effect of increasing P pollution in the exporting countries (Nesme et al., 2016). The impacts of trade in terms of water pollution (termed "gray" water footprints; O'Bannon et al., 2014) and groundwater depletion (Dalin et al., 2017) are increasingly recognized.

Because exporting countries can often produce food with relatively high resource use efficiencies, international food trade has potentially facilitated resource "savings" in a global sense for certain resources (Chapagain et al., 2006; Kastner et al., 2014; Konar et al., 2013; Oki & Kanae, 2004; Schipanski & Bennett, 2012). However, these potential resource savings may be offset by broader effects of trade on other environmental issues, including biodiversity, pollution, and GHG emissions (Chaudhary & Kastner, 2016; Dalin & Rodríguez-Iturbe, 2016). In addition, the increasing importance of international food trade has also served to separate consumer choices from the environmental impacts of production (Clapp, 2015; Dalin et al., 2017; DeFries et al., 2010; Lenzen et al., 2012) and allowed high-income countries to spare land while displacing pressure on ecosystems to the developing world (Meyfroidt & Lambin, 2011; Weinzettel et al., 2013).

9.1.2. Virtual Water Trade

The study of trade from the perspective of water used for food production is very instructive in that it allows for an analysis of dependencies on local and global water resources. At the regional scale, water resources may be insufficient to meet the food demand of the local population. Already, some regions of the world (e.g., the Middle East) experience chronic water scarcity: the population exceeds the limits imposed by the availability of freshwater resources for food production (e.g., Allan, 1998). When a society has limited access to a vital resource such as water, it can either decide to use it more efficiently by reducing waste or other losses, and/or try to import water from somewhere else. However, the amounts of water required for food production are enormous and not easily transported. Instead of transferring water, societies trade food commodities or acquire large tracts of agricultural land to produce food in other regions of the world. Thus, food trade and large-scale land acquisitions (LSLAs) are associated with a virtual transport of the water used for crop production (Hoekstra & Chapagain, 2008). The notion of "virtual water" was developed (Allan, 1998) to stress that this water is not physically present in commodities; it is the water cost of their production, which is similar to the concept of the water footprint (see Box 6). Thus, food trade corresponds to an exchange of virtual water. Recent studies have shown that virtual water trade has more than doubled since the mid-1980s (Figure 20; Carr et al., 2013). Globally, about 24% of the water used for food production is traded (Table 1). Because about 10% of precipitation over land masses or 16% of terrestrial evapotranspiration is used by agro-ecosystems (Table 1), virtual water trade accounts for about 2.4% of precipitation over land and 3.8% of terrestrial evapotranspiration, a nontrivial amount of water. Recent studies have shown that virtual water trade accounts for 11% of the global depletion of groundwater. In other words, 11% of the nonrenewable use of groundwater resources worldwide is due to exports, particularly from Pakistan, India, and the United States (Dalin et al., 2017).

Overall, food security strongly depends on virtual water transfers (Figures 20 and 21; Suweis et al., 2013). Through the intensification of trade, some regions have become strongly dependent on food produced with water resources they do not control because they are located elsewhere (Chapagain & Hoekstra, 2008; Konar et al., 2011). Such a globalization of water resources has been escalating since the 1980s (Carr, D'Odorico,

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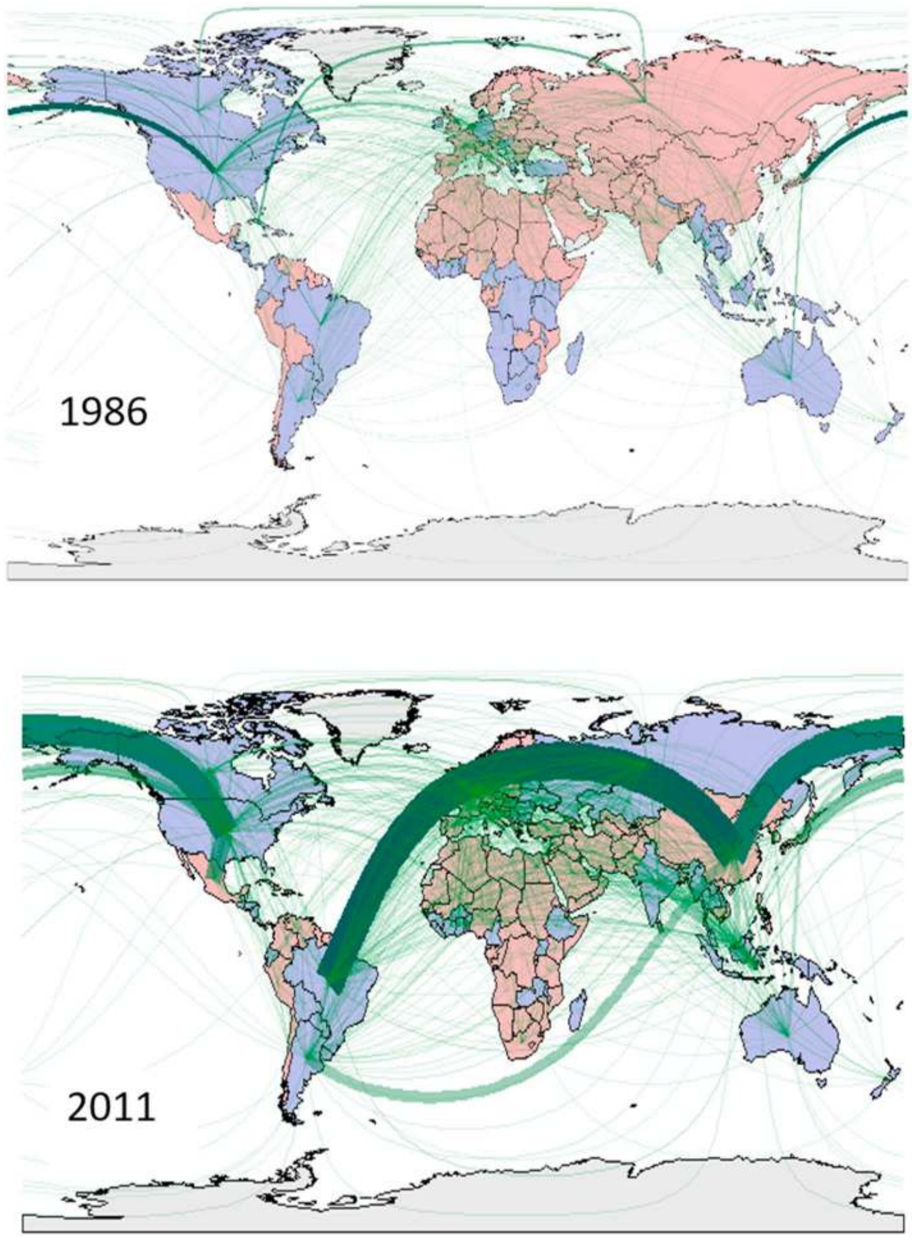

Figure 21. Global patterns of virtual water trade. Countries in pink are net importers, and countries in purple are net importers (after Carr & D'Odorico, 2017).

Laio, & Ridolfi, 2012; Carr et al., 2013; Dalin et al., 2012), and its implications on food and water security have just recently started to be appreciated (see section 10.2).

9.1.3. Virtues and Vices of Virtual Water Trade

Recent work has stressed the pros and cons of trade. Through virtual water trade, local food demand can be met even in water-scarce regions without engendering famine, conflict, or mass migration (Allan, 1998, 2001); this often occurs at the expense of societal resilience and environmental stewardship while generating environmental externalities (Carr et al., 2013; D'Odorico et al., 2010; Suweis et al., 2013). The possible implications of the globalization of water for food and energy security remain overall poorly understood, and it is unclear whether trade will generally act as a buffer against, or an intensifier of, vulnerability for nations relying on food imports. On one hand, trade can allow countries to maintain populations greater than would be supported by local natural resources (e.g., Suweis et al., 2013) and can act as a stabilizer when local production conditions are variable. On the other hand, this can leave importing countries more exposed to economic

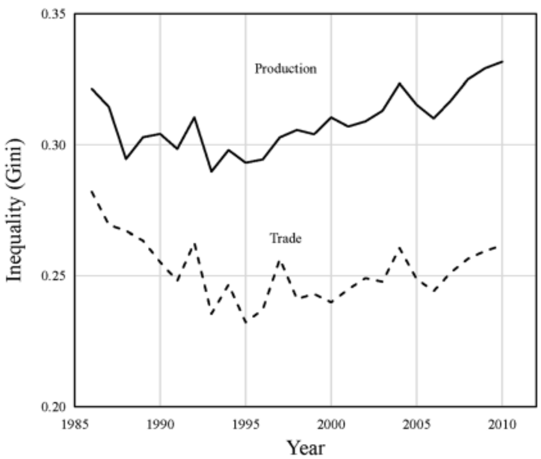

Figure 22. Effect of the redistribution of virtual water through trade on inequality in access to water (including virtual water). Solid line, only water for domestic production; dashed line, water for domestic production + virtual water trade (after Carr et al., 2015).

and/or environmental shocks that occur beyond their borders and beyond their direct control (e.g., D'Odorico et al., 2010; Oki et al., 2017; Puma et al., 2015; Suweis et al., 2015). In some developing countries, imports of underpriced or subsidized agricultural products may threaten local subsistence farmers and disrupt their systems of agricultural production and livelihoods, with the effect of increasing trade dependency (Hoekstra, 2013). In the wake of the 2007/2008 global food crisis, it became clear that trade-dependent resource-scarce countries in particular continue to have a limited capacity for absorbing shocks to the food system (e.g., Fader et al., 2013; Suweis et al., 2013; see section 10.2). At the same time, it has been shown (section 9.1.4) that trade may partly reduce inequalities and injustice in the access to water for food production (Carr et al., 2015; Seekell et al., 2011).

9.1.4. Inequality and Injustice in Access to Freshwater Resources

Populations and natural resources (e.g., water, minerals, and arable land) are unequally distributed across the globe (Carr, D'Odorico, Laio, Ridolfi, & Seekell, 2012; Carr et al., 2015; Kummu & Varis, 2011; Seekell et al., 2011). Trade across all spatial scales provides a mechanism by which actual and/or virtual resources are redistributed, thus changing inequality patterns with regard to any given resource. Note that, as resource and population distributions vary across spatial scales, inequality also occurs across local, subnational, and international scales. Geographic conditions and climate dictate the natural distribution and local access to water resources, with potential a virtual transfer and redistribution of those water resources via trade of industrial and agricultural products (Allan, 1998). This unequal distribution and redistribution of resources is not necessarily unjust, and while trade and/or human migration affects inequality in the distribution of water resources (Carr, D'Odorico, Laio, Ridolfi, & Seekell, 2012; MacDonald et al., 2015; Reuveny, 2007), unless they affect the fulfillment of human rights, they may not necessarily impact injustice (Carr et al., 2015). However, the distribution and redistribution of livelihood is dependent on natural resources (water and food) and populations and thus inherently contains ethical considerations. The UN (Article 11, General Comment 12, and General Comment 15 of the International Covenant on Economic, Social and Cultural Rights) acknowledges that water for domestic use and agriculture is a human right (see section 5.4). This human right to water can be related to the distribution and redistribution of water resources and populations, thus providing some framework by which to assess justice or injustice in water use for food, at least at a national scale (Carr et al., 2015, 2016). Within a nation, inequalities are related to poverty, conflict, and subnational distribution networks (Barrett, 2010; Misselhorn, 2005). Even cultural food preference and lifestyle can play a role (Barrett, 2010; Prentice & Jebb, 1995). Thus, water use for food is linked to human dietary requirements and sources of staple food commodities (proteins, fats, and calories), which typically are impacted by social, cultural, and political influences (Gerten et al., 2011).

Various metrics are available to measure inequality, such as entropy and indicators of variability (e.g., the coefficient of variation), but the Gini coefficient is commonly used (Gini, 1936). The Gini coefficient ranges between 0 and 1 and measures the extent to which the current distribution of resources differs from an egalitarian distribution (e.g., with 10% of the global population having access to 10% of the resources). Inequality in water use for food production alone has increased over time; however, subsequent trade of food products overall acts to reduce inequality (Figure 22). Carr et al. (2015) note that roughly three quarters of the virtual water flows are among water-rich nations and do not reduce inequality. Interestingly, some nations trade in such a manner that it increases inequality and reduces per capita water use relative to well being and malnourishment thresholds (Carr et al., 2015). Although the impact of individual trade links on inequality can be determined (Carr et al., 2016), other changes, such as reductions in food waste (Kummu et al., 2012) or shifts to more water efficient sources of dietary proteins (Gephart et al., 2014; Jalava et al., 2014), can play a large role in ameliorating the impact of inequalities in water use for food.

9.1.5. Drivers of Virtual Water Trade

Many drivers controlling the flow of virtual water have been explored, from GDP and rainfall on arable land (Suweis et al., 2011) to geographical distances (Tamea et al., 2013). By exploring the impact of multiple factors, such as embedded water, population, GDP, geographical distance, arable land, and dietary demand, the main drivers of virtual water flow appear to be GDP, population, and geographical distance with a nonnegligible effect of exporter production (Tamea et al., 2014). Subsequent work has leveraged this information to explore both link and flux predictions, population, geographical distance, and GDP strongly controlling link activation and the fluxes along those links (Tuninetti et al., 2016). Econometric analyses have been used to investigate the extent to which water is a source of comparative advantage (Debaere et al., 2014), in addition to the classic factors (i.e., labor, capital, and land, Wichelns, 2001, 2004) typically considered by international trade theories. Virtual water was found to be a moderate source of comparative advantage with water-rich countries exporting more water-intensive products (Debaere et al., 2014).

9.2. Evidence of Possible Water Limitations on Population Growth and the Effect of Trade

Whether the planet Earth will be able to feed the growing human population has been the focus of an ongoing debate lasting more than 200 years (see Box 1). Water availability is expected to become increasingly crucial to food security and human welfare under the increasing demographic pressure (e.g., Falkenmark & Rockström, 2004; Gleick, 2003). Projections of population growth coupled with predictions of water availability and agricultural productivity have highlighted the manner in which humankind might run out of water for food production in the next few decades under a variety of climate change and land use scenarios (e.g., Foley et al., 2011; Rosegrant et al., 2001). Thus, new strategies are urgently needed to avoid new severe global water and food crises (see section 11).

Current demographic theories (Box 1) rarely consider the scarcity of resources, such as water, as a limiting factor for population growth (Lee, 2011). However, in some regions of the world the local limits to growth have already been exceeded (Allan & Allan, 2002). Several countries already consume more food than allowed by locally available freshwater resources. This is possible because the water-poor countries rely on the import of food and virtual water from other nations. Thus, the limits to population growth (or carrying capacity) depend on the local water resources and virtual water/food trade. The temporal dynamics of population, local carrying capacity, and posttrade carrying capacity can be used to investigate country-specific changes in trade dependency, self-sufficiency, and the extent to which local self-insufficiencies can be successfully addressed by trade (Porkka et al., 2017). Future projections of the increasing demand for water resources under climate change and population growth scenarios (Ercin & Hoekstra, 2014) require a better understanding of how food production, human diets, and international virtual water trade are expected to change in the decades to come. Recent studies have provided some preliminary insights into future trajectories of water demand and international virtual water trade (Ercin & Hoekstra, 2014; Konar, Reimer, et al., 2016a; Sartori et al., 2017; Zhou et al., 2016).

For countries importing food, trade has the effect of increasing the carrying capacity (i.e., the maximum population that can be supported by the available resources). In this case, the long-term trajectory of population growth needs to account for such an increase in carrying capacity, as shown by Suweis et al. (2013) with a simple logistic model of population dynamics (Figure 23). In other words, the populations of importing countries are relying on virtual water imports for their long-term trajectory of demographic growth (Figure 23). The opposite is not true, however, for countries exporting food. In fact, there is no evidence of their carrying capacity being reduced because of trade (Suweis et al., 2013). An analysis based on demographic, crop production, and trade data has shown that in exporting countries the long-term trajectory of population growth tends to converge to a carrying capacity calculated on the basis of local water resources without accounting for the fact that part of those resources are presently contributing to virtual water exports (Suweis et al., 2013). This finding means that importers and exporters are counting for their long-term growth on the same pool of virtual water resources (Suweis et al., 2013). This unbalanced situation could eventually lead to export reduction, which will likely impede the import-dependent countries from meeting their water (and food) demands. Some major exporting countries have already reduced their exports in response to spiking food prices during the food crises of 2007–2008 and 2011 (see section 10.1.1 and Fader et al., 2013). These results highlight a global water unbalance and point out the long-term unsustainability of global food and virtual water trade. Unless new freshwater resources become available or investments in a more water efficient agriculture are made, trade-dependent populations will experience major water stress conditions (Suweis et al., 2013).

9.3. International Investments in Agricultural Land and Water Resources

The globalization of food emerges from international investments, particularly the acquisition of agricultural land (Rulli & D'Odorico, 2014). In recent years (2004 to present) large scale land acquisitions (LSLASs) have escalated, especially in the developing world (Anseeuw et al., 2012; Cotula, 2013a, 2013b; International

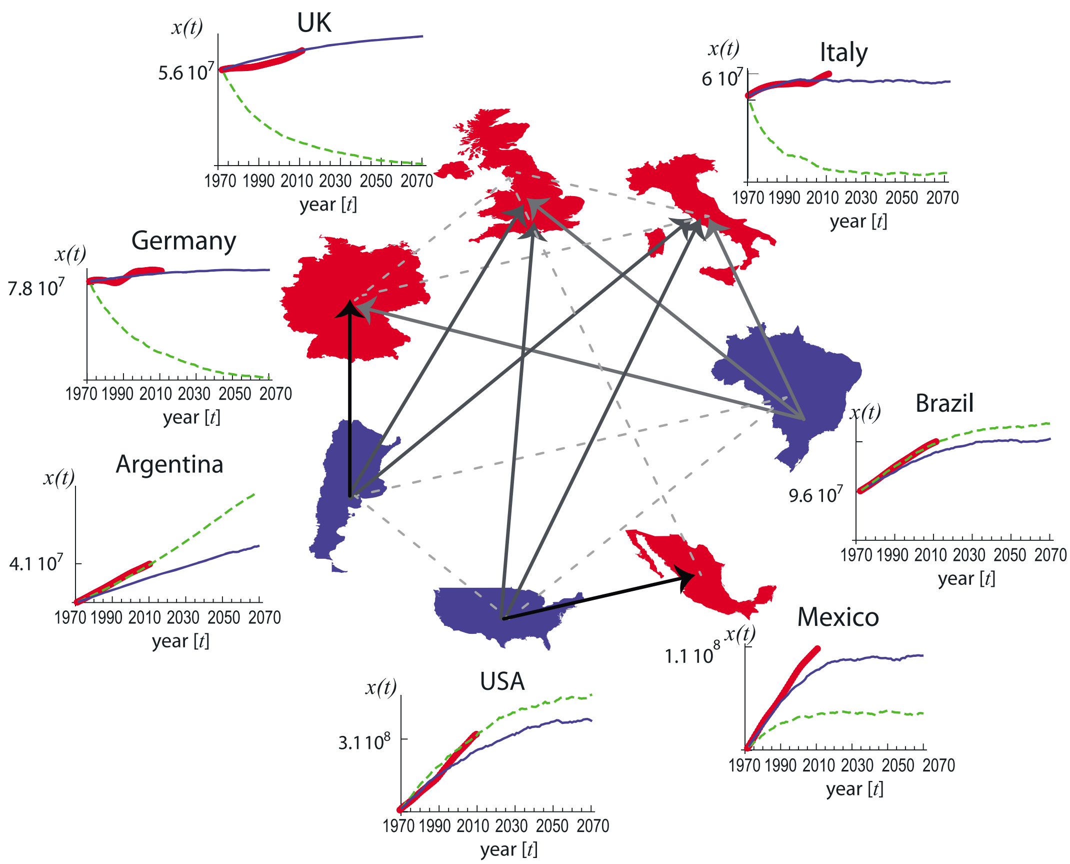

Figure 23. Population dynamics in net exporter (in blue) and net importer/trade-dependent countries. The blue lines are demographic growth trajectories of a logistic model with posttrade carrying capacity (i.e., after having accounted for trade), and the green lines are trajectory with local carrying capacity (i.e., without accounting for trade). The red lines are data points from demographic records. In trade-dependent countries demographic growth follows the posttrade carrying capacity (i.e., relies on trade), and in exporter countries, it follows the local carrying capacity (i.e., it does not account for exports; from Suweis et al., 2013).

Land Coalition, 2011). The number of new foreign land acquisitions has radically increased since 2008; estimates of acquisitions exceed 40 million hectares of arable land globally (Anseeuw et al., 2012; Nolte et al., 2016). Investors include foreign agribusiness firms, domestic corporations, mixed domestic-international ventures, and foreign governments, as well as retirement funds (Cotula, 2013a, 2013b; Kugelman & Levenstein, 2013; Robertson & Pinstrup-Andersen, 2010). The investors acquire land for agriculture, forestry, mining, and conservation (Fairhead et al., 2012; Klare, 2012; Matondi & Mutopo, 2011) in the form of purchases, leases, government concessions, licenses, or permits. Agricultural land is used for staple and cash crops, and biofuels. In most cases, however, the land is acquired but not put under any productive use (e.g., Kugelman & Levenstein, 2013).

LSLAs have been at the center of a heated debate: Supporters of LSLAs maintain that foreign direct investments bring about opportunities for the economic development of target countries (e.g., employment, infrastructure, technical knowledge, and access to markets) with good profits for the investors' businesses (e.g., Chakrabarti & Da Silva, 2012). There are, however, serious concerns about the impact that this appropriation of land and land-based resources could have on rural livelihoods, economic development, food security, and access to water in local communities affected by land acquisitions (Borras Jr & Franco, 2010; De Schutter, 2011; Rulli et al., 2013; Von Braun & Meinzen-Dick, 2009).

Promoters of LSLAs may argue that the land was previously unused "virgin land," dismissing the important role played by that land for the provision of a number of ecosystem services, such as fuelwood, timber, bush meat, livestock grazing, and wildlife habitat (D'Odorico, Rulli, et al., 2017). Local communities lose access to the land and its products, thereby engendering social tension, conflict, migrations, and forced evictions (Adnan, 2013; Feldman & Geisler, 2012; Siciliano, 2014).

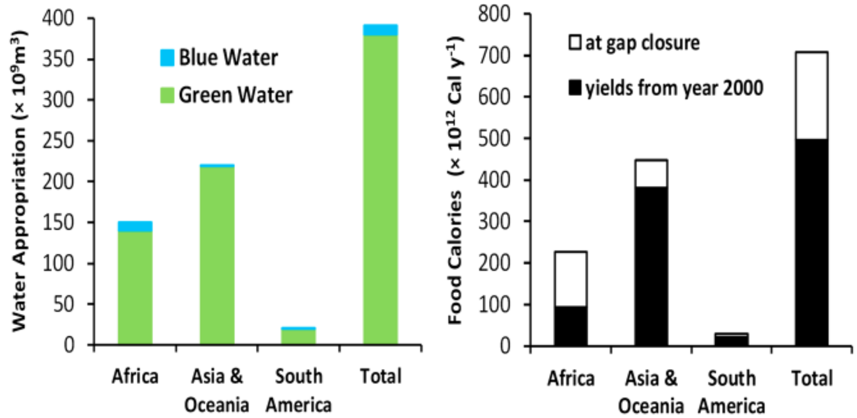

Figure 24. Water and food appropriation associated with land acquisitions (from D'Odorico, Rulli, et al., 2017).

9.3.1. Implications for Food Security, Rural Livelihood, and the Environment

The implications for food security are important, particularly if the land was previously used for agriculture by the local populations. In fact, with some exceptions, the crops produced on the acquired land are typically exported and sold on the global market (e.g., Lisk, 2013). It has been estimated that the food crops that land investors plan to cultivate on the acquired land could feed about 300–550 million people, which corresponds to about 30–50% of the undernourished global population (Figure 24). These numbers are concerning because most countries targeted by land investors are affected by undernourishment. This phenomenon establishes long-distance teleconnections and interdependencies between crop production areas and global demand (Rulli & D'Odorico, 2014). On the receiving end, the globalization of food markets and the vulnerability and exposure to food crises and climatic shocks (Marchand et al., 2016; Seekell et al., 2017) make transnational investments in agricultural land a strategic food security priority in order to gain resilience through diversification of the agricultural regions that importer and investor countries rely on. Interestingly, most target countries are endowed with productive agricultural land that in some regions require relatively small amounts of irrigation water (Figure 24) and are not affected by aridification under climate change scenarios (Chiarelli et al., 2016).

As small-scale farming is the most prominent system of food production globally, LSLAs and expansion of commercial agricultural models are producing a global agrarian transformation that has radical societal implications in the target regions. As noted in section 11.1, there is evidence that most of the world's rural populations depend directly on natural resources and local land for self-subsistence (Godfray et al., 2010; International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD), 2009; Wily, 2011). Moreover, the major share of land small-scale farmers rely on is governed by traditional, customary, and indigenous systems of common property. In sub-Saharan Africa, for example, it has been calculated that 70% of this land can be categorized as customary common property (Deininger, 2003; Wily, 2011).Transnational LSLAs impact the property access and use of land by traditional users with evidence that traditional systems of common property are most affected (Dell'Angelo, D'Odorico, Rulli, & Marchand, 2017). The societal implications of this agrarian transformation include a variety of critical problems (D'Odorico, Rulli, et al., 2017), such as dispossession of traditional users and systems of production (D'Odorico & Rulli, 2014; De Schutter, 2011), evictions and forced migrations (Adnan, 2013; Feldman & Geisler, 2012; Siciliano, 2014), ethical concerns related to violations of human and land tenure rights (Anseeuw et al., 2012; Toft, 2012) with particularly negative impacts on women (Behrman et al., 2012; White, 2012), rise in social conflicts and dynamics of coercion (Dell'Angelo, D'Odorico, Rulli, & Marchand, 2017), and multidimensional impacts on rural livelihoods in developing countries (Davis et al., 2014a; Oberlack et al., 2016).Through LSLAs, land can be put under productive use to the benefit of investors and local communities, arguably (De Schutter, 2011), because of "trickle down" effects on employment, and access to modern technology and markets (e.g., Chakrabarti & Da Silva, 2012). An often overlooked impact, however, is the land degradation and land use change associated with large-scale land investors (e.g., D'Odorico, Rulli, et al., 2017). In fact, forests and savannas may be cleared to accommodate new mines or farmlands (D'Odorico, Rulli, et al., 2017). Several studies have found that in Indonesia and Cambodia LSLAs are a preferential mechanism for deforestation, with rates of forest loss exceeding those in similar adjacent areas outside land concessions (Carlson et al., 2012; Davis, Yu, Rulli, et al., 2015). In other regions of the world, the effect of land acquisitions on forest loss can be indirect. For instance, for Brazil, Hermele (2014) reports that acquired land often replaces pastures with cropland, with herders and ranchers then encroaching on forested areas to find new grounds for livestock grazing.

9.3.2. Water Appropriation and Water Grabbing

The recent escalation in international investments in land has substantial hydrological implications (Rulli et al., 2013). Among the studies on LSLAs and land grabbing, an alternative hypothesis has developed: what if the main driver of the contemporary global land rush were the need for water rather than for land? (Allan et al., 2012; Franco & Borras Jr, 2013; GRAIN, 2012; Mehta et al., 2012; Skinner & Cotula, 2011; Woodhouse, 2012a, 2012b). Dell'Angelo et al. (2018) have described a "global water grabbing syndrome" to take into account the increasing dynamics of freshwater appropriation occurring as a result of globalization. A fundamental mechanism of transnational water appropriation is associated with large-scale land investments in agriculture. Studying the issue of land acquisitions through hydrological analytical tools provides insights into contemporary hydropolitical trends. Tools such as water footprints and virtual water transfer applied to the study of transnational land investments show that globalization dynamics strongly affect the water resources of developing countries (Breu et al., 2016; Rulli et al., 2013; Rulli & D'Odorico, 2013). Rulli and D'Odorico (2013) estimate that LSLAs account for the appropriation of about 0.4×10^{12} m^3 (Figure 24).

The global assessment of appropriation of water through large-scale acquisition, which was defined as global water grabbing, quantified the amount of water appropriated for crop production from acquired land and evaluated potential effects on food security in the countries affected by these investments (Rulli et al., 2013; Rulli & D'Odorico, 2014). The term "water grabbing" has also been used to identify the direct and immediate physical appropriation and diversion of local water resources. Mehta et al. (2012:197) define water grabbing as "a situation where powerful actors are able to take control of, or reallocate for their own benefits, water resources already used by local communities or feeding aquatic ecosystems on which their livelihoods are based." This general definition can be applied to a variety of different socioenvironmental and political processes of water appropriation besides LSLAs (Torres, 2012), for example, mining (Sosa & Zwarteveen, 2012), water withdrawals for hydropower (Islar, 2012; Matthews, 2012), and other forms of diversion of water for industrial uses (e.g., for coal plant refrigeration; Wagle et al., 2012).

9.3.3. Socioenvironmental Impacts of Water Grabbing

Several negative social and environmental consequences of water grabbing dynamics have been discussed in the literature. Environmental problems associated with water grabbing range from biodiversity loss, as in hydropower development in the Mekong River basin (Matthews, 2012), to issues of direct contamination of drinkable water as a result of intensive agriculture in Kenya (Arduino et al., 2012). From a social perspective, issues such as loss of agricultural self-subsistence capacity, dispossession, marginalization of indigenous communities, forced migrations, impoverishment, and disappearance of cultural practices have also been investigated (Mehta et al., 2012). Other studies specifically address the direct impacts of water grabbing on problems associated with increasing water competition, reduction of water availability, and increased limitations to water access in rural communities (Bossio et al., 2012; Duvail et al., 2012; Wagle et al., 2012). Nevertheless, these affected users and groups are not passive; in many instances they are capable of collective re-action and self-organization. Rodríguez-Labajos and Martínez-Alier (2015) describing a conceptual map and a synthesis of water conflicts globally, illustrate how in many cases social movements born in conflictive contexts developed innovative propositions and modalities for alternative water governance principles, values, and approaches.

10. Resilience in the FEW Nexus

A key issue at the origin of the FEW nexus concept was the need to maintain food, energy, and water security in the face of competition among components of these systems and different global-change pressures (Bazilian et al., 2011; Bigas, 2013; Bogardi et al., 2012). Resilience in the FEW nexus therefore entails the ability of interacting food, energy, and water systems to cope with different pressures in order to maintain food, energy, and water security (Figure 1). This section focuses particularly on the importance of food security. The definition of food security adopted by the FAO specifies that food availability, access, and adequacy requirements (see Box 1) need to be met "at all times": Human beings cannot remain without food or with unsafe/inadequate food even for short periods of time. Although the demand for food products would be expected to be relatively inelastic (in the sense that the total food demand is inelastic, though the composition of food consumption may change, e.g., Adreyeva et al., 2010), the supply undergoes fluctuations as a result of natural and anthropogenic factors (e.g., Ben-Ari & Makowski, 2014; Calderini & Slafer, 1998; Carter et al., 2011). Food systems need to be resilient to a variety of shocks operating at different scales that could affect either food production or availability, such as extreme weather, pest outbreaks, market crises, failing institutions, and political conflict (e.g., Misselhorn et al., 2012; Schipanski et al., 2016). These pressures can ricochet through food trade systems, including export restrictions imposed by key producing countries to address concerns over domestic shortfalls in production (Headey, 2011; Puma et al., 2015). Systems of production therefore need to be robust and either recover after these shocks or adapt to them to be able to deliver food in sufficient amounts with nutritionally adequate quality and affordable prices (Timmer, 2000).

The study of the resilience of food systems should involve the environmental, institutional, economic, and political dimensions of food security and examine how they can affect agricultural production, food trade, and price dynamics to determine the availability, accessibility, and adequacy requirements of food security (Box 1). Such an approach has been attempted by some partial equilibrium trade models (e.g., the International Model for Policy Analysis of Agricultural Commodities and Trade by the IFPRI) developed to support policymakers in reducing poverty and hunger (e.g., Godfray et al., 2016). Other models have been developed to investigate the short-term response to shocks (e.g., Puma et al., 2015; Tamea et al., 2016; D'Amour et al., 2016; Gephart, Rovenskaya, et al., 2016; Marchand et al., 2016). These models do not invoke equilibrium conditions, which could be hard to attain in the short-term response to an abrupt production shock. Rather, they rely on a simple set of rules (conservation of mass, meeting domestic demand before addressing importers' needs, and reducing exports before increasing imports) to show the spread of a perturbation through the global system of production and trade (Marchand et al., 2016). Other approaches invoke the general resilience theory (Fraser et al., 2015; Walker & Salt, 2006, 2012) to evaluate the effect of a variety of factors that are known to affect resilience in socioenvironmental systems, such as reserves or other types of redundancy, diversity (particularly response diversity and diversification of food sources), variability, openness, connectivity, and modularity in trade networks, social capital (e.g., trust, leadership, information sharing), and adaptive governance. To date, only some of these factors have been investigated in the context of food security because the multiscale nature of the problem and difficulty in quantifying some aspects of the food system present a tremendous challenge.

10.1. Redundancy and Reserves

In classic resilience theory, a system that is redundant is more resilient because in case of shocks (e.g., a drop in production or reduced access to food markets) other resources are still available to meet everyone's food needs at all times.

10.1.1. Excess in Production

A classic example of redundancy is the existence of an excess of production in various regions around the world. In case of shock, it is possible to meet the local demand by importing food from those regions. The intensification of trade and the consequent increase in trade dependency on a regular basis (i.e., not only in conditions of crisis) has reduced redundancies, thereby eroding societal resilience (D'Odorico et al., 2010). Thus, in an interconnected world, the dependence on international trade has increased while the resilience of the food system has decreased to the point that local deficits in crop production have led to global food crises. Global food crises were observed in 2008 and 2011 for the first time after decades of abundance. In those years, crop failure induced by extreme environmental conditions in major food producing regions of the world led to an increase in crop prices (e.g., Barrett, 2013), an effect likely amplified by human factors, such as commodity speculation and fear. The rising food prices strongly affected access to food by the poor (e.g., Brown et al., 2012). To contain such a price escalation, some major exporting countries issued export bans that left import-dependent countries in a state of food insecurity (Brown et al., 2012; Fader et al., 2013). Thus, the globalization of food through trade and the consequent intensification of trade dependency may reduce the resilience of the food system because markets could fail for economic (i.e., unaffordable food prices) and political (e.g., export bans) reasons.

10.1.2. Biophysical Redundancies

In the longer run other redundancy factors could contribute to resilience. For instance, the presence of untapped resources, such as land and freshwater, would allow for an increase in crop production during a period of prolonged crisis, assuming that the institutions are well equipped to facilitate adaptation in the agricultural sector. Thus, the presence of underperforming agricultural land with relatively big yield gaps, the availability of unutilized freshwater resources to close those gaps, and the possibility of sustainably expanding the cultivated land are all examples of biophysical redundancies that could be used in the mid-term response to shocks in the food system. In other words, biophysical redundancy accounts for unused biotic and abiotic environmental resources and represents a form of "stand-by redundancy," whereby some spare resources are idle and will be taken into the production in case of failure in other parts of the food system. It has been estimated that the biophysical redundancy of 102 out of the 155 countries included in a recent study (Fader et al., 2016) has decreased in the last two decades. In 75 of these countries, the biophysical redundancy is not sufficient to feed 50% of their population that, collectively, accounts for 4.8 billion people (i.e., 70% of the global population; Fader et al., 2016). The notion of biophysical redundancy has some clear limitations because some of the idle or unused resources play an important environmental role for the provision of habitat for pollinators and other species, water purification, and other ecosystem services that are crucial to agriculture and human well being. As noted in section 11, agricultural expansion often comes at huge environmental cost in terms of land use change, habitat loss, carbon emissions, and species extinction. Thus, yield gap closure (also included in the notion of biophysical redundancy) appears to be a better response to shocks in the system than agricultural expansion. However, both putting additional land under the plow and closing the yield gap are measures that can occur only in the middle to long term and are not quick responses to crises; both measures require capital, technology, and knowledge that are not equally distributed among countries.

10.1.3. Crop Diversity

Redundancy can be realized through crop diversity. The ecological literature has stressed how a highly diverse ecosystem can be highly resilient because the ecosystem is likely to include more species that perform the same ecosystem functions but are differently sensitive to environmental conditions (response diversity). Thus, when a species is stressed, others would be able perform the ecosystem function (Walker et al., 2006). Known as insurance hypothesis (Naeem & Li, 1977), this idea strongly inspired the Millennium Ecosystem Assessment (2005) and has been extended to agroecosystems using crop diversity indicators (Seekell et al., 2017).

10.1.4. Food Reserves

The most obvious form of redundancy is represented by food stocks, which have been used to mitigate the effect of crop failure and famine since biblical times. These reserves are accumulated in years of plenty and used in years of scarcity, thereby making the food system more resilient (Adger, 2006; Fraser et al., 2015). Despite this very intuitive understanding of the dynamics of food stocks and of the role they play in the national and global food security, these reserves can be difficult to manage because of technical problems related to storage and preservation and because of their effects on supplies and prices (Lilliston & Ranallo, 2012; Von Braun, 2007). Food stocks can be established at the farm, national, or regional scale and managed with different goals, including food security (World Bank, 2012), price stabilization (Wiggins & Keats, 2009, 2010; Wright, 2011; Wright & Cafiero, 2011), food aid, and financial speculations (i.e., buy grain when it is cheap and sell it when prices skyrocket; Von Braun, 2007). Recent studies (Laio et al., 2016) have shown that over the last few decades (1961–2011) regional and global per capita food reserves have remained stationary, despite a widespread concern that food stocks might be shrinking (Brown, 2013). However, it has been estimated that the global per capita stocks could be halved by 2050 (with 20% probability). There are some interesting regional differences: while Western Europe, North Africa, and the Middle East keep smaller and less volatile (hence, with lower probabilities to be reduced by 50%) per capita food stocks, North America and Oceania have bigger and more volatile (higher having probabilities) per capita stocks. In sub-Saharan Africa per capita food reserves are smaller and more volatile (i.e., with a relatively high halving probability), which indicates an overall higher food insecurity (Laio et al., 2016).

10.1.5. Economic Redundancies

Studies on famines and deprivation have highlighted that, during many food crises, the problem has been the lack of access to food rather than lack of food (Sen, 1981, 1982). Loss of economic access is often induced by spikes in food prices that prevent the poor from having sufficient financial resource to buy food. Because more wealthy segments of the population are in a better position to buy food, wealth can give a household or a country the ability to cope better with food crises. In other words, the wealth of individuals or of entire countries may be used as an indicator of economic resilience. To this end, Seekell et al. (2017) suggest using a country-specific indicator defined as the ratio between the income of the lowest quintile of the population (the focus here is on whether the poor will be able to buy food) and food cost in same country. This ratio is not constant because affluent societies are known to spend only a small fraction of their income on food (Engel's law).

10.2. The Effect of Globalization and Connectedness Through Trade

The resilience of the food system is affected by the globalization of food through trade (D'Odorico et al., 2014; Porkka et al., 2013). The effect of import dependency and interconnectedness of the food system is difficult to evaluate because we are dealing with a complex system that is undergoing transient growth (population growth, production trends, an increase in the number of trade partnerships) and is prone to shocks from environmental and socioeconomic drivers.

A quantitative approach to investigate the long-term ability of the system to recover from shocks or perturbations is based on the theory of dynamical systems, Lyapunov stability, and exponents (Lyapunov, 1992; Strogatz, 2014). In this framework, the dynamics are expressed through a set of coupled differential equations that can be linearized typically around either a steady state or a dynamic equilibrium. The linear stability analysis is typically used to determine whether the perturbation is in the long run amplified or damped, in other words, whether the system is stable and to what extent in the long run it is able to recover from perturbations (i.e., resilience). This approach was adopted by Suweis et al. (2015), who studied the stability of the coupled global food–population dynamics within a network whose nodes and links represent the countries of the world connected by trade. At each node, the population dynamics are expressed by a demographic logistic model with carrying capacity that depends both on domestic food production and trade patterns (Suweis et al., 2015). The resilience of these dynamics directly depends on the globalization of food through trade, including the amount of food traded, the number of links describing trade between countries, and the topological properties of the trade network. Using reconstructions of food production and trade based on FAO data (FAOSTAT, 2013), this analysis shows that in the past few decades the system has become increasingly vulnerable to instability (i.e., less resilient) as an effect of demographic growth, dietary shifts, and the increasing interconnectedness of the trade network. Indeed, some nodes (i.e., countries) are starting to show the first episodic signs of instability, particularly in water-poor and trade-dependent countries (Suweis et al., 2015). This analysis of the long-term response to shocks is in agreement with the short-term propagation of perturbations in the trade network during a food crisis (Marchand et al., 2016; Puma et al., 2015; Tamea et al., 2015); both approaches have shown how the fragility of the coupled food-demographic system has increased as an effect of the growing globalization of food through trade.

If trade and interconnectedness have the effect of reducing the resilience of the system as a whole, it is paramount to investigate to what extent it would be possible to globalize without becoming more vulnerable. A possible solution of this problem is suggested by ecological systems, which often exhibit some degree of modularity (Newman, 2006). There is evidence that systems with a modular structure—that is, with groups of countries (modules) that interact more among themselves than with countries from other modules—are able to contain the spread of perturbations within the targeted module, whereas the other modules remain only marginally impacted (May et al., 2008; Stouffer & Bascompte, 2011). In other words, the modules act directly to buffer the propagation of shocks (i.e., crises) to other communities, thereby increasing the stability and resilience of the entire system (Gilarranz et al., 2017; Walker & Salt, 2006). Interestingly, the virtual water trade network exhibits a growing degree of modularity with a ratio between internal and external (i.e., between communities) fluxes that is approaching 70% (D'Odorico et al., 2012). To date, however, the effect of modularity still needs to be investigated in the context of the resilience of trade and food security.

An alternative approach to understand the impact of virtual water trade on population growth is through carrying capacity plots (Porkka et al., 2017), which distinguish different strategies and their success by showing the historical evolution of a region or population's local food supply potential and (observed) net food imports relative to their local and posttrade carrying capacity. Porkka and collaborators confirm that food import is the strategy nearly universally used to overcome local limits to growth. Nevertheless, they also highlight that these strategies are implemented to varying extent and with varying success (Porkka et al., 2017). Therefore, whether dependency on imports is necessary and desirable, a clear policy priority at both local and global scale is needed and it ideally would attempt to keep the demand of food under control (e.g., further improvements in food supply, Jalava et al., 2014, 2016, and/or reduce food loss and waste, Jalava et al., 2016; Kummu et al., 2012).

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11. A Look Into the Future

There is wide agreement that humanity's rate of resource use exceeds what can be sustainably generated and absorbed by Earth's systems (Galli et al., 2014; Hoekstra & Wiedmann, 2014; Rockström et al., 2009; Steffen et al., 2015; Wackernagel et al., 2002; see also Box 1). Substantial uncertainty persists for an apparently basic question—by how much is food demand likely to grow in the coming decades—with estimates typically ranging from a required 60% to 110% increase by the year 2050 over circa year 2005 levels (Alexandratos & Bruinsma, 2012; FAO, 2009a; Tilman et al., 2011). More recently, Hunter et al. (2017) estimated that an increase in cereals production of 25–75% over 2014 levels could be sufficient to satisfy projected demand in 2050. The breadth of future GHG emissions trajectories—and the magnitude of their cascading consequences for agricultural productivity—leaves considerable unknowns regarding future food production under a changing climate (Rosenzweig et al., 2014). A radical transformation of the global food system is likely required in order to increase production while faced with the considerable uncertainties related to demand and climate impacts.

New strategies for achieving FEW security worldwide may benefit from adoption of an integrated approach aimed at an improvement in the availability, access, and nutritional properties of food while enhancing the provision of affordable, clean, and reliable energy (e.g., based on solar energy, hydropower, or wind power). Moreover, a secure FEW system will incorporate a sustainable use of natural resources, maintain environmental streamflows, and restore ecosystem services. The FEW system will need to invert the ongoing trend of increasing vulnerability and enhance its resilience with respect to climate shocks, demographic growth, and consumption trends.

The previous sections have highlighted the existence of several major challenges in this multiobjective strategy to food, water, and energy security. For instance, the sustainability of energy production can be improved by increasing the reliance on renewable energy sources, which would decrease the rate of fossil fuel depletion, reduce CO_2 emissions, and consequently allow societies to improve their ability to meet climate change targets. Renewable energy sources based on biofuels, however, would claim huge volumes of water and large expanses of land, thereby inevitably competing with the food system (section 6.1.4). Moreover, biofuel production often entails direct and indirect land use change and associated GHG emissions, indicating that in the short term these energy sources might have a negative impact (a "carbon debt") on the environment (Fargione et al., 2008). Nonfuel-based renewable energy production (e.g., solar energy) may also require substantial (though smaller) amounts of water and therefore compete with food crops in water-stressed regions (section 6.1.7).

The increasing demand for food and energy by the growing and increasingly affluent human population can hardly be met with the limited land and water resources of the planet unless we transform the FEW system. As noted in the previous sections, approaches focusing on ways to increase food and energy production instead of curbing the demand would ignore the existence of limits to growth imposed by the natural resources the planet can provide and are likely to achieve higher production rates at huge environmental costs (e.g., land use change, freshwater withdrawals, and pollution), resilience losses (section 10), and increased food insecurity for the poor. To be sure, there are still margins for increased production (Davis et al., 2014b, 2016; Mueller et al., 2012) through improvements in efficiency, technological innovation, and agroecologically efficient farming systems, but these measures are likely to be insufficient to meet long-term global food and energy security needs (Falkenmark & Rockström, 2006; Godfray et al., 2010; Sachs, 2015). The general pattern observed worldwide exhibits stagnating crop yields after decades of growth (Ray & Foley, 2013). There is the need for a complete rethinking of the FEW system to develop a comprehensive strategy for food, water, and energy security, based on enhancing the production and moderating the demand (e.g., Bajželj et al., 2014). Although a conclusive answer to the question of how to sustainably meet the food, energy and water needs of the rising and increasingly demanding human population is still missing, here we review a number of new and old approaches and ideas that could contribute to future food, water, and energy security. Such approaches can be, in general, technological (e.g., new water, energy, and food technology), cultural (e.g., based on environmental and health education), or institutional (e.g., through land and water governance, or new agricultural, dietary, or energy policies).

11.1. Approaches to Increase Production

Large yield gaps, or the difference, between current and attainable yields still exist in many parts of the world, particularly in sub-Saharan Africa (Mueller et al., 2012) and offer the potential to increase global production of

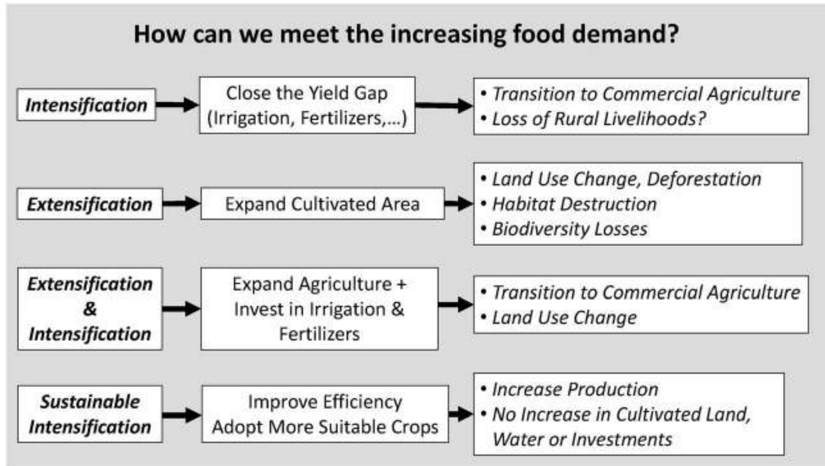

Figure 25. Production-based approaches to meeting the increasing food demand.

major crops by as much as 58% under currently available technologies and management practices (Foley et al., 2011). There is broad consensus that efforts to enhance crop yields on currently cultivated lands are crucial for avoiding additional agricultural expansion (Figure 25), the consequences of which would be profound and undesirable for natural systems and functioning (Foley et al., 2011; Godfray et al., 2010; Tilman et al., 2011). Agricultural intensification, however, is not free of environmental impacts in that it contributes to GHG emissions, freshwater and coastal water pollution, depletion of freshwater resources, and consequent loss of aquatic habitat (e.g., Diaz & Rosenberg, 2008; Jägermeyr et al., 2017; Vitousek et al., 2009; Vörösmarty et al., 2010).

In light of the environmental impacts of conventional intensification, some scientists are advocating for an approach to food security that relies on a "sustainable intensification" of agriculture (Figure 25), which aims to close the yield gap while minimizing the environmental impacts (Erb et al., 2016; Garnett et al., 2013; Tilman et al., 2011). Moreover, as with historical yield trends, harvest frequencies have generally increased through time, but many places with the potential to transition to double-cropping systems have yet to do so (Ray & Foley, 2013). On the one hand, yield and harvest gap closure offers great promise for increasing the food self-sufficiency of many developing nations (e.g., van Ittersum et al., 2016) because the areas with the largest potential for production increases are those places that currently rely heavily on food imports (FAO, 2013) and have some of the highest rates of projected population growth to midcentury (UN Department of Economic and Social Affairs, 2015). On the other hand, these remaining yield gaps raise questions about how best to promote the diffusion of high-yielding crop varieties and agricultural technologies, given that these agricultural advancements have yet to reach many places even 50 years after the start of the green revolution (Pingali, 2012). Moreover, it is unclear whether additional inputs (e.g., irrigation water) are adequately available in low-yield areas (e.g., Davis et al., 2016) and, if so, how to avoid their unsustainable use (e.g., Pradhan et al., 2015). Thus, particularly with regard to nonmobile resources, such as land and water, it will likely be essential to ensure that increases in production occur in places where and when natural resources can support it (e.g., Brauman et al., 2016; Davis, Rulli, Garrassino, et al., 2017; Hoekstra et al., 2012; Mekonnen & Hoekstra, 2016).

There are social, economic, and institutional factors that need to be accounted for while advocating for agricultural intensification versus alternative farming approaches (Tscharntke et al., 2012). Most of the existing literature on this subject has recognized the pros of yield (and harvest) gap closure as an alternative to agricultural expansion (Figure 25) at the expense of natural ecosystems (e.g., grassland, forests, or savannas), particularly in the tropics (Erb et al., 2016). "Land sparing" can, in many contexts, minimize habitat losses, land degradation, CO_2 emissions, and declines in biodiversity (e.g., Godfray et al., 2010; Naylor, 2011; Phalan et al., 2011). This approach, however, is not a panacea because its profound social impacts have often been overlooked by focusing on agrotechnological solutions without considering their effect on production systems, such as smallholder farmers (Tscharntke et al., 2012). Intensification efforts require investments that are increasingly made by large-scale agribusiness corporations, particularly in the developing world. Such investments may affect the system of production and its inputs, for example, through contract farming or out grower schemes (Da Silva, 2005; Eaton & Shepherd, 2001) or land use, access, and tenure rights, as occurs for LSLAs (Breu et al., 2016; Cotula, 2009; International Land Coalition, 2011), which are discussed in section 9.3.

Agricultural intensification is most effective in countries where relatively large yield gaps still exist, such as sub-Saharan Africa, while ensuring that new fertilizer and water are used in the most efficient way possible (e.g., West et al., 2014). To boost crop yields, investment in modern agricultural technology (irrigation infrastructure, machinery, fertilizers, and other inputs) is required, which many rural communities in lower-income countries cannot afford. If neither local land users nor domestic investors (e.g., government agencies or commercial farming companies) are able to improve crop yields, in years of increasing crop prices, foreign corporations or foreign-domestic joint ventures are not likely to miss the profit opportunities existing in underperforming agricultural land (D'Odorico & Rulli, 2013). Indeed, recent years have seen a wave of investments in agricultural land in the developing world, with import-dependent nations seeking to increase the pool of land and water resources under their control and targeted countries pursuing avenues to promote rural development and agricultural technology transfers (Deininger, 2013). However, there is a growing body of scientific and anecdotal evidence showing that the development and food security goals of these land deals are often not achieved (e.g., GRAIN, 2012; Klare, 2012; Kugelman & Levenstein, 2013) and, instead, often bring substantial social and environmental consequences (see, e.g., D'Odorico, Rulli, et al., 2017). Such land deals ultimately may result in the displacement of subsistence or small-holder farmers by large-scale commercial agriculture, as well as the development of new agricultural land at the expense of savannas, forests, or other ecosystems (e.g., D'Odorico & Rulli, 2014; Davis, Yu, Rulli, et al., 2015). Because most of the cultivated land worldwide is managed by small-scale farmers (IAASTD, 2009), this ongoing shift in systems of production may strongly reshape the agrarian landscape around the world with important impacts on rural livelihoods because it increases the dependence on a volatile food market.

Thus, agricultural intensification may be the result of important transformations in land tenure, farming systems, and livelihoods. Developing countries may enhance crop yields by introducing modern agricultural technology while promoting greater efficiency in food production through a transition in their agricultural sector toward commercial-scale farming. Commercial agriculture lends itself better to capital inputs from investors and could result from LSLAs or other forms of investment, such as contract farming (agribusiness corporations do not buy the land, but the crops, while facilitating access to technological inputs), or mixed outgrower schemes (e.g., Da Silva, 2005). However, there could be negative impacts on rural communities and their livelihoods because LSLAs may turn farmers into employees and increase their vulnerability to food price volatility (e.g., De Schutter, 2011) The transition to large-scale farming, however, might be unnecessary: small-scale farms, which account for most of the global calorie and nutrient production (Herrero, et al., 2017; Samberg et al., 2016), can be very productive. There is evidence in the economic literature (e.g., Henderson, 2015; van Vliet et al., 2015) about the inverse relationship between farm size and productivity, meaning that smallholder farmers, when provided with adequate inputs, may often achieve yields that outperform commercial, large-scale agriculture. Identifying mechanisms that support yield enhancements, technology transfers, and secure land tenure to these critical stakeholders is a key component of advancing global food security, promoting poverty alleviation, and enhancing food system resilience.

Overall, intensification typically requires the introduction of modern green revolution technology in areas of the developing world in which relatively large yield gaps exist. This includes the development of irrigation systems, application of fertilizers, and use of bioengineered crops and other biotechnologies (e.g., Fedoroff et al., 2010), as well as the implementation of new farming systems (e.g., aquaponics and hydroponics).

11.1.1. Biotechnology

Although the use of fertilizers and irrigation can reduce the gap between actual yields and the maximum potential yields of existing crops, new advances in biotechnology can increase the maximum potential yields by engineering crop varieties with improved "harvest index" (i.e., the ratio between the edible and total plant biomass), water use efficiency, photosynthetic efficiency, or drought tolerance.

Between the 1960s and 2005 the green revolution has allowed for a 135% increase in crop yields worldwide by intensifying production through irrigation, fertilizers, and improvements in the harvest index. In the next few decades crop yields will have to keep increasing (doubling between 2005 and 2050) in order to meet the increasing demand for agricultural products (Ort et al., 2015). This is a major challenge because, recently, crop yields have been stagnating after decades of growth (Ray et al., 2012). The analysis of factors limiting the increase of crop yields shows that so far technological improvements aiming at the enhancement of photosynthetic efficiency (i.e., the efficiency with which plants capture and convert sunlight energy into plant biomass) have played only a marginal role in the increase of crop yields, and for most crop plants, the photosynthetic efficiency is far below the biological limits (Ort et al., 2015). The next stage of the green revolution could use modern technologies from genetic engineering and synthetic biology to improve the mechanisms of light capture, sunlight energy conversion, and carbon uptake and conversion (Dall'Osto et al., 2017; Ort et al., 2015). For instance, in full sunlight conditions, most plants absorb more light than they can use. To avoid damaging photooxidation from excess light, plants typically dissipate excess light as heat (Berteotti et al., 2016). To improve efficiency, plants could capture less light or improve the way they respond to changes in light availability resulting from variations in cloudiness (Kromdijk et al., 2016). Additional gains can be obtained by developing crop varieties with improved water use efficiency, pest resistance, or temperature stress tolerance (e.g., Fedoroff et al., 2010; Way & Long, 2015).

Genetic engineering technology is commonly used to develop genetically modified organisms, including new crop varieties. Unlike traditional breeding techniques and artificial selection for desired traits, transgenic methods allow for more precise genetic modifications by inserting specific genes from other species to improve crop performance (e.g., drought tolerance and insect and herbicide resistance). The use of transgenic crops in agriculture has been and still is at the center of a heated debate because of possible risks and unintended consequences, including possible gene mutation, accidental activation of "sleeper" genes, interactions with native plant and animal populations, and gene transfer (e.g., transfer of antibiotic resistance and allergenic genes; Phillips, 2008). Other controversial points deal with intellectual property rights and the control of the biotechnology corporations on the agricultural sector. A detailed analysis of this debate is beyond the scope of this review.

11.1.2. Genetically Engineered Livestock

Transgenic methods, which have been extensively used to improve crop varieties (section 11.1.1), can be adopted to induce genetic modifications in livestock species by inserting specific genes in organisms that do not have a copy of those genes (e.g., Hammer et al., 1985). Research on transgenic pigs has focused on the reduction of pollution from fecal phosphorus. Other studies have investigated mammary gland-specific transgenic livestock to change the fat content in goat's milk, reduce saturated fats in dairy products, and improve disease resistance in lactating cows (e.g., resistance to mastitis, a disease affecting milk quality and animal health; see Maga, 2005).

11.1.3. In Vitro Meat Production

As noted in section 2, the ongoing increase in meat consumption worldwide is challenging the agricultural system. Livestock production uses roughly 30% of global ice-free terrestrial land and contributes to 18% of global GHG emissions associated with deforestation, methane emission, and manure management (Tuomisto & Teixeira de Mattos, 2011). It has been argued that the increasing demand for meat could be met by culturing animal tissues in vitro in the lab, without having to raise livestock. These methods could strongly reduce the carbon, land, and water footprints, as well as exposure to foodborne pathogens (e.g., salmonella, Campylobacter, *Escherichia coli*, and avian and swine influenza), and cardiovascular diseases (Post, 2012) by making healthier meat products. Moreover, in vitro meat production would address ethical concerns on animal welfare.

In his book "Thoughts and Adventures," Winston Churchill (1932) predicted that "… Fifty years hence, we shall escape the absurdity of growing a whole chicken in order to eat the breast or wing, by growing these parts separately under a suitable medium…" (Post, 2012). Churchill's prophecy is now about to become true. In the last few decades scientists have developed methods to produce muscle tissue ex vivo (outside the body of living organisms). Meat culture technology was initially developed for medical applications to produce insulin and implants. Three different approaches (Tuomisto & Teixeira de Mattos, 2011) have been used, namely, stem cell isolation and identification (stem cells turned into a specific cell type such as bone or muscle cells), ex vivo culture of cells taken from a live animal and put in vitro, or tissue engineering (e.g., based on DNA engineering; Post, 2012).

Applications to the meat industry are facing some major challenges because, to be marketable, cultured meat needs to look and taste like real meat. Thus, research on in vitro meat production is working on appearance, texture, and taste to improve the resemblance to real meat. Today, only small amounts of meat have been

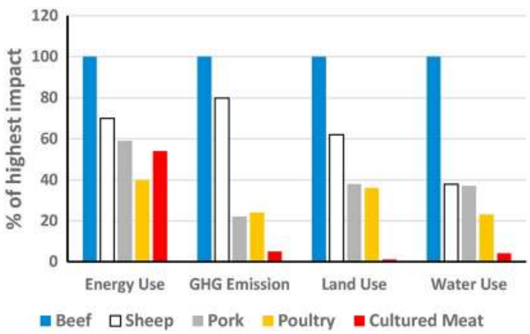

Figure 26. Energy input, greenhouse gas (GHG) emissions, land use, and water use of edible meat relative to the case of beef (data source: Tuomisto & Teixeira de Mattos, 2011).

produced in vitro and served in a handful of restaurants in the United States. It has been estimated that, compared to meat from livestock production, cultured meat allows for substantial savings in land and water resources, emits less GHGs, and uses less energy than ruminants (Figure 26; Mattick et al., 2015; Post, 2012).

11.1.4. Aquaponics and Hydroponics

It is commonly believed that crop plants need soil, in addition to water, nutrients, and light, for their growth. However, it is possible to grow plants without soil but in water with adequate mineral additions. Known as hydroponics, this technique can be used indoors and outdoors, in recirculating, as well as in flow-through, systems. The main advantages of hydroponics with respect to soil cultivation is that plants do not need to invest much in root growth to find nutrients; they grow faster and take less space. Moreover, hydroponics allows for more efficient nutrient/fertilizer regulation. This technique, however, can be expensive when considering the cost of the system, its maintenance, and energy requirements.

A more effective use of resources can be attained with a multitrophic system, known as aquaponics, that combines hydroponics with aquaculture. In other words, nutrient-rich water from fish tanks is used for plant growth (Figure 27). This system is inspired by old agricultural practices, such as the introduction of fish in rice paddies or the use of nutrient-rich fish-tank water for irrigation (e.g., Goddek et al., 2015). In aquaponic systems, fish produce nitrogen-rich waste that is mineralized by bacteria and taken up by plants (Figure 28). Thus, bacterial biomass and vegetation filter the water in the fish tank, thereby allowing for a recycling of water and minerals (potassium (K) and P); this system turns waste products from aquaculture into nutrients for hydroponic production. In this sense, aquaponic is a good example of circular economy, as described in section 11.4.1. The main limitation of this system is that it requires relatively large capital investment and skilled maintenance, and is therefore more suitable for commercial farming than for subsistence agriculture in the developing world.

11.2. Sustainable Increase in Production Through Low-Technology Approaches.

The use of modern technology and the intensification of agricultural production are often invoked as the desired approach to meeting the increasing demand for crops without causing additional land use change (Foley et al., 2011; Godfray et al., 2010). As noted repeatedly in the previous sections, the downside of this

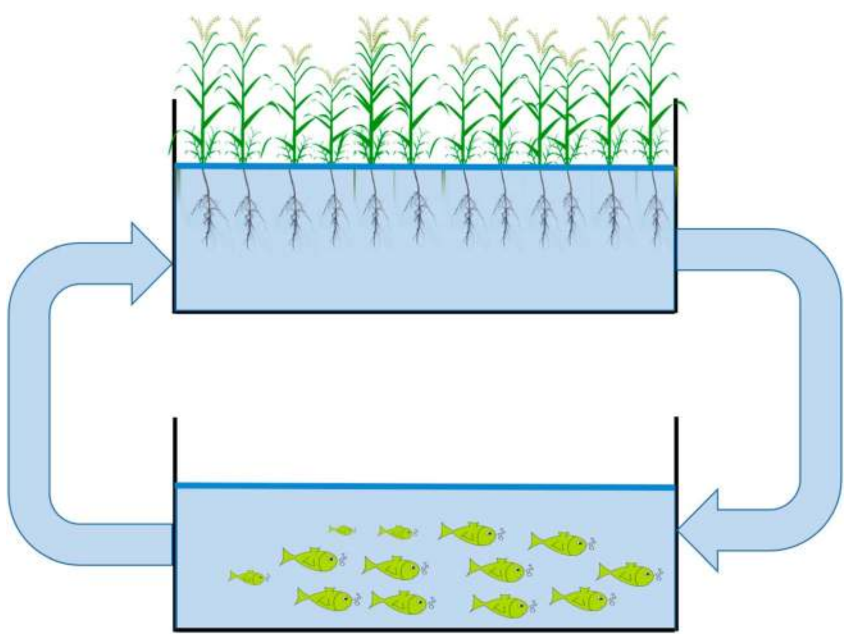

Figure 27. Schematic representation of an aquaponic system.

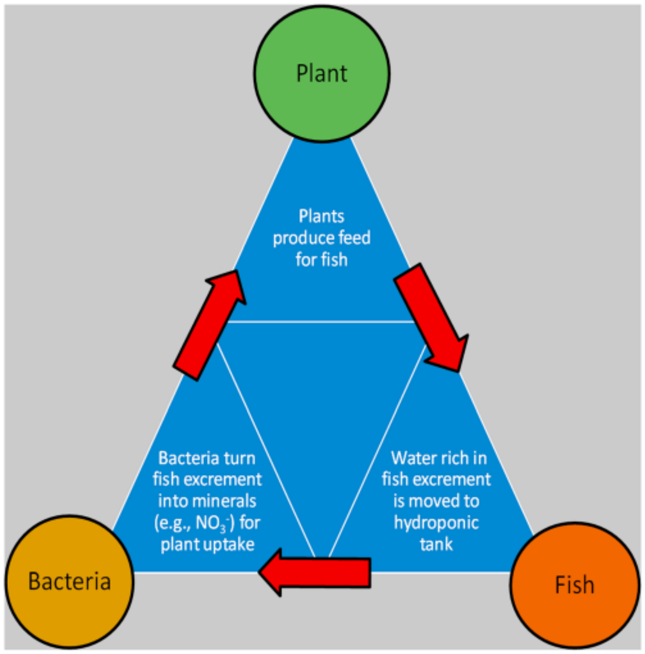

Figure 28. The circular economy of aquaponic systems.

approach is that it typically requires investments that rural communities in the developing world cannot afford (see section 11.1). Therefore, in many cases agricultural intensification might entail a transition from small-holder semisubsistence farming to large-scale commercial agriculture.

11.2.1. Agroecology

An alternative approach to achieve food, water, and energy security is offered by agroecology. Small-scale farming can capitalize on local knowledge to attain relatively high yields without having to resort to agribusinesses and their technology (e.g., Altieri et al., 2012). In recent years, there has been a renewed interest in peasant agriculture and its use of polycultures (Altieri & Nicholls, 2004), agroforestry, green manure, compost turfing, and high-residue farming (Mitchell et al., 2012), without adopting soil tillage or agrochemicals. These traditional (agroecological) practices conserve soils, water, biodiversity, and ecological integrity, while favoring resilience. It would be impossible to review here this rich body of literature but we will instead focus on the significance of these methods in the context of meeting the growing food demand.

It has been argued that a shift to agroecology can substantially increase crop production (50–100% increase in rainfed yields) in a sustainable way and that small-scale peasant agriculture is not condemned to achieve low yields as often assumed in the literature. Rather, there is evidence that small family farms can be much more productive and resilient than larger ones (Altieri et al., 2012). The use of polycultures in agroecology allows for the attainment of higher and more stable yields, enhances economic returns, and favors diet diversity, while making more efficient use of land, water, and light resources (Altieri et al., 2012). Thus, small-scale farming with agroecological methods could contribute to meeting the growing demand for agricultural products. Recent estimates indicate that about 525 million small-scale farms exist around the world and provide a livelihood for about 40% of the global population (IAASTD, 2009). However, the ongoing changes in the agrarian landscape worldwide entail the replacement of small-holder agriculture with large-scale commercial farms. This transition can be related to a number of factors, such as the globalization of agriculture through trade, LSLAs, better access to credit by commercial farmers, differences in land tenure, use of agricultural subsidies in economically more developed countries, and lack of protection of domestic production against subsidized foreign agricultural products (IAASTD, 2009). This transition has the effect of reducing the opportunities to use small-scale agroecological methods as an approach to increase food availability.

11.2.2. Increasing Efficiency While Preserving Resilience

A continuation of current trends in production, consumption, and resource use is wholly unsustainable. There is an urgent need to enhance food security without increasing the human pressure on the environment (Figure 25). A current push in the literature is to identify solutions that minimize trade-offs across multiple agricultural, environmental, and economic dimensions (see, e.g., Billen et al., 2015; DeFries et al., 2016; Erb et al., 2016; Nelson et al., 2009). Some of this work has shown the potential to maintain or reduce current levels of resource use while increasing crop production, thereby eliminating large inefficiencies in production systems. One such study found that if nitrogen fertilizer was spatially distributed more efficiently, it would be possible to increase cereal production by ~30% while maintaining current levels of nitrogen application (Mueller et al., 2014). Likewise, it is possible to use different irrigation and soil management strategies to close the crop yield gap by one half without increasing cropland area or irrigation use (Jägermeyr et al., 2016). Other work showed that, by redistributing crops on the basis of their suitability, it is possible for the United States to realize a modest water savings (5%) and improve calorie (+46%) and protein (+34%) production without adversely impacting feed production, crop diversity, or economic value (Davis, Seveso, et al., 2017). Similarly, recent research investigating global scenarios of crop redistribution to minimize irrigation water consumption has shown that it is possible to increase food production and feed an additional 825 million people while reducing irrigation water consumption by 12% without losing crop diversity or expanding the cultivated area (Davis, Rulli, Seveso, & D'Odorico, 2017).

Collectively, these results show the benefits of a more efficient use of natural resources for food or energy production. There could be, however, some unwanted effects. (1) Highly optimized systems are not necessarily more resilient (e.g., Walker & Salt, 2006). They often lack important redundancies that play an important role in providing resilience to the FEW system (see section 7). (2) When resources are used more efficiently their consumption can increase rather than decrease. Known as Jevon's paradox (e.g., Bauer et al., 2009; Polimeni et al., 2008), this rebound effect has been observed for irrigation systems and has been termed the irrigation paradox (Foster & Perry, 2010; Scott et al., 2014). Indeed investments in water-saving irrigation technology may result in a decrease in groundwater levels and environmental flows (Pfeiffer & Lin, 2010; Ward & Pulido-Velazquez, 2008). Unless policies limit the extent of the irrigated land, what typically happens is that more land is irrigated and water-resource availability decreases, which may exacerbate water scarcity and soil salinity problems (Scott et al., 2014). Of course, these changes also have some positive effects, such as increased crop production. (3) Approaches aiming at an increase in agricultural efficiency need to first clarify which resource needs to be used more efficiently (Hoekstra, 2013). If irrigation water is applied to close the yield gap (the full irrigation strategy), the land is used very efficiently but not necessarily the water. But, if water is scarce and large expanses of land are available, it makes more sense to use the land less efficiently and the water more efficiently by irrigating a larger area but with smaller water applications. This practice is known as deficit irrigation in that it leaves crops in a water deficit state (Hoekstra, 2013). These caveats stress the need to account for food demand, livelihoods, and the environment when developing more effective strategies for achieving a sustainable food system.

11.3. Change in Consumption Rates

Consumption rates depend on the number of consumers (i.e., population size) and the consumption rate per capita, which in turn depends on diet and food waste.

11.3.1. The Population Factor

The population factor (Box 1) has been somewhat more marginal in the recent food security debate, but is starting to resurface in the analysis of sustainable food systems (Crist et al., 2017) Often considered "the elephant in the room," some of the old prophecies on the existence of biophysical limits to population growth (e.g., Ehrlich, 1968; Malthus, 1798; Meadows et al., 1972) are going to be central in the analysis of the future of food security (Box 1). It has been argued that there is an urgent need to contain the escalating demand for food commodities by stabilizing the global population (Motesharrei et al., 2016; Warren, 2015). This has revamped the debate on the efficacy of population policies and reproductive health education (Crist et al., 2017), as well as other longer-term approaches based on both social and economic development, including empowerment of women and access to education, poverty eradication, and other factors affecting fertility rates (Lee, 2011; see also Box 1).

11.3.2. To What Extent Is It Possible to Promote More Sustainable and Healthy Diets?

Though food supply may be adequate at the global scale, high levels of undernourishment persist in many parts of the developing world (Box 3), while habits of overconsumption have become commonplace in the United States and Europe (Alexandratos & Bruinsma, 2012). Thus, in addition to production-side solutions that have been proposed for meeting future demand, recent work has pointed toward the need for efforts to draw down per capita demand (e.g., Bajželj et al., 2014; Chaudhary et al., 2018; Davis et al., 2014b; Davis et al., 2016; Shepon et al., 2018), particularly in countries with diets with a large fraction from animal products, and to promote better physical and economic access for less integrated markets. Approaches to promote a shift toward healthier and environmentally more sustainable diets can be based on a variety of interventions, including raising awareness, education, "nudge" methods (e.g., easier access to meat alternatives, changes in default menu option, meal plans, and portion size), economic incentives, taxation (e.g., taxes on sugary drinks; Colchero et al., 2016), and law restrictions. The latter three approaches, however, can be difficult to accept in free market economies and liberal societies (Wellesley et al., 2015).

Although a consumption focused approach to food security may be difficult to implement, given the social and cultural associations of diets, new studies have demonstrated linkages between sustainable dietary choices and health (Tilman & Clark, 2014) and explored sustainable diets (Gephart Davis, et al., 2016). Thus, approaches based on health awareness can also improve environmental sustainability. Other strategies to enhance awareness and education rely on the effect of sustainability labels on food choices (Leach et al., 2016) or rely on academic institutions to take the lead in evaluating and improving the water, carbon, and nitrogen footprints of the institutions, starting with the food served (Compton et al., 2017; Leach et al., 2013; Natyzak et al., 2017). Indeed, universities and other nonprofit organizations can be leaders in developing internal food sustainability policies and, in doing so, set the standards for other institutions in a manner similar to that of major divestment initiatives in "unethical" businesses related to apartheid, tobacco, or fossil fuels. Such divestment efforts started from the management of endowments of major university and religious organizations and spread to the broader market (Ansar et al., 2013). Presently, universities are pioneering efforts aimed at calculating and reducing the nitrogen, carbon, and water footprints within their institutions or promoting low meat diets (Compton et al., 2017; Leach et al., 2013; Natyzak et al., 2017).

There are, however, some major barriers to a dietary shift away from a meat-based diet. The greatest barriers are cultural and are associated with the appreciation of meat by those who are used to having it as the central part of their meals, enjoy its taste, lack knowledge about how to prepare vegetarian meals, or believe that meat has a higher nutritional value than other food types. Moreover, in many societies meat consumption is perceived as a sign of affluence, status, masculinity, authority, and physical strength (Ruby, 2016). These cultural factors shape a society's consumption patterns and make dietary shifts a difficult task (Pohjolainen et al., 2015). Appreciation for meat is typically stronger among men, younger people, families with children, and rural communities in which meat consumption is considered an important part of their tradition, whereas plant-based diets are perceived to have no taste or nutrition value (Pohjolainen et al., 2015). Knowledge gaps about the environmental and health impacts of meat, and false perceptions about the nutritional properties of vegetables, can constitute important barriers to a shift toward diets that use less meat. There is also a generalized reluctance to the use of meat substitutes (e.g., tofu and veggie burgers) because of unfamiliarity with their taste and texture, and many people do not know how to replace meat with proteins from vegetable sources (Graça, Calheiros, & Oliveira, 2015; Graça, Oliveira, & Calheiros, 2015).

Although cultural barriers are hard to remove, some of the knowledge gaps listed above could be addressed by educating citizens about the nutritional, health, and environmental implications of their food consumption habits. Attempts at promoting dietary shifts could be more effective if they target (and are tailored to) specific social groups—namely, the student population, who could start getting used to meat substitutes at a young age; women, who appear to be more inclined to vegetarian diets than men (Ruby, 2016); or citizens concerned about the health impacts of an excessive use of meat (e.g., hypertension, cardiovascular diseases, or type 2 diabetes). Other educational initiatives could appeal to concerns about environmental impacts, animal ethics, and welfare (Ruby, 2016). New policies could promote healthier and sustainable diets by setting higher nutritional and environmental standards for school meals (Donati et al., 2016). To reduce meat consumption some school districts and workplaces are already adopting meat-free days in their meal plans, while promoting health education to decrease employers' long-term healthcare costs.

In some affluent countries, there are already signs of reduced meat consumption, which indicates that, as societies become wealthier, concerns about health and environment lead to a more moderate consumption of meat, according to a Kuznet-like inverted-U curve (Cole & McCoskey, 2013). Reductions in meat consumption can be favored by urbanization, education, empowerment of women, or the use of sustainability labels (Grunert et al., 2014; Leach et al., 2016). In the developing world, however, the expected trend is still that of an increase in meat consumption in the next few decades (Alexandratos & Bruinsma, 2012; Tilman et al., 2011).

Other possible strategies to promote a dietary shift can be based on food price policies (e.g., Andreyeva et al., 2010). For instance, less sustainable food types, such as meat or unhealthy processed foods could be taxed, whereas subsidies could be used to reduce the prices of vegetables, meat substitutes, and other more sustainable and healthier food products (Donati et al., 2016). Such policies could ensure that food prices account for environmental costs (e.g., through a carbon tax) and use part of the tax revenues for the improvement of taste, texture, and nutritional properties of meat substitutes (Pohjolainen et al., 2015). The efficacy of policies acting on food prices, however, could be modest in affluent societies where only a relatively small fraction of the income is typically spent on food, a pattern known as Engel's law.

11.3.3. Livestock Transition

Trends toward greater animal protein in diets mean that livestock production systems need to become far more efficient. In this regard, the ongoing transition toward monogastric production is encouraging. Indeed, recent work has shown that shifting grain-fed beef production entirely to chicken and pork production would feed an additional 367 million people (Cassidy et al., 2013). As with closing crop yield gaps, the industrialization of animal production poses a huge challenge to the sector's vital and ongoing role in

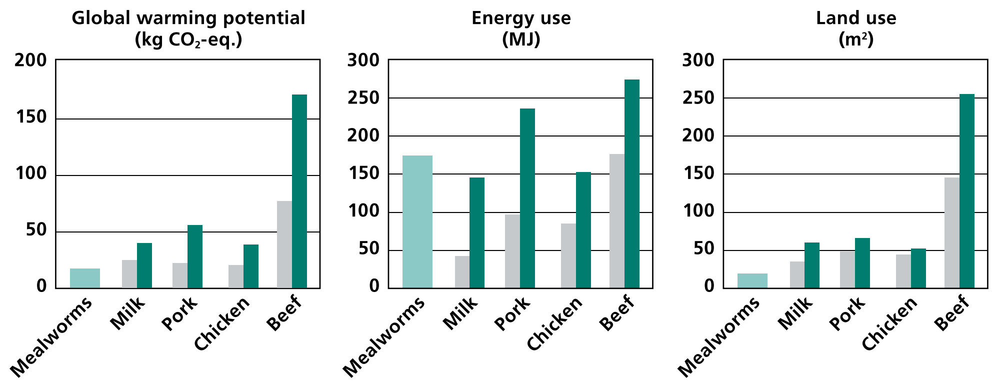

Figure 29. Impacts of the production of 1 kg of protein from mealworms and other food sources: Minimum (gray) and maximum (dark green) footprints (after Oonincx & de Boer, 2012; Van Huis, 2013; van Huis et al., 2013).

poverty alleviation because livestock, and agriculture in general, are important for various aspects of rural livelihoods (e.g., income, nutrition, field preparation, transportation, household assets; Thornton, 2010). Likewise, the expansion of sustainable forms of aquaculture (see Box 4) offers an alternative, and potentially more environmentally sustainable, way to meet some of this future demand for animal products (Godfray et al., 2010). Even more so than for crop production, the future of the livestock sector is far from clear (Thornton, 2010).

The last few decades (1961–2011) have seen an increasing reliance on poultry and swine meat, and a decrease in the fraction of ruminant meat consumption, worldwide (Thornton, 2010). This trend (livestock transition, see section 2.2 and Figure 7) allows for a reduction of the land used and carbon footprints of meat per unit calorie (Davis et al., 2016; Tilman & Clark, 2014).

11.3.4. Alternative Meat Types

As noted in the previous sections, a possible approach to feed the world with the limited resources of the planet is to reduce the consumption of meat, particularly of the meat types that have the greater environmental footprints. Alexander et al. (2017) reviewed a series of alternative meat types, including insects, cultured meats (e.g., in vitro meat), and imitation meats; they found that insects and imitation meats had particularly low land use requirements relative to conventional meat. However, imitation meats had relatively minor reductions in land use requirements compared to poultry and dairy, further emphasizing the importance of dietary change and waste reductions (Alexander et al., 2017). Other studies have highlighted the environmental, health and economic benefits of eating insects (Van Huis, 2013). Most insects have relatively high bioconversion rates (i.e., feed-to-live animal ratios), close to 5 times those of cattle. Moreover, the edible biomass fraction is much higher in insects (about 80% in crickets) than in livestock (about 55% in poultry and pork and 40% in beef). Therefore, the feed-to-edible meat ratio is much more favorable for insects than for livestock, which explains their smaller land and carbon footprints (Figure 29; Oonincx & de Boer, 2012). Insect meat is also healthier because of its high protein and low fat contents. Further, because insect production requires low technological inputs, it can be practiced by small-scale farmers, thereby improving the food security and nutrition of rural populations, as well as their livelihoods (Van Huis, 2013).

Insects may be used either for direct human consumption or as feed for the aquaculture and livestock industries. The feed used for insect production can be based on various types of organic waste, including cellulosic materials. Therefore, reliance on insect meat may allow for an effective recycling of waste and favor the establishment of a circular economy (Figure 30), whereby food waste is turned into protein-rich feed and food (Vickerson, 2016).

11.4. Waste Reduction and Reuse

As noted in section 2, about 24% of global food production for human consumption is lost or wasted through the food supply chain (Parfitt et al., 2010). Recent work has demonstrated the environmental benefits of reducing food waste (Kummu et al., 2012; Shafiee-Jood & Cai, 2016) and shown that consumer waste of animal

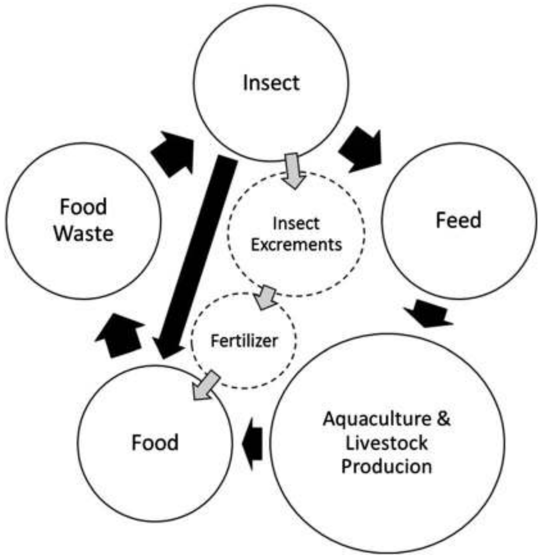

Figure 30. Circular economy of insect meat and food waste.

products is particularly costly in terms of land use (West et al., 2014) and crop production (Davis & D'Odorico, 2015). All of these studies provide important insights into how consumers may consider healthier and less environmentally burdensome consumption choices (Box 2).

It has been estimated that food waste accounts for 23% of the arable land, 24% of freshwater resources used for crop production, and an amount of food per capita of roughly 625 kcal per cap per day, including large quantities of nutrients, micronutrients, and minerals (Spiker et al., 2017). These figures speak for themselves. A strategy aimed at improving the use of land and water for food production needs to invest in food waste reduction and reuse. Many studies have investigated how food waste can be reduced by removing inefficiencies in the food supply chain from agricultural production to postharvest storage, processing, distribution, and consumption. Possible actions include crop production planning to avoid surpluses that cannot be placed on the market; improvements in storage, refrigeration, and transportation facilities, particularly in the developing world; changes in the logistics of food retailing and distribution to account for the limited shelf life of perishable products; and consumer education on how to make more effective purchase plans and deal with "expiration" and "sell-by" dates (Ghosh et al., 2015; Gustavsson et al., 2011; Stuart, 2009; Thi et al., 2015). In developed countries, some of the quality standards for fresh produce overemphasize aesthetic criteria and idealizations about fruit or vegetable size and shape, or product uniformity with the effect of discarding products that are perfectly healthy and edible. Consumer education could encourage the use of substandard or unappealing food products, and products that are unsuitable for human consumption could be repurposed and used as animal feed or for bioenergy production (Peplow, 2017).

Food waste can also be contributed to by retailer overbuying, oversized packages, and stores' compliance with "sell-by" or "use-by" dates. To redress some of these factors, it is possible to act at the retailer and distributor level. Of note is France, where a recent law forbids the destruction of unsold food as it approaches its "best by" date. Rather, supermarkets need to donate these products to food bank charities, though the process of food delivery to humanitarian organizations remains a difficult task as it requires timeliness and coordination (Chrisafis, 2016). The EU Commission has subsequently established a multistakeholder platform with the explicit task of developing a strategy to reduce food waste.

Another particularly important opportunity in the FEW nexus is to enhance the recovery, treatment, and reuse of wastewater. In terms of water scarcity, wastewater offers a potential alternative source of irrigation in some contexts (e.g., Grant et al., 2012). Improved access to sanitation is not only a UN Sustainable Development Goal in and of itself, but improved sanitation systems offer massive potential to recover critical plant nutrients, particularly P, to offset agricultural nutrient demands at the global scale and, to some degree, to influence household energy goals through renewable sources such as biogas (Trimmer et al., 2017). Recycling of nutrients from urban waste streams is especially important for the P cycle because of the nonrenewable nature of this resource and the relatively high P content of sewage sludge (e.g., Cordell et al., 2009; Mihelcic et al., 2011). However, in addition to the infrastructure needed for urban sanitation, multiple socioeconomic and environmental factors can play a role in the efficacy of nutrient recycling in any given city (as reviewed by Metson et al., 2015, for phosphorus).

11.4.1. Toward a Circular Economy in the FEW System

Despite all the efforts our societies can make to reduce food waste through more efficient food supply chains, consumer education, and the use of food banks, some of the losses existing in the food system are unavoidable. Nevertheless, spoiled or unsold food can still be used for other purposes, such as energy production, feed for livestock, or insect meat production (Figure 30). This approach is an important step in the direction of a circular economy, to "reuse what you can, recycle what you cannot reuse, repair what is broken, remanufacture what cannot be repaired" (Stahel, 2016).

Our current system of production often uses a linear model (Figure 31), whereby natural resources are extracted to produce a sequence of goods that are then used until they are disposed. This process leads to

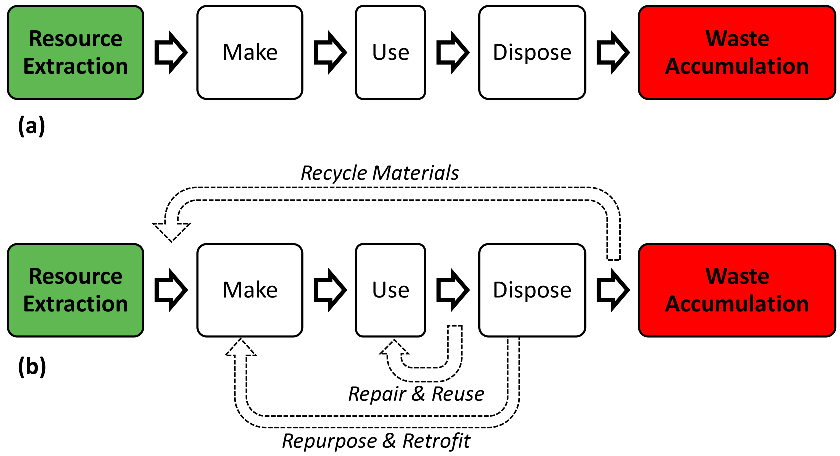

Figure 31. Schematic diagram of (a) linear model of production and (b) toward a circular economy through reuse and recycling to reduce resource depletion and waste accumulation.

the depletion of natural resources and accumulation of waste. Because in this linear system manufacturing moves goods through value adding steps, economic growth implicitly entails resource depletion and waste production, a model of production that is clearly unsustainable. Nature, however, works in cycles, with a sequence of processes organized in a circular pattern: what is waste for a certain process becomes an input (i.e., a resource) for the next one (Stahel, 2016).

Some of the systems reviewed in the previous sections, such as hydroponic production or the food/waste/insect/feed/food cycle, are ways to imitate nature and its circular economy. Even in those cases in which complete loops cannot be established, it is possible to use a more circular consumption pattern in the sense that we can reduce the use of new natural resources and generate less waste. For instance, we can repair and reuse some goods (i.e., extend their service life), retrofit and repurpose commodities that have become obsolete or unsuitable for their initial use, and recycle materials. In the specific case of the FEW system, food waste can be used to produce biogas (repurposing), feed, compost (recycling), or even other food commodities. This requires additional labor and investments in technological innovations with the overall effect of creating new jobs and reducing the environmental damage from resource use and waste accumulation. Although the industrial revolution has replaced labor with energy from fossil fuels (e.g., Sachs, 2015), the transition to a circular economy would use less resources, employ more labor, reduce the carbon footprint of human activities, and add about $2.3 trillion (U.S. dollars) to the European economy by 2030 (Stahel, 2016).

Table 6
A Comparison of Different Forms of Global Water Saving

Saving mechanism	Max water savings (%)	Reference to data source
Virtual water		
green + blue water consumption	6%	Chapagain et al. (2006)
Waste reduction		
blue water consumption	<24%	Kummu et al. (2012)
Changes in Diet (Reduced dietary protein from animal products—25% of total)		
green water consumption	6–21%	Jalava et al. (2014)
blue water consumption	4–14%	
Crop water management		
blue water withdrawals	17%	Jägermeyr et al. (2016)
Optimal crop redistribution		
blue water consumption	12%	Davis, Rulli, Seveso, & D'Odorico (2017)
green water consumption	14%	

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Some authors have stressed the existence of important limitations in the circular economy paradigm because it is unrealistic to build the global economy on a closed loop of material-end energy flows between the economic and the natural systems (Korhoner et al., 2018). Complete recycling will never be attained. For instance, the recycling of materials always results in the unavoidable production of toxic waste and other side products for which we currently have no economic use. The second law of thermodynamics has been invoked to explain that recycling will always require energy and entail the production of waste (Georgescu-Roegen, 1971). Although a circular economy could be in principle sustained by renewable energy, to date, only about 25% of the energy demand of human societies relies on renewable resources (Ayres, 1999; Converse, 1997; Craig, 2001; Korhoner et al., 2018). Despite these limitations in the applicability of the circular economy paradigm, this framework allows us to stress how resource-efficient food systems could emulate the dynamics of natural cycles (e.g., of water or nutrients). Even without aiming at complete recycling of materials and reliance on renewable energy, systems of production that promote recycling, reuse, and refurbishing can reduce the footprint of human societies.

11.5. Relative Importance of Consumption-Based Approaches

The measures to reduce consumption in the food system may have different impacts on natural resources (Table 6). Their relative importance has seldom been evaluated. For water, however, it is possible to quantify the maximum water savings from waste reduction, dietary shifts, crop water management, and improved crop redistribution (D'Odorico & Rodriguez-Iturbe, 2017). Interestingly, all these mechanisms can yield maximum water savings that are of the same order of magnitude (10–24%). Of course, only part of these maximum savings can be feasibly attained, and this fraction likely depends on the saving mechanism.

Box 7. Restoring the Circular Economy of the Nitrogen Cycle

An interesting example that is relevant to agriculture can be found in the nitrogen (N) cycle. In a natural ecosystem such as a forest or a grassland, most of the reactive N is recycled within the system as it is moves from live vegetation to soil organic matter (litterfall or plant mortality) to be subsequently mineralized and nitrified, and taken up by plants (e.g., Schlesinger, 1991). Losses of N to the atmosphere (denitrification) or water bodies (leaching) are unavoidable, and the overall reactive N pool (organic + inorganic) is generally replenished by atmospheric deposition and fixation of nonreactive atmospheric N (Figure B7a). Before the use of industrial fertilizers, agroecosystems functioned substantially in the same way, except that crops were harvested and removed from the cultivated land along with the organic N contained in grains, vegetables, roots, tubers, and fruits. No-till agriculture leaves part of the crop residues in the field to reduce nutrient losses, soil evaporation, and erosion. However, in the long run, soils would be depleted of N and other minerals without adequate fallow periods to recover, and/or the supply of adequate amounts of natural fertilizers, such as manure or compost (Figure B7b). With the use of industrial fertilizers, farmers have been able to open the N cycle and turn agriculture into a more linear system of production. Instead of relying only on natural fertilizers, it is possible to manufacture new reactive nitrogen through industrial synthesis, a process (the Haber-Bosch process) that requires an energy input to obtain high temperature and pressure (e.g., Erisman et al., 2012). This leads to a linear model of production (Figure B7b), with the accumulation of reactive nitrogen in the environment (i.e., in food/crop waste and wastewater), a phenomenon that has well known environmental implications, such as the eutrophication of lakes, rivers, and coastal waters; the emission of greenhouse gases; and rainfall acidification (e.g., Elser & Bennett, 2011; Galloway et al., 2004). Thus, the nitrogen cycle typical of natural ecosystems (Figure B7a) has been disrupted by agriculture (Figure B7b) by (1) removing N in harvested crops (which started at the beginning of agriculture in the Neolithic period) and (2) increasing the external input of reactive N, which has opened even more the nitrogen cycle's loop (at the time of the Green Revolution). With no-till agriculture, composting, and the use of manure, we can reduce the need for "new" reactive nitrogen production (i.e., industrial fertilizers), thereby reducing the energy input and the accumulation of reactive N in the environment. Moreover, the inclusion of nitrogen fixers (e.g., pulses and soy beans) in crop rotations can reduce the reliance on synthetic fertilizers Figure B7c.

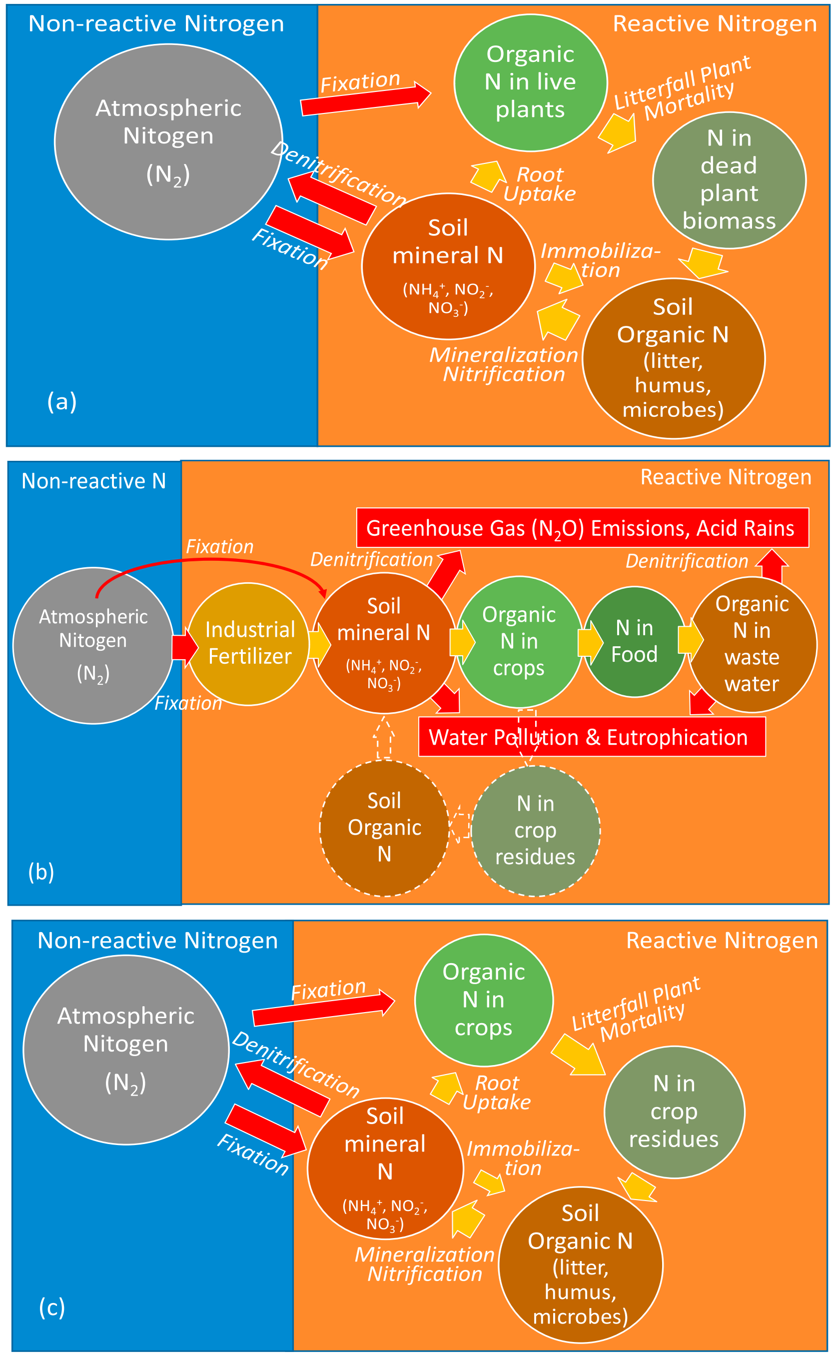

Figure B7. Schematic representation of the nitrogen cycle of "natural" ecosystems (a), fertilizerdependent agro-ecosystems (b), and ecological farming systems (c).

12. Concluding Remarks

Humanity faces an enormous challenge in the 21st century to meet the growing and changing demands for food and energy in a sustainable manner while dealing with changes in water availability and the pressures of society on water quality. We have reviewed the various challenges and opportunities facing each of the food, water, and energy systems independently and some of the key ways that these systems are linked. Critical uncertainties relate to how much food demand will increase in relation to population growth and dietary change with growing affluence, how this new demand will be met, and how the response to this demand will intersect with water use. Although new technologies and alternative production models offer considerable potential to improve global food and energy production, some of the largest gains in food availability can come from shifts in consumption patterns—particularly away from red meats and toward reductions in food waste—or through closure of yield gaps with targeted use of fertilizer and improvements in water use efficiency. Indeed, new approaches to food and energy security will likely have to rely on the enhancement of production through the adoption of new technology and consumption reduction through more sustainable diets, efficient use of resources, and decreased waste. The scientific debate over whether crop production should be increased by expanding cultivated land or by increasing crop yields (intensification of agriculture) has often supported the former approach because it prevents the environmental damage resulting from land use change. In this review, however, we have stressed how some regions have lagged behind the rest of the world when it comes to adoption of new technology because it requires investments in agriculture that local, small-scale farmers often cannot afford. Thus, advocating for agricultural intensification may promote the transition from subsistence farming to large-scale commercial agriculture (e.g., through LSLAs), a process that is occurring across the developing world with important implications for rural livelihoods, local food security, and the environment. Approaches based on sustainable intensification, dietary shifts, and waste reduction appear to be possible alternatives to address future needs.

Numerous tensions are emerging within the FEW nexus, which largely relate to the interacting demands for water from the food and energy sectors. These tensions are perhaps clearest for first-generation biofuels and the confluence of multiple factors that contributed to the global food crisis of 2007/2008 (Headey & Fan, 2008). The growing importance of globalization in the food system further complicates water, food, and energy interactions by disconnecting food consumers from production, displacing land and water use across political boundaries, and obscuring the relationship between national consumption and its environmental impacts. However, the inherent linkages among food, water, and energy systems also present opportunities in that some strategies targeted at improving the sustainability of one system can have synergistic effects that serve multiple goals across all three systems. Enhancing these beneficial linkages at the FEW nexus, such as waste capture and recycling in the circular economy, will be critical to enhancing the resilience of food, water, and energy security at the global scale.

The view emerging from this article is that there are some major gaps in the understanding and management of the global FEW system. More specifically, (1) there is an urgent need to link sustainable FEW solutions with real-world outcomes and to engage in research that interacts with local experts and stakeholders; (2) more emphasis needs to be placed on nutrition instead of just food to examine the nutritional implications of different climate and management scenarios; (3) while substantial additional water will be required to support future food and energy production, it is not clear whether and where local freshwater availability is sufficient to sustainably meet future water needs. For instance, the extent to which irrigation can be expanded within presently rainfed cultivated land to close the yield gap without depleting environmental flows remains poorly understood; (4) new energy systems (e.g., unconventional fossil fuels such as shale oil, shale, gas, or oil sands) require much greater water amounts than their conventional counterparts; their impacts on the FEW nexus have just started to be explored (Rosa et al., 2017, 2018); (5) investments in energy production and mining should also account for the possibility that some of these economic activities may remain stranded (i.e., not developed) because of water scarcity (Bonnafous et al., 2017; Northey et al., 2016, 2017); (6) in addition to effects on water resources there is a myriad of environmental impacts (e.g., GHG emissions, pollution, depletion of high-grade phosphate rock reserves, and soil losses) that need to be accounted for while evaluating the environmental trade-offs of energy and food production; and finally, (7) research on FEW systems and sustainability often suffers from limited and incomplete data (e.g., sub-Saharan Africa). Therefore, there is the need for creative strategies aiming at identifying new data sources or proxies that can improve our understanding of the FEW nexus.

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All the data reviewed in this manuscript are taken from the original studies and publicly available data sets cited in the main text and figure captions. This manuscript did not generate new data. L. R. was supported by the Ermenegildo Zegna Founder's Scholarship.

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