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Rewiring food systems to enhance human health and biosphere stewardship

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Supplementary material for this article is available online

Abstract

Food lies at the heart of both health and sustainability challenges. We use a social-ecological framework to illustrate how major changes to the volume, nutrition and safety of food systems between 1961 and today impact health and sustainability. These changes have almost halved undernutrition while doubling the proportion who are overweight. They have also resulted in reduced resilience of the biosphere, pushing four out of six analysed planetary boundaries across the safe operating space of the biosphere. Our analysis further illustrates that consumers and producers have become more distant from one another, with substantial power consolidated within a small group of key actors. Solutions include a shift from a volume-focused production system to focus on quality, nutrition, resource use efficiency, and reduced antimicrobial use. To achieve this, we need to rewire food systems in ways that enhance transparency between producers and consumers, mobilize key actors to become biosphere stewards, and re-connect people to the biosphere.

1. Introduction

Humanity relies upon the biosphere to provide resilient life-support systems that foster societal development and human wellbeing [1]. However, as a society, we are reshaping the biosphere in ways that are undermining this central capacity. Human activities and technological developments have substantially increased in scale and speed since the 1950s, a period referred to as the Great Acceleration [2]. While the total material wealth, food availability, and wellbeing of humanity has improved, there is increasing scarcity of critical resources such as water, soil and energy, and ecosystem services have been degraded to such an extent that it threatens to undermine long-term societal development [3–5].

Food production is now a major driver of global environmental change, and food consumption is a key determinant of human health, wellbeing, and the social-economic development [6–10]. Between 1965 and 2005, the share of the world population living in countries with sufficient food availability doubled from approximately one third to two thirds, and the proportion of humanity living on less than 2000 kcal day^{-1} dropped from about 50% to only 3% of the global population [5]. However, malnutrition, including undernutrition, obesity, and micronutrient deficiency, is now the number one driver of decreased life expectancy, and diet related factors represents six out of the top eleven risk factors for early death [11]. Malnutrition, in all its forms, and in nearly every country, directly affects one in three people, and is

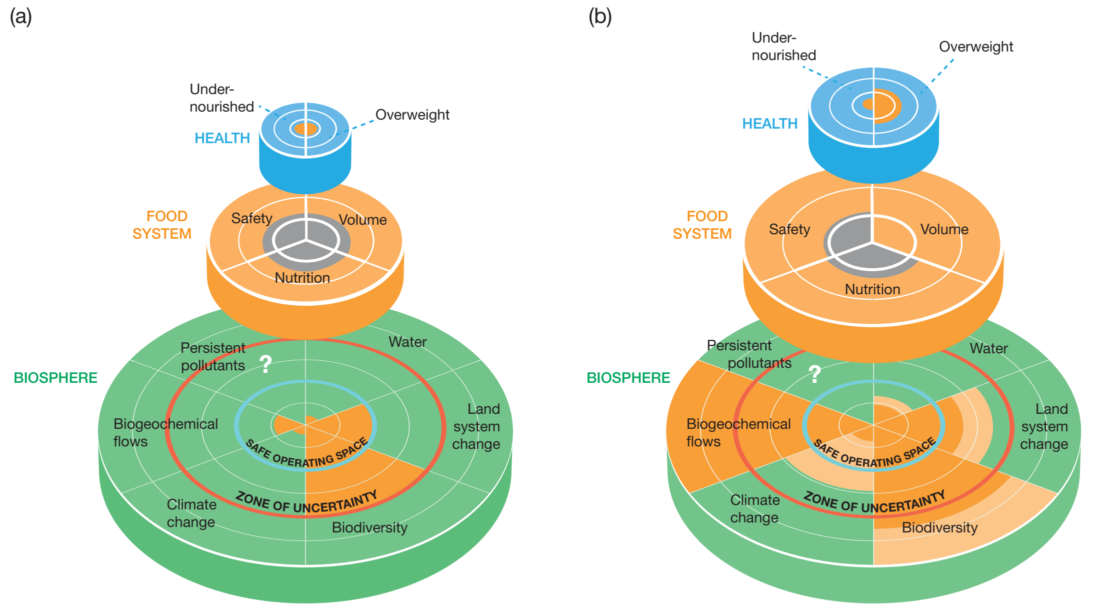

Figure 1. The food system and its impact on health and the biosphere comparing 1961 (*a*) and today (*b*). For each sub-system, negative impacts are illustrated as a contrasting colour radiating outwards. The health and food systems have grown in size indicating a larger population (health) and overall volume of food produced (food system). We are today producing enough volume per capita to feed the global population, which we did not in 1960 (grey colour wedge), but we still have problems of similar magnitude with nutrition and safety (grey). Health demonstrates that we have gone from 19% to 11% of the world population being undernourished[a] and from 23% to 39% being overweight[b] (orange). Biosphere demonstrates that food production (dark orange) substantially contributes to the overall human impact (light orange) to pushing some planetary boundaries outside the safe operating space. We did not estimate overall human impact on planetary boundaries in 1961. For data see text and supplementary information section 2 and 3.
[a] data from 1990 instead of 1961.
[b] data from 1975 instead of 1961.

responsible for serious public health problems, including both nutritional deficiencies (such as anaemia and vitamin A deficiencies) and cardiovascular and other circulatory diseases heart diseases [10]. Poor dietary habits are also reportedly one of the leading causes of low quality of life [12, 13].

Food policies that connect health and sustainability have the potential to produce strong synergies between biosphere sustainability and human health [6, 14]. For example, there is now consistent evidence that diets high in plant- and low in animal-based foods emit less greenhouse gases, use less water and energy, and reduce mortality [15–17]. However, much remains to be done to foster healthy diets and improve biosphere stewardship of food production landscapes and seascapes [6, 18]. To find solutions, we need to better understand the key processes that shape consumption and production practices, and that connects consumers and producers, both to each other, and to the biosphere. The Great Acceleration has substantially altered these relations in ways that are not yet fully understood.

In this paper we use a social–ecological framework [19, 20] to illustrate changes in food systems since the 1960's, how these changes have impacted human health and the biosphere, and how they have altered interconnectedness of social and biophysical dimensions of food systems. We finally identify a set of solutions to improve health and biosphere stewardship.

2. A social–ecological framework for sustainable food systems

During the last decades, frameworks that examine relations between global food systems, human health and/or sustainability have been developed (see for example [21–24]). Many of these frameworks focus on identifying all the components of food systems, making the frameworks so complex that it is hard to identify the interlinkages between the biophysical and social systems that shape production and consumption patterns. In this paper we use insights from social-ecological systems research [19, 20, 25] to develop a simplified framework that focuses on the key feedbacks between production and consumption.

We conceptualize diet related human health as a product of food systems in which it is embedded, and food systems in turn are supported by the biosphere (figure 1). This conceptualization is based on the classic conceptualization of ecological economics [26]. It sees the economy as embedded within society, which is embedded within the biosphere that sets fundamental boundaries for human activities [19, 20] (see also supplementary information (SI), figure SI1 available at stacks.iop.org/ERL/12/100201/mmedia).

We use this conceptualization to compare changes in health, food systems and biosphere during the Great Acceleration. In terms of food systems changes we look at food *volume, nutrition*, and *safety*. The overall

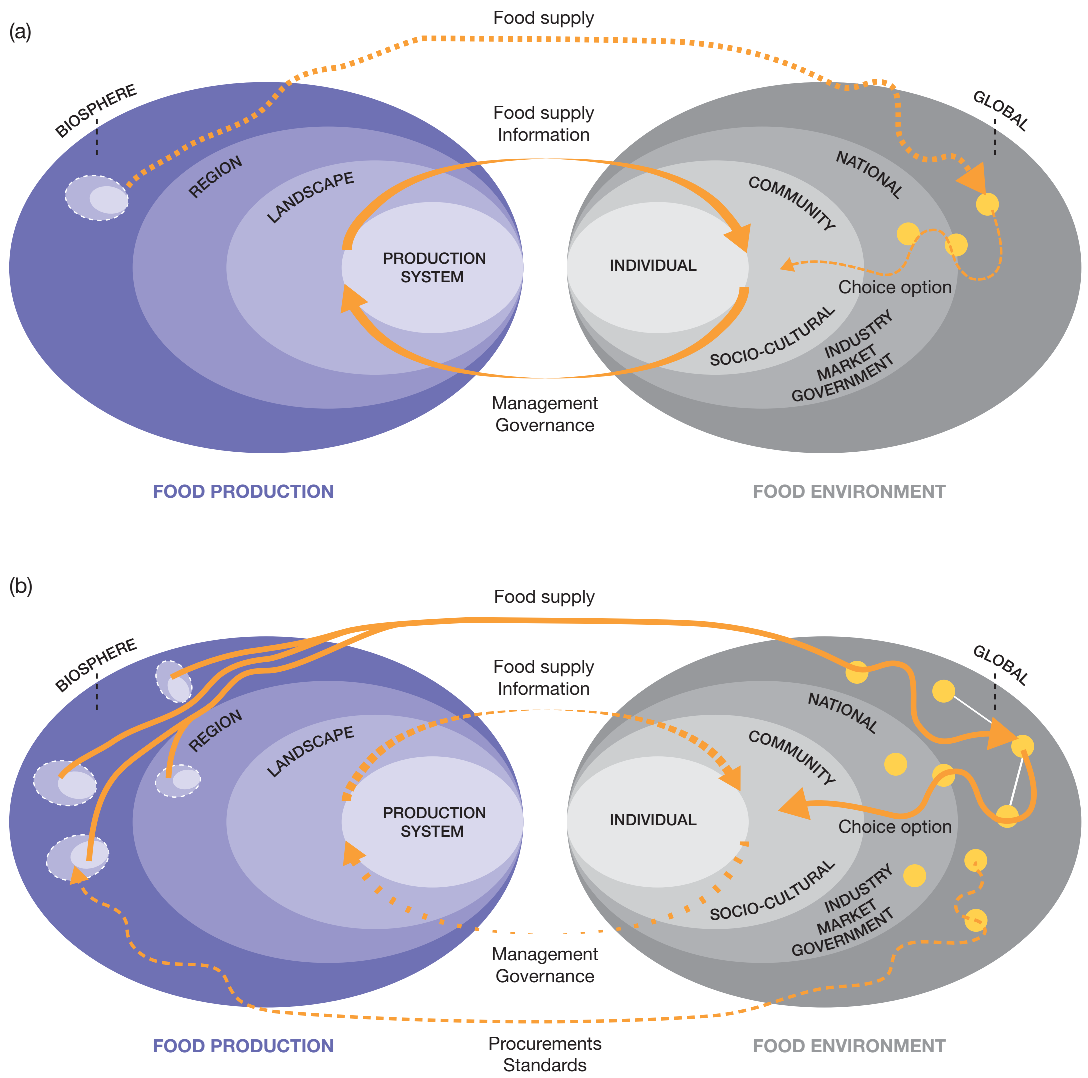

Figure 2. Processes that drive change in food production and consumption. The figure is a simplified illustration of how the links between consumption and production has changed between 1961 (*a*) and today (*b*). Solid lines illustrate strong interactions, dotted lines weak interactions. Yellow circles illustrate key actors (companies and institutions) operating at larger spatial scales. The figure illustrates that processes at larger scales are more influential today, with weaker links between local production and consumption. Some key actors have become more dominant with unproportional influence on consumers' choice options, food supply, and food production practices.

food system can grow as the volume increases, and its quality can change in relation to altered capacity to provide enough calories per capita, the nutritional content and its safety. Health is represented by the proportion of the global population that is *undernourished* and *overweight*. The health dimension can also grow as it represents the overall size of the population (if population growth, more people need to be fed). The biosphere is represented by the *planetary boundaries* [27, 28], where we analyse the food system impacts on six of the nine original planetary boundaries, chosen as the ones where we assessed that food was a large contributor. The outcomes of food systems on the planetary boundaries can be within the safe operating space, in the zone of uncertainty (where there are increased risks of catastrophic tipping points), or outside of the planetary boundaries (with large risks of destabilising the biosphere) [adapted from 24, 22]. The biosphere cannot grow or expand.

Biophysical and socio-economic contexts at larger scales shape both production and consumption in food systems (figure 2). The global biosphere both supports food production systems and is affected by the accumulated impacts of farming and fishing at smaller scales. Producers' decisions on what to produce or harvest are shaped by socio-economic factors and policies, as well as the environment in which they are embedded. Socially, individual food choices are influenced by local community context including culture, class, norms, values, and ethnicity. At regional and international scales food choices are shaped by formal and informal markets, corporate lobbying, as well as governmental policies, subsidies and trade agreements. These large-scale factors enable, and signal to communities what to eat by influencing availability, affordability, convenience, and desirability of various foods, while the consumer demand at a smaller-scale can influence actions taken by larger scale actors.

3. Outcomes of changes in food production on human health and the biosphere

The Great Acceleration substantially changed the world's food systems in ways that produced considerable consequences for human health and the biosphere. We compare the start of the Great Acceleration in the early 1960s, which also corresponds to the start of food production data collection by the UN Food and Agriculture Organization (FAO), with the current situation, i.e. the most recent year for which data on food, health, and the biosphere were available (figure 1). Below we describe change in the food system in terms of volume, nutrition and safety. We then discuss how those changes influenced health (being overweight, and undernourishment), and the biosphere (in terms of planetary boundaries). For details of methods and data, see SI, sections 1 and 2.

3.1. Food production systems

Since 1961, the *volume* of food production in terms of total kcal produced has increased more than three-fold (table SI1). These gains exceeded population growth (an increase with 240%) and thus increased food production capita from 2189 kcal cap day^{-1} in 1961 to 2884 kcal cap day^{-1} today. Production of cereal crops increased over 400%, cattle production increased with 230% and pigs with 450%. Chicken production grew thirteen-fold. More recently, aquaculture has been the fastest growing food sector. Between 1990 and 2010, cultivation of fish and shellfish in terrestrial freshwater and marine systems increased over four-fold [30]. Along with increases in overall production, productivity per animal and/or hectare has also increased. Global cereal productivity per hectare increased 2.2-fold [31] and the amount of meat produced per pig and chicken almost doubled [32].

The nutritional content of food has not improved and may have declined since the 1960s. Hereford and Ahmed [33] show that current food production per capita can provide enough calories, but likely not enough nutrients for fulfilling human-health requirements. For example, the global fruit and vegetable supply per capita is insufficient, and availability of pulses (excluding soybeans that are mainly used as animal feed) has declined [33]. Further, DeFries *et al* [31] showed how the global cropland area devoted to high nutrient-dense cereals such as barley, oats, rye, millet, and sorghum collectively has declined from 33% to 19% between 1961 and 2013, while the high-yielding cereals that are less nutrient dense (rice, wheat, and maize) increased from 66% to 79% [31]. Human consumption of unhealthy food items has also increased. For instance, consumption of processed meats and sugary sweet beverages increased by as much as 35%–50% between 1990–2015 [10].

Food safety has both improved and decreased since the 1960s. Improvements in food handling and supply chain traceability have reduced the frequency of outbreaks of foodborne diseases. However, diseases caused by consuming unsafe food still kill 420 000 people yr^{-1} (40% of which are children under five years) [34]. However, there has been little evaluation of the impact of food safety regulations on food systems and sustainability, and there are examples of where new food safety regulations have had adverse effects on rural livelihoods, biodiversity, and sustainability [35]. Furthermore, changes to food systems are also creating new health risks. One example is the overuse of antimicrobials, substances that kill or inhibit the growth of microorganisms, which is producing antimicrobial resistant strains of human pathogens [36]. Between 2000 and 2010 antimicrobial use grew by 33% [36], and absent regulation furthers this trend. Increases in antimicrobial resistance impair human health by increasing the spread and risk of diseases [37, 38], and increase the risk of surgery [39]. Furthermore, over use of antimicrobials alters gut microbiota in ways that have been linked to obesity [40, 41].

3.2. Health outcomes

Since the 1960s, more people can live longer and healthier lives. Changes in food system have reduced undernourishment, but created new problems due to over-nourishment. From 1990–2015 the proportion of the world's population that are undernourished almost halved dropping from 19% (one billion people) to 11% (800 million people) [42]. Over the same time period, the proportion of children whose growth was stunted dropped from 40% to 24% [42] (table SI1). While undernourishment has decline, over-nourishment has increased. Today, 44% of countries, where data is available, contain both undernourished and obese populations [10]. Since 1980, the world's population of obese people has more than doubled to 600 million. The proportion of people who are overweight rose from 23% to 39% (1.9 billion) [43]. Obesity is currently increasing most rapidly in low and middle-income countries. Diet-related non-communicable diseases, particularly cardiovascular diseases and diabetes, are also rising as a consequence [43]. These diet related diseases represent 80% of mortality in low and middle-income countries [43].

3.3. Biosphere outcomes

Since the 1960s, humanity's impact on the biosphere has greatly increased, and a substantial part of this impact is due to changes in food systems. No universal metrics for tracking the state of biosphere outcomes exist or have been consistently used since the 1960s. Here, changes to the biosphere are estimated using the planetary boundary framework, which also includes the conceptualization of a safe-operating space for the Earth system [27, 28]. Steffen *et al* [28] quantified whether human activities currently are within this safe operating space, in the zone of uncertainty or outside the planetary boundaries for nine different variables.

Here, the impact of current food systems on the six control variables most impacted by food systems is estimated, i.e. for biogeochemical flows, biodiversity, climate change, land system change, water, and persistent pollution (all data and methods can be found in the SI, section S2).

This estimate suggests that in the 1960s, humanity was already outside the zone of uncertainty for the biodiversity control variable, and that this was largely due to changes in food systems (figure 1(*a*)). By 2015, both biodiversity and biogeochemical flows exceed planetary boundaries due to food systems. Land system change and climate change are outside of the safe operating space, with land system change being pushed into the zone of uncertainty by food systems alone, while food is suggested to drive 25% of climate change [44]. Humanity is still within the safe-operating space for freshwater, where food production accounts for about 70% of global freshwater use [45]. Little is known about persistent pollutions. In summary, by 2015, the biosphere was outside the safe operating space for four variables, with food systems being responsible for crossing three of these boundaries. (SI section 2, table SI2 and table SI3).

3.4. Synthesis

Our findings are synthesized in figure 1, which compares health, the food system, and the biosphere in 1961 and 2015. Since the start of the Great Acceleration, the global food systems have increased in both overall and per capita volume, possibly slightly reduced nutritional content of food, and improved some aspects of food safety while reducing others (figure 1, middle layer). This has resulted in mixed impacts on human health. Currently, we can feed more people, and have decreased the proportion that are undernourished, while we have increased the proportion of overweight and obese people (figure 1, top layer). Food system development has also resulted in reduced resilience of the biosphere, since four out of six planetary boundaries has crossed the safe operating space, largely driven by food (figure 1, bottom layer) (for a summary of data on assumptions on biosphere outcomes, see table SI3).

4. Processes that have driven change in food system, health and biosphere outcomes

The processes that connect producers and consumers of food have also changed dramatically during the Great Acceleration, which affects management and governance of food production systems. Some of the key feedbacks, and especially the scales at which they occur, have changed between the biophysical production systems and the social systems influencing consumption. Here, we primarily focus on how the role of trade and consolidation of key actors during the Great Acceleration have altered the spatial scales of flows of *food*, and *information* about production systems, in ways that influence *governance and management of food production* system, as well as *choice options* for consumers (figure 2). Trade and consolidation of key actors are two processes where substantial change has happened, and which have the capacities to alter the interrelations and scales of interactions between the social food environments and the biophysical food production systems.

4.1. Increased trade changes feedbacks between production and consumption

Food has been traded for millennia, but the distances and frequency of this trade have increased substantially during the Great Acceleration. Globally, food imports quadrupled between 1965 and 2005 [5], resulting in a more even food distribution [5], but also a distancing of producers and consumers. Currently 38% of the world's fish and fishery products, 14% of poultry, and 13% of cereal production, are traded on international markets [46]. For fisheries products this figure grew by 50% between 1998 and 2008 [46].

When nations specialize, they generally become more efficient and reduce costs through economies of scale, thus reducing prices of the specific food commodities produced [47]. Similarly, a competitive advantage can be used to attain global sustainability of production systems by identifying the geographical regions best suited for e.g. reducing carbon emissions from land use change [48] or redistributing global fertilizer use to minimize eutrophication [9]. Trade in agricultural, fisheries, and forestry products are part of many countries' development strategies. Indeed trade liberalization has been a key economic policy for many nations during the last half century, particularly for agricultural products and fish [49]. However, globalized trade also means that similar food commodities are available globally, streamlining diets and facilitating increasing consumption of saturated fats, red meats, and empty carbohydrates [50, 51].

In terms of production systems, the complexity of global production networks means that first tier suppliers or retailers often do not have full understanding of the extent and impact of their trade [52]. This is further aggravated by decreasing food prices, which do not include the costs of environmental and social externalities, and which have reduced our capacity to monitor and make decisions acknowledging effects on human health and the biosphere [52, 53]. Crona *et al* [53], show that price signals indicating stock decline in fisheries can be masked in multiple ways in today's production system, including technological advancements in gears, or through substitution. In the latter case fish species are substituted or even falsely labelled, resulting in consumers remaining unaware that the species or stock they normally consume may no longer be harvestable.

Consequently, consumers in today's globalized seafood production system are not well positioned to prevent local fisheries collapsing through sustainable purchasing behaviour, as the system does not afford them the signals and transparency needed to

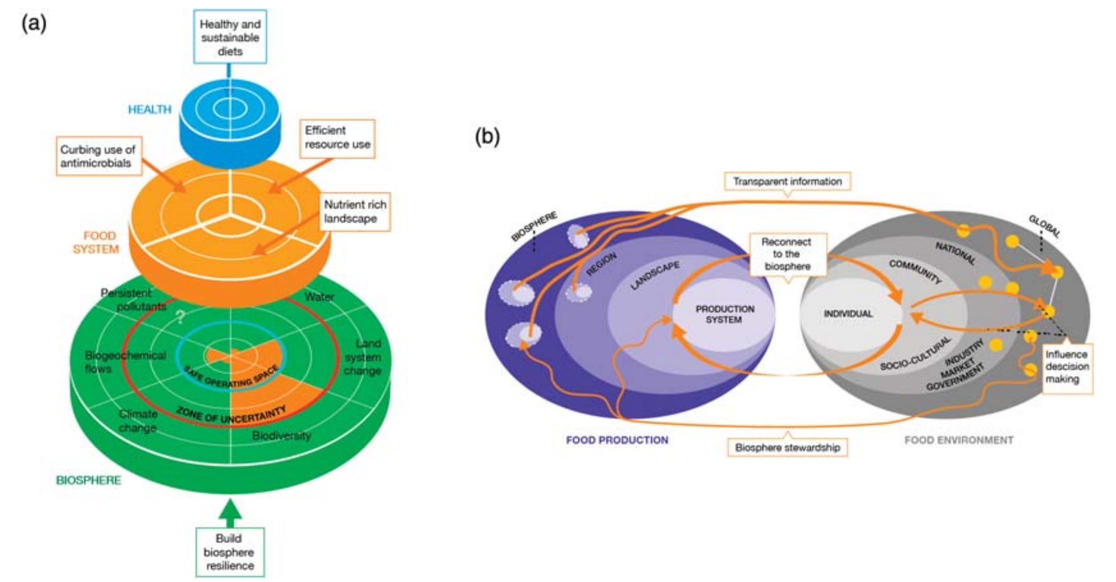

Figure 3. Entry points for more healthy and sustainable solutions to food, health and sustainability focus on (*a*) changing the production system by improving nutrition and resource use efficiency, curbing the use of antimicrobials and building resilience, and (*b*) rewiring the links between production and consumption by enhancing transparency between producers and consumers, improving the decision context in food environments, mobilizing key actors to become biosphere stewards, and re-connecting people to the biosphere.

do this. Producers and consumers have become more decoupled, as consumers have less information about food production methods, making social and environmental impacts from production less transparent (figure 2). However, some *governance* structures are being adopted to improve transparency in *procurement practices* and *standards,* which can be used to support better production practices (see also section 5.2.2).

4.2. Consolidated food systems affect consumer food choices and production practices

The total number of actors that produce, process, and move food to consumers has increased over time [54], yet the power in the supply chains has been consolidated to a few actors that have disproportionate influence over food production, ranging from retailers to primary sourcing agents such as the fisheries and grain distributors (e.g. [55–57, 58]) (figure 2). Consequently, consumer demand has less influence over supply and management practices in production systems. Instead, individual food choices are often increasingly constrained by the strategies of lead firms in food value chains affecting affordability and availability [59].

The spread of supermarkets and convenience stores has had a major influence on the options available to consumers. Retailers are important actors responsible for considerable consolidation in the downstream end of food supply chains. Rapid increase in supermarkets and convenience stores has been driven by urbanization and rising number of women in the workforce, driving demand for more convenient foods in both developed and developing nations [58]. First, their purchasing departments decide on food options, prices, promotions, and customer education [59–63]. This affects quality, availability, and sustainability of food options and has been a key factor invoked to explain the growing consumption of processed and fast food, oils and sugar-sweetened beverages, all at the heart of the growing burden of obesity [51]. Secondly, centralized procurement systems have limited the ability of small-scale producers to compete [64], instead favouring primary suppliers that are vertically integrated to handle production, processing, and packaging, as well as wholesale and retail distribution throughout the market chain [52, 65]. In fisheries, this consolidation drives retail prices down and fishers become 'price takers' rather than dictating prices to reflect the cost of catching increasingly scarce fish [66].

Consequently, compared to the start of the Great Acceleration there are today weaker feedbacks between local production and consumption [64]. There are, however, stronger feedbacks at larger scales, where interaction between production and consumption is largely driven by a limited number of key actors that influence both supply and production methods of food, and the options that consumers have (figure 2).

5. Finding solutions by rewiring food systems and improving production

This new interconnected and rapidly changing world can provide opportunities for human wellbeing and development by embracing positive food systems advances, such as sufficient volumes, and more variable and convenient food choices. However, we need substantial changes to food systems to reduce malnutrition in all its form, and to ensure food systems that have less impacts on the planetary boundaries (figure 3). This section does not present a comprehensive list of

Box 1. Initiatives that enhance resource use efficiency for improved sustainability

Pulses on the plains. Shifting protein consumption from animals to legumes is one way of enhancing recourse use efficiency. Legumes could also help reduce our need for nitrogen fertilizers (nitrogen fixers), especially if intercropped with other crops. Scientists predict that the demand for pulses could increase substantially, but public campaigns and other efforts are needed to change peoples' perceptions and habits. In the US, pulses are not typically grown, apart from soybeans, partly because they require extra effort in weeding and with pests. But increasing demand for pulses in India is now driving increasing production on the plains in the US [80]. In Sweden the areal cultivated with legumes has increased with 55% since 2011, primarily due to changes in EU subsidies, but also due to a rapid increase in consumer demand, mainly due to sustainability concerns [81].

Food waste initiatives. There are many initiatives to tackle food waste around the world, including digital solutions such as apps that guide consumers or farmers in ways of sharing left over food, and smart kitchen and storage technologies. However, regulatory frameworks and educational efforts are potentially even more important. France is one country standing out in terms of national regulations, since they have made it illegal for supermarkets to waste food, forcing them to donate leftovers to food banks and charity. French restaurants have also been legally forced to offer 'doggy bags' (or '*le gourmet bag*' as it has been called in France).

important changes needed in food systems. Instead, the examples are chosen to represent different dimensions (safety, volume, nutrition) of food systems of relevance for health and biosphere outcomes (figure 3(*a*)), and solutions addressing interconnections between food production and consumption (figure 3(*b*)). There is scientific support behind the suggested solutions, and they have previously been discussed in the literature.

5.1. Improving food production systems for better health and sustainability outcomes

5.1.1. Create nutrient-rich landscapes

The volume-focused production policies should be complemented by stronger efforts to secure nutrition rich production, i.e. evaluating and selecting crop varieties, fish and livestock based on their nutritional content. This requires that new metrics are being developed that account for the nutritional yields of crops and production systems. These can be similar to nutritional facts labels, but adapted for production units (e.g. one hectare) [31]. One approach is to manage for 'nutrient-rich landscapes', which often involves increased production diversity at different scales [67–70]. Nutrient-rich landscapes have been shown to improve the nutrition of people in impoverished smallholder communities [71], especially when these production systems are coupled to strengthened market access [72].

5.1.2. Efficient use of resources by cutting waste and changing diets

Efficient demand-side solutions, such as cutting post-harvest losses [9], and shifting dietary patterns [15, 16] can reduce pressure on natural resources. Since we currently waste up to a third of all food produced, tackling food waste across the supply chain is a growing item on many agendas (for examples, see box 1). In terms of more resource efficient dietary patterns, recent estimates have shown that we could potentially provide enough calories to meet the basic needs of an additional four billion people if the current crop production used for animal feed and other non-food uses (including biofuels) were targeted for direct consumption [8]. Two recent systematic reviews [15, 16] show that greenhouse gas emissions, land conversion, and water use can be reduced by up to 50%–80% by adopting plant-based diets that also are beneficial for health outcomes. Shifting proteins from animal based to leguminous crops is an important effort (see box 1 for examples).

5.1.3. Reducing antimicrobial use

Intensification is a general trend in animal farming and it is therefore urgent to find means that limit excessive antimicrobial use within the animal food production sector. The challenges are in large similar between developed and developing countries, and also between terrestrial and aquatic systems [73]. The global population of susceptible microbes can be considered a common pool resource where no individual or single country has a strong enough incentive to conserve this 'commons', thus action needs to be taken through coordinated global efforts [73]. These actions includes substantial scaling back of the massive overuse of antimicrobials, national commitments to educational campaigns about the consequences of antimicrobial resistance, better surveillance and open data that allows tracing of antimicrobial use, and routine surveillance and containment initiatives of the most dangerous multiresistance strains [73].

5.1.4. Foster resilience of production systems and the biosphere

Strengthening biodiversity and multifunctionality of both production systems and the landscapes in which they are embedded is fundamental for building resilience of both production itself, and of the biosphere [74–77]. This implies accounting for the multiple ecosystem services and social benefits that food producing systems can deliver for humanity beyond food itself, such as pollination, water filtration, and recreation, but also diversity of livelihood options [78, 79].

5.2. Rewiring food systems and enhancing biosphere stewardship

5.2.1. Reconnect people to the biosphere for improved stewardship

The disconnect experienced as the food production system becomes more distant from consumers, and dominated by a few actors calls for initiatives that can reconnect individuals and communities to food,

Box 2. Initiatives that rewire the links between consumers and producers

The Nossa Feria markets in Curitiba. The city of Curitiba in Brazil has established a program called *Nossa Feria* to ensure access to fresh vegetables and fruits and which rotates weekly in lower income neighbourhoods. The markets are regulated so they offer a mix of fresh and local produce at 40% below the average retail price. The programme is developed to also enhance rural livelihoods. The municipality acts as the 'middle man', and ensures that farmers in the peri-urban areas get a consistent and stable source of income from their sales. The market also ensures a meeting point between the urban population and the peri-urban farmers.

Behind the Brands. The Oxfam campaign 'Behind the Brands' aims to make it easier to assess the environmental and social performance of big actors in the food industry by making their work visible and comparable, which in turn can challenge these companies to improve on their work. Ten of the world's most powerful food and beverage companies[8] are tracked and scored in seven areas—women, small-scale farmers, farm workers, water, land, climate change, and transparency. The scorecard reports and rankings (assessed once or twice annually) can be found on an interactive website where individuals can communicate directly with companies to urge them to take responsible actions. The first assessment was done in February 2013. The initial overall scores were between 19% and 54% (on a scale from 1%–100%). At the last assessment published in April 2016, the scores raised to be between 26% and 74%, which indicated improvements, but also that much work remains to be done. For the transparency criteria, the scorecard assesses how committed companies are to disclosing where they source their products and raw materials from, and under which conditions, as well as examining their lobbying practices, tax disclosure, and how they enforce their requirements on suppliers [94].

The Global Salmon Initiative (GSI) was launched in 2013 and involves 12 of the largest salmon producers in the world, representing around 50% of global salmon production by volume. The initiative aims at stimulating better environmental practices in the salmon industry and, ultimately, continued production of sustainable and healthy protein for a growing world population. The prime focus is currently on feed and nutrition, biosecurity and meeting industry sustainability standards. In 2016, 110 farms were certified by the Aquaculture Stewardship Council (ASC), and all salmon farms are proposed to be certified by 2020. While the environmental effects of this initiative remain to be thoroughly evaluated, GSI create incentives and pressure for farmers to enter eco-certification and thereby increase the transparency between consumers and producers. Moreover, the GSI constitutes an example of collaboration between industry partners to stimulate enduring change, thereby holding potential to generate benefits for both business and the environment [95].

Keystone dialogues for ocean stewardship. Eight of the world's largest seafood companies have committed to improving transparency and traceability, and reducing illegal, unreported and unregulated fishing in their supply chains. Antibiotic use in aquaculture, greenhouse gas emissions, and plastic pollution are other areas that will be addressed. The seafood companies also committed to eliminating any products in their supply chains that may have been obtained through modern slavery, including forced, bonded, and child labour. The effort came about after a scientific analysis identifying the top 13 companies responsible for most of the fisheries in our oceans globally [55], and then invited these to a dialogue on how to increase their role as biosphere stewards [96].

facilitating a broader engagement with food systems in healthy and sustainable ways [82]. In some places, culture and language still remain tightly intertwined with the ecology of the landscape, creating and maintaining 'biocultural refugia' [74]. In such contexts, food connects human and ecosystem health through daily operations, agricultural and post-harvest practices, and cultural rituals [82–86]. In places where many of these connecting practices have been lost, there is growing interest in locally produced and branded products, slow-food movements, and farm-to-fork restaurants, which are all efforts to reconnect people to farming. In urban areas, community gardens can enhance knowledge about food production and food systems, as well as lead to public health benefits from the increased access to green spaces, which can serve as recreation and promoters of physical activity, cultural heritage, and sense of place [87–89]. One example of an effort to reconnect urban citizens with farmers in the peri-urban region is the *Nossa Feria* markets in the Brazilian city of Curitiba (see box 2). Still, these niche efforts are not enough to provide the bulk of people's diets, and will unlikely be what supports the major part our global food needs. While not every component of our daily diet will be tightly linked to the biosphere, at least some of these experiences can cognitively reconnect people with the biosphere and that connection can improve the capacity of people to act as biosphere stewards [1, 20].

5.2.2. *Enhance transparency between producers and consumers*

Globalization of food systems has made tracing food from 'farm to fork' or 'sea to plate' increasingly complex. We need to improve our capacity to trace the impacts of food production across the supply chain. A first step could be for actors in food systems to map the social and ecological aspects of their own supply chain [51]. Certainly, third-party certifications, product standards, and eco-labelling have played their role in fostering transparency, and improving production practices and information provided to consumers [90, 91]. Assessments of a food product's full lifecycle are other ways to trace environmental and social impacts, but even those present substantial limitations [92, 93]. Governments and policy makers can play an important role in reducing the producer-consumer knowledge gap and increasing transparency. Efforts that both government and non-governmental actors can take include educational initiatives, quality

[8] Associated British Foods (ABF), Coca-Cola, Danone, General Mills, Kellogg, Mars, Mondelez International (previously Kraft Foods), PepsiCo and Unilever. These 'Big 10' collectively generate revenues of more than $1.1bn a day and employ millions of people directly and indirectly in the growing, processing, distributing and selling of their products. Today (Feb 2013), these companies are part of an industry valued at $7 trillion, larger than even the energy sector and representing roughly 10% of the global economy.

control, food labelling, and taxation among other things. To successfully increase transparency, new networks and agreements across sectors and domains need to be developed. In box 2 we give examples of these new types of collaborations that enhance transparency between consumers and producers (especially the Behind the Brands campaign and the Global Salmon Initiative).

5.2.3. Influence consumer decisions

Although there is accumulating evidence on what constitutes healthy and sustainable dietary patterns, there is less scientific consensus about what enables people to adopt better diets. Remaining questions include how to structure and implement policy interventions, regulations, and incentives to most effectively influence behaviour [6, 97]. Some efforts try to change individual behaviour though nudging tools that entice people to behave in certain ways without using coercion or force, examples include reducing a plate size for people to consume and waste less [98, 99]. Certification programs and wallet cards may also nudge people's behaviour, but they can also disseminate mixed messages which can leave consumers with a choice dilemma between health, environmental sustainability, and social factors [100, 101]. International coordination can help avoid a race to the bottom, where the effect of consumer behaviour initiatives in one place can push externalities elsewhere. This can, for example, be the case when food products, processing, or markets are sent to other locations where restrictions are more relaxed, costs are lower, or consumers are less demanding of food safety, sustainability, and/or wellbeing issues in supply chains [6].

5.2.4. Mobilize key actors to become biosphere stewards

The emerging dominance of certain key actors, especially in the corporate sector, who have disproportional and unique roles in global dynamics have placed them as potential stewards for increasing human and planetary health [55]. However, these actors are sometimes unaware of their own potential to foster positive change [51], and even if they are aware, they may not know where to begin. Industry roundtables and councils are starting points, where competitors are banding together to tackle tough sustainability problems, signal interests, and recognize that competitors need to work together to address global food system problems [102]. The Keystone dialogues (see box 2) is one example that aim of enhance capacity among the largest fishery companies to become stewards of the ocean. These industry efforts can be the beginning of stewardship, which is an adaptive process of responsibility to shepherd and safeguard the valuables of not just oneself but also of others [20]. Stewardship requires continuous learning and knowledge generation across knowledge systems [103]. To be successful, these processes will require voluntary agreements as well as strong regulatory and fiscal frameworks [97].

6. Conclusions

We used a social-ecological framework to illustrate how major changes to the volume, nutrition and safety of food systems between 1961 and today have almost halved undernutrition while doubling overweight, and resulted in reduced resilience of the biosphere, pushing four out of six analysed planetary boundaries across the safe operating space of the biosphere. There needs to be substantial changes in food systems for them to strengthen human health and promote biosphere stewardship. These changes include the promotion of foods rich in nutrition (rather than volume alone), more efficient use of natural resources in food production, addressing future risks with antimicrobial use, and enhancing the resilience of production systems and the biosphere (figure 3(*a*)). Before the Great Acceleration, there were stronger feedbacks between the local food producing systems and consumers (figure 2(*a*)). Current trade patterns and consolidation of the food sector has resulted in disconnect between people and the biosphere, with asymmetric feedbacks between production and consumption making food systems opaque (figure 2(*b*)). People still have a strong dependence on food production systems, but the capacity to monitor changes in these systems in ways that can affect demand for more sustainable and healthy production have declined. We need to rewire different parts of food systems, to enhance information flows between consumers and producers at different scales, influence food-system decision makers, foster the biosphere stewardship of key actors in food systems, and reconnect people to the biosphere through the culture of food (figure 3(*b*)).

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