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Trends in Global Agricultural Land Use: Implications for Environmental Health and Food Security

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Abstract

The eighteenth-century Malthusian prediction of population growth outstripping food production has not yet come to bear. Unprecedented agricultural land expansions since 1700, and technological innovations that began in the 1930s, have enabled more calorie production per capita than was ever available before in history. This remarkable success, however, has come at a great cost. Agriculture is a major cause of global environmental degradation. Malnutrition persists among large sections of the population, and a new epidemic of obesity is on the rise. We review both the successes and failures of the global food system, addressing ongoing debates on pathways to environmental health and food security. To deal with these challenges, a new coordinated research program blending modern breeding with agroecological methods is needed. We call on plant biologists to lead this effort and help steer humanity toward a safe operating space for agriculture.

Contents

1. INTRODUCTION

Agricultural lands constitute the largest biome on this planet (43), occupying a third of the global ice-free land area (117). Agriculture is still a major livelihood for 40% of the world's population and contributes to ∼30% of GDP in low-income countries (**http://data.worldbank.org/**). It also provides food, fiber, biofuels, and other products for the current human population of 7 billion.

Agriculture provides more than enough calories for all people on the planet, yet 800 million people remain undernourished (54), and approximately 2 billion suffer from micronutrient deficiencies (162). Furthermore, human populations are projected to grow to nearly 10 billion by 2050 and more than 11 billion by 2100 (165). At the same time, with increasing wealth, there is greater per capita consumption of meat, refined fats, refined sugars, alcohols, and oils, which are either more resource-consuming to produce or of limited nutritional value than diets comprising grains, legumes, fruits, and vegetables (155). Thus, there is increasing pressure on agriculture to meet the needs of current and future human populations.

Undernourishment: a condition in which dietary energy consumption is less than a predetermined threshold required to conduct sedentary or light activities

Agriculture, however, is already one of the greatest environmental threats (156). Clearing forests and other natural vegetation results in climate change and biodiversity loss. Agriculture is the biggest user of freshwater on this planet and is the major cause of freshwater eutrophication. Balancing the environmental costs of agriculture with the need to feed current and future populations is a major challenge. This is doubly so, as global environmental changes can feed back and hamper future production. Climate change is already a major threat to production, estimated to have caused ~4–5% declines in maize and wheat production over the last 30 years (96).

Malnutrition: a diet that is either deficient or excessive in calories or nutrients, or has micronutrient deficiencies, to the extent that it affects health

Many solutions have been proposed for navigating the pathway to a sustainable food system (55). Some scholars advocate for new technological systems, such as genetic engineering (49) or vertical farming (38), whereas others argue for organic agriculture (11) or local food systems (71). Still others argue that agriculture does not need a revolution and that we simply need to improve current farming practices (31). Other arguments shift the focus from farm-level solutions to the entire food supply chain, from production to processing to consumption (80), and consider issues such as food waste and diets (89, 155). Some authors question the entire framing of the sustainable food challenge, suggesting food sovereignty as an alternate paradigm (90, 176).

In this article, we start by reviewing the major trends in the evolution of agriculture from the Industrial Revolution to the emerging trends and projections for the twenty-first century. As alluded to above, these trends generally depict success in terms of increasing production, but problems of hunger, malnutrition, and environmental impacts remain. Accordingly, the remaining sections of this article address the implications of these land use trends for environmental health and food security, touching on current debates and controversies. We conclude by drawing implications for plant biology. The scope of our review is limited to crops and livestock and does not consider fisheries or forestry.

2. THREE CENTURIES OF EXPANSION—CHANGES SINCE 1700

Humans have modified the Earth's landscapes since time immemorial (124, 137). First through the control of fire, then through the domestication of plants and animals, and finally through the harnessing of energy from fossil-fuels, humans have greatly expanded their footprint on this planet (164).

But the extent and pace of human land use activities accelerated over the last 300 years (163), with the emergence of the Industrial Revolution and associated rapid growth and transformation of human societies. Between 1700 and 2007, croplands and pasturelands each expanded fivefold (~3 to ~15 and ~5 to ~27 million km^2, respectively) (**Figure 1**). Most cropland expansion replaced forests, whereas most pastureland expansion replaced grasslands, savannas, and shrublands (**Figure 1**), with some notable exceptions (e.g., the North American prairies were replaced by croplands, whereas a large amount of Latin American deforestation today is still for grazing).

The global expansion of agriculture followed the development of human settlements and the world economy (68, 100, 125). In 1700, large-scale agriculture was mainly confined to the Old World (**Figure 2**), to Europe, India, China, and Africa (118). European colonization created new settlement frontiers in the Americas, Australasia, and South Africa, while Russians moved into southern Russia and east of the Ural Mountains (68). Between 1850 and 1950, agriculture expanded rapidly in North America, starting on the Eastern Seaboard and migrating westward over time, and also pushed eastward in the former Soviet Union (118). However, in the last 50 years, the agricultural frontiers have shifted to the tropics, toward Latin America, Southeast Asia, and Africa (118). Meanwhile, many temperate regions of the world witnessed stabilization of agricultural lands and even abandonment. In North America, as the agricultural frontier shifted west, croplands were abandoned along the Eastern Seaboard around the turn of the twentieth

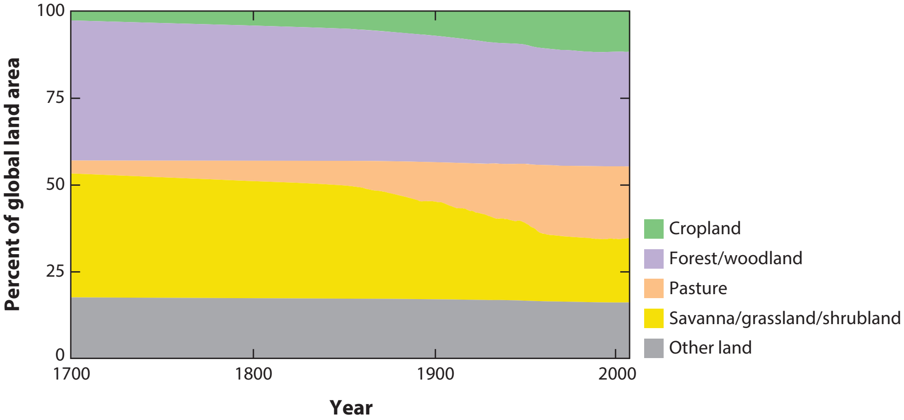

Figure 1

Global land cover trends from 1700 to 2007. Estimates of cropland and pasture area are based on historical reconstructions using methods described in References 27 and 2. Cropland and pasture area were overlaid on a map of global potential natural vegetation (27) to estimate changes in the other land cover categories.

century, followed by regeneration of the eastern forests during the twentieth century (72, 120, 175). Similarly, croplands have decreased in China and Western Europe (100). More recently, post-Soviet abandonment of agriculture occurred in Russia, Ukraine, and Belarus (132). Some abandonment of agriculture followed by regrowth of forests has also occurred in parts of Latin America, although rapid deforestation continues elsewhere on that continent (2).

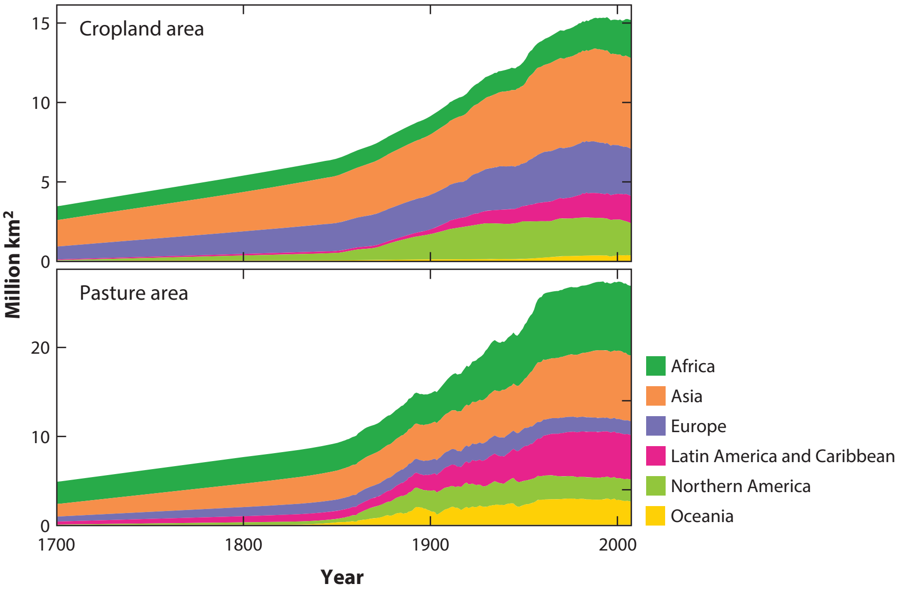

Figure 2

Regional trends in cropland and pasture area from 1700 to 2007. Estimates of cropland and pasture area are based on historical reconstructions using methods described in References 27 and 2.

3. THE GREEN REVOLUTION—CHANGES SINCE 1960

Despite inexorable agricultural expansion over the past 300 years, clearing has slowed since the 1950s. Thus, although rapid clearing of tropical forests and savannas for agriculture continues (92), these rates are small compared with those affecting temperate latitudes between 1850 and 1950 (**Figure 2**).

Despite reduced clearing rates, and reduced agricultural land area per capita globally, our agricultural lands have continued to provide food and other agricultural products for the rapidly rising human population. Indeed, cereal production per capita increased from 0.29 to 0.39 tonnes per person between 1961 and 2014 (**http://www.fao.org/faostat/en/#home**) as a result of increasing productivity of land over time. The Green Revolution is the term commonly used to denote the suite of technologies that enabled crop yields (i.e., crop production per unit area) to increase rapidly in Asia and Latin America since the 1960s.

Green Revolution: new crop varieties and increased inputs that caused dramatic yield improvements in Asia and Latin America since the 1960s

Yield: agricultural production per unit area of land, using units such as kg/ha

3.1. The Package Deal: Seeds, Water, Nutrients, Machinery

The increased productivity of land was enabled by a suite of technological advances that can broadly be divided into three categories. First, advances in plant biology improved our understanding of genetics, development, and physiology and their relationship to crop performance. Plant breeders were able to develop new varieties of crops with desirable traits such as dwarfing, high yields, and increased resistance to pests and diseases (46). These new high-yield varieties of maize, wheat, and rice were rapidly developed and deployed around the world in the 1950s and 1960s (46) (**Figure 3**), albeit with bias toward certain world regions (Latin America and Asia but not the Middle East or Africa).

Evenson & Gollin (47) conducted an exhaustive study of the impact of international agricultural research on the development, diffusion, and influence of modern crop varieties from 1960 to 2000. They found that more than 8,000 modern varieties had been released for 11 major crops by 2000. With the notable exception of sub-Saharan Africa, farmer adoption of new cultivars occurred soon

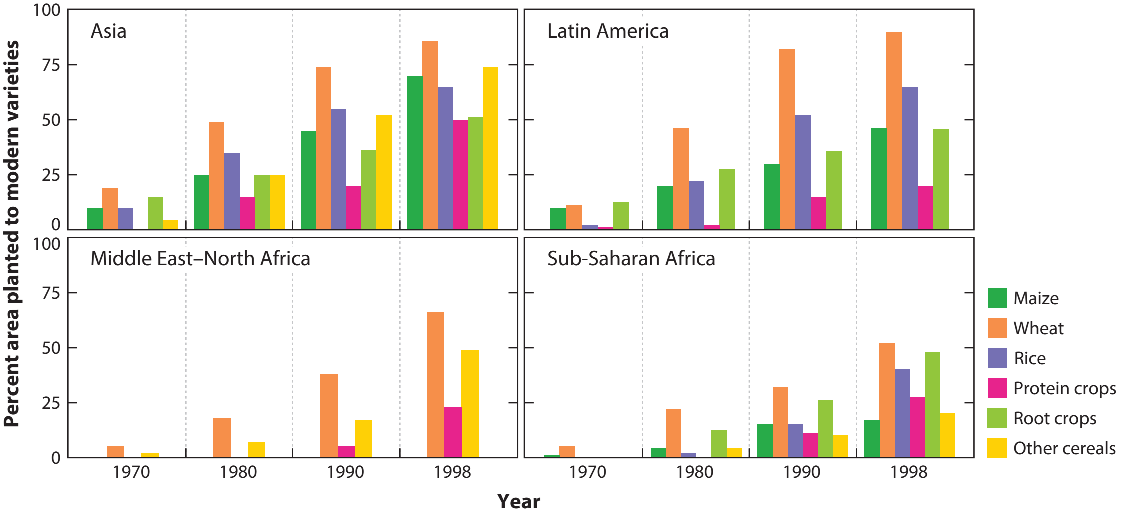

Figure 3

The adoption of modern varieties around the world. Figure adapted from 36 using data presented in 37. Adapted with permission from AAAS.

after their release. Remarkably, the use of modern varieties accounted for 21% of the growth in yields in the early phase of the Green Revolution in all developing countries between 1961 and 1980, and nearly 50% of the growth in yield in the late phase from 1981 to 2000.

Haber-Bosch process: an industrial procedure to fix nitrogen from the atmosphere with hydrogen to create ammonia, a critical component of synthetic fertilizers

The second major advance was the development of the Haber-Bosch process, which permitted synthesis of nitrogen fertilizer from the plentiful nitrogen available in the atmosphere. This discovery was a major breakthrough for agriculture, as nitrogen is a major limiting nutrient in soils. The application of additional nutrients, in combination with irrigation, pesticides, and new crop varieties, led to a major boost in crop productivity (46). Total fertilizer use quadrupled during 1961–2014, with the biggest increases in Asia (and also through much of the rest of the world), but with little increases in Africa (**Figure 4**). It has been estimated that 40–60% of yields in the United States and England (and much higher proportions in the tropics) are attributable to commercial fertilizers (147). More than a quarter of the world population over the past century is estimated to have been fed by synthetic nitrogen fertilizers (45).

The third major advance was the harnessing of energy from fossil fuels, which enabled other technological advances, including vast improvements in the mechanization of agriculture, as well as the production of synthetic fertilizers and pesticides. These developments, coupled with low (subsidized) energy costs, allowed farmers to efficiently exploit (and overexploit) groundwater resources. From 1961 to 2014, the global area equipped for irrigation doubled, from 0.16 billion ha (12% of cropland) to 0.33 million ha (21% of cropland) (**Figure 4**). Asia contributed predominantly (75%) to this growth. Irrigated yields were 1.6 times higher than rainfed yields during 1988–2002, and 24% of the total harvested area that was irrigated contributed to 33% of the total production (135).

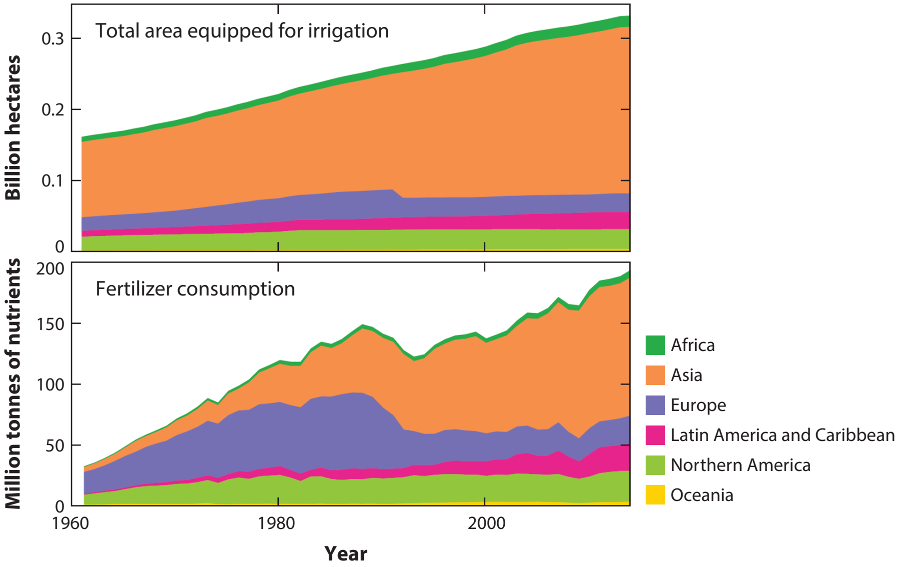

Figure 4

Regional trends in irrigated area and fertilizer consumption from 1961 to 2014. Data were downloaded from the Food and Agriculture Organization Corporate Statistical Database (FAOSTAT) (**http://www.fao.org/faostat/en/#home**). FAOSTAT reports fertilizer data for 1961–2002 separately from the more recent (2002–2014) data. Data were harmonized by calibrating the historical data to match more recent data based on the ratio between the two in 2002. This correction was made by region and nutrient.

Irrigation also enabled farmers to extend the growing season into the dry season. Farmers were able to increase production through multiple cropping of existing cropland coupled with new shorter-season varieties of crops (35). Total harvested land area (i.e., area counted twice when two crops are grown in a season) increased faster than standing cropland area during the 1961–2011 period (35). For example, double-cropped area in Brazil's Mato Grosso increased sixfold from roughly 0.5 to 2.9 million ha between 2001 and 2011 (140). On the global level, these increases in harvest intensity contributed to 9% of production growth during 1961–2007 (5).

In summary, the Green Revolution was a package deal of new seeds and new inputs made possible by the availability of cheap energy.

3.2. Changes in Crop Types and Crop Yields

While the Green Revolution led to general increases in crop yields, there is massive variation in how yields, harvested area, and production changed across different crop types (**Figure 5**). Some crops saw marked yield increases. Maize yield in the United States remained approximately 1.7 tonnes/ha from 1866 to 1935 but has since increased to ∼10 tonnes/ha (166); similarly, wheat

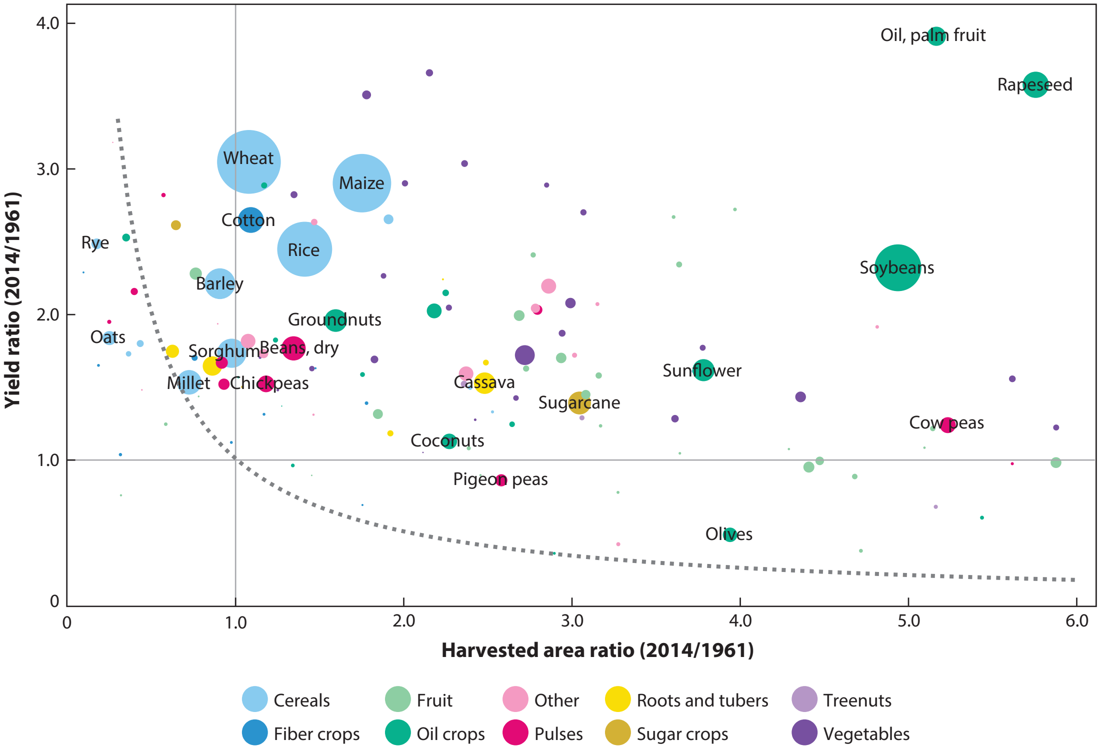

Figure 5

Trends in global harvested area and yields from 1961 to 2014 using data from the Food and Agriculture Organization Corporate Statistical Database (FAOSTAT) (**http://www.fao.org/faostat/en/#home**). Figure adapted from 158. Vertical axis shows the 2014/1961 yield ratio, and the horizontal axis shows the 2014/1961 harvested area ratio. In cases where crops were absent in 1961, the ratios were calculated using the earliest year with nonzero values. Size of the circle represents crop harvested area in 2014, and color represents major crop groups. Crops above the dotted curve experienced increases in total production from 1961 to 2014, and production declined for crops below the curve.

yield in the United Kingdom remained approximately 2 tonnes/ha until the 1930s but has increased since to ~8 tonnes/ha today (6).

Crop wild relative: a wild plant species that is genetically related to a domesticated plant

Crop genetic resources: crop or crop wild relative plant material found in farmer's fields, or in situ or ex situ banks, required for current and future crop breeding efforts

Since 1961, the biggest production increases have occurred in oil crops (eightfold increase)—especially oil palm, rapeseed, and soy—owing to increases in both harvested area and yields (**Figure 5**). In contrast, production increases in major cereals—rice, wheat, and maize—occurred through yield increases and experienced little change in harvested area. The minor cereal crops (e.g., sorghum, millet) decreased in harvested area by 31% between 1961 and 2014. Yet their total production increased by 33%, reflecting a 93% increase in yields per hectare. Although most crops increased production between 1961 and 2014, a few did not, such as oats, whose production declined by 54%.

Green Revolution yield increases have not continued apace everywhere. Overall, for 24–39% of maize-, rice-, wheat-, and soy-growing regions of the world (for example, maize in Kansas, wheat in France, and rice in Nigeria), yields either never improved, stagnated, or collapsed (123), with the situation being worse for food crops (rice, wheat) versus fodder crops (maize and soy). Based on this information, current yield trends were estimated to be insufficient to meet the needs of the future (122), although this is debated (78), as discussed further in Section 7.1. One important potential reason for yield stagnation is climate change, which is estimated to have decreased maize and wheat production by 3.8% and 5.5%, respectively, from 1980 to 2008 (96). However, stagnating yields could also be attributed to a multitude of other reasons, including loss of soil fertility and salinization, cultivars approaching yield potentials, pest and disease buildup, water scarcity, and policies supporting environmental outcomes over yields (123).

Another important trend to consider is changes in crop yield variability from year to year, as more volatile crop yields can lead to unstable farmer incomes and price hikes affecting consumers. Recent estimates suggest that year-to-year variability in climate accounted for roughly a third of the observed year-to-year variability in yields between 1979 and 2008 (121). But, at the global scale, there is no strong and clear pattern that crop yields have become more volatile over time (79, 109), although statistically significant increases in yield variability were detected in 9–22% of maize-, rice-, wheat-, and soy-harvested areas from 1981 to 2010 (79). There is some evidence that climate trends are partly responsible for these increases in yield variability (79, 109).

3.3. Trends in Crop Diversity

Large swaths of agricultural land currently operate under monocultures or monoculture rotations, with double or triple crops per year (29). Increases in farm size in upper-income countries (97) and the preponderance of monoculture suggest that spatial diversity of cropping has also declined at the landscape level (e.g., 1). Further, several studies suggest that the industrial agricultural transition led to a reduction in area cropped with traditional varieties (111). Nevertheless, farmers in traditional agroecosystems often maintain high varietal and species diversity on their farms and across communities and regions, although this is higher for staple than nonstaple crops (83).

The current hotspots of crop diversity are concentrated in Europe, Africa, Asia, and West South America, with low diversity in Australia, North America, and South America (75). A global map of the major crop belts highlights specialized locations for particular crop groups, such as major cereals, and luxury crops such as cocoa and coffee (**Figure 6**). Historically, genetic diversity has been eroded by domestication of crop wild relatives (17), and major concern exists for the erosion of wild types and crop genetic resources of the world today (30). However, meta-analysis suggests that in recent decades genetic diversity of breeder varieties does not show clear downward trends (167).

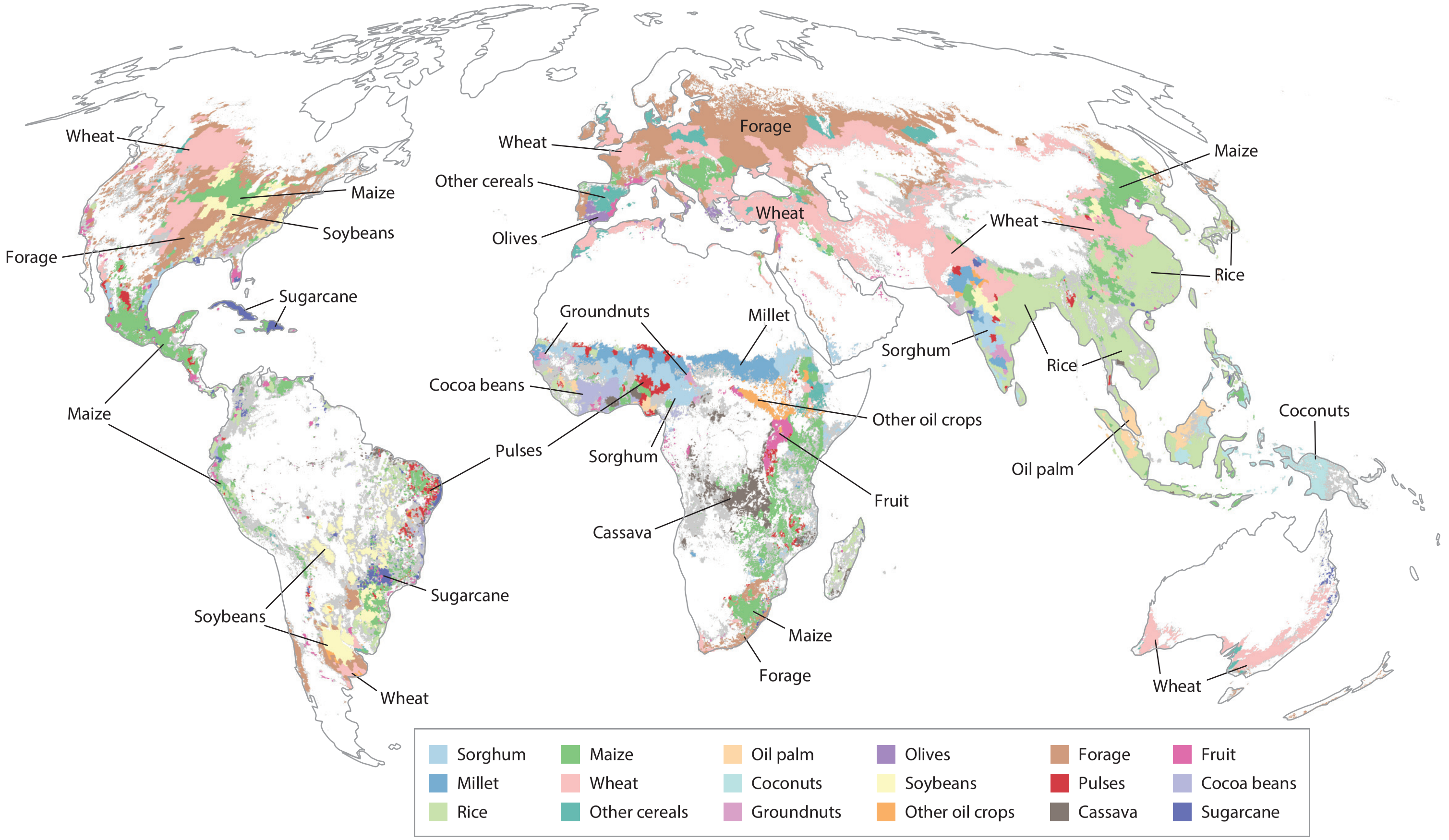

Figure 6

Crop belts of the world (circa year 2000). We show the dominant crop or crop group, derived from a geospatial database of 175 individual crops (**http://www.earthstat.org**). For clarity, not all regionally important crops are indicated. For example, bananas and plantains in Africa are labeled as fruit.

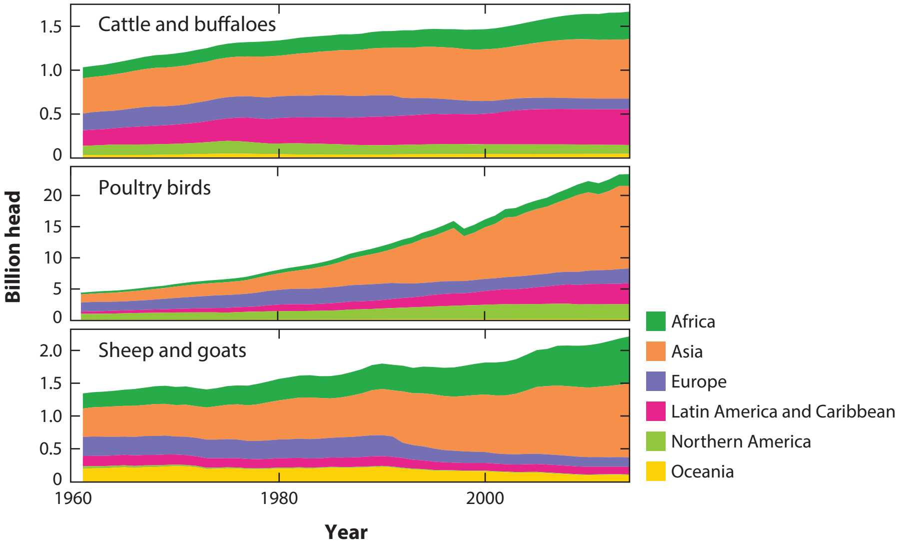

Figure 7

Regional changes in livestock numbers from 1961 to 2014. Data were downloaded from the Food and Agriculture Organization Corporate Statistical Database (FAOSTAT) (**http://www.fao.org/faostat/en/#home**).

3.4. Trends in Livestock Intensification

Following the Green Revolution, there was also a livestock revolution, which largely occurred as a result of people consuming more animal products as they got richer. Since incomes are increasing faster in low-income countries, which also often have higher rates of human population growth, accelerated growth in animal numbers has taken place (36). In 2014, the world had 23.4 billion poultry birds, 1.7 billion cattle and buffaloes, 2.2 billion sheep and goats, and 0.9 billion pigs (**http://www.fao.org/faostat/en/#home**). The global stocks of chickens and pigs increased at a faster pace than the human population between 1960 and 2000, by a factor of 5 and 2.5, respectively (64). The numbers of cattle and buffaloes and sheep and goats have increased by 62% and 64%, respectively, between 1961 and 2014 (**Figure 7**). The largest increases were witnessed in Asia and Africa (**Figure 7**).

In addition to increases in animal numbers, significant livestock intensification has also taken place. This has largely been achieved by increasing animal densities and production units; the use of concentrated feeds, pharmaceuticals, and vaccinations; improved efficiencies in processing infrastructure (64); and improved feed efficiencies. Globally, 62% less land and 46% less greenhouse gas emissions (GHGe) are used now to produce one kilocalorie from livestock than were used in 1961. This intensification of production has occurred at the expense of an 188% increase in nitrogen use for increasing feed production (33). A shift from ruminants to more intensive pig and poultry production has been partly responsible for this trade-off; intensive systems need less land, and proportionally fewer ruminants implies less methane emissions per kilocalorie of livestock, but increased feed requirements imply more nitrogen fertilizer use. Collectively, livestock intensification has resulted in approximately 36% of the calories produced on global croplands being diverted to animal feed (28), and the rise in livestock numbers has generated large concentrations of animal wastes (see Section 3.5).

Greenhouse gas emissions (GHGe): mainly carbon dioxide, methane, and nitrous oxide emissions in the case of agriculture

Intensification of livestock has nevertheless occurred at different rates in different parts of the world and in some cases has led to reductions in animal numbers. For example, the United States produces 60% more milk with 80% fewer cows now than in the 1940s (25). Significant intensification and also growth of the livestock sector have occurred primarily in Latin America and Asia. This is in stark contrast with sub-Saharan Africa, where productivity per animal has remained stagnant for decades, and all the growth in the sector has resulted from increases in animal numbers.

3.5. Separation of Crops and Livestock

Mixed crop-livestock systems are a traditional form of agriculture that remains predominant in most smallholder and subsistence farming systems in developing countries (74). The integration of crops and livestock offers many management benefits. Animals can deliver nutrient-rich manures for the crops and draft power for bed preparation, while crops and their residues can be used for forage (74). Mixed-crop livestock systems are nevertheless on the decline in many parts of the world (113, 130). This separation of cropping and livestock systems has increased the problem of manure waste management and increased the need to import feed in livestock systems and for chemical fertilizers in cropping systems. Recoupling livestock and cropping systems offers a major path to sustainable management in agriculture (74). In sub-Saharan Africa, such recoupling could nearly close the nutrient cycle, returning up to 80% of the nutrients extracted by crops back into the soil system (141). However, although mixed crop–livestock systems offer many benefits, they also require higher capital to establish and can be extremely difficult to manage (151).

4. EMERGING TRENDS AND FUTURE PROJECTIONS

The Green Revolution was clearly a major success in terms of increasing crop production. Crop production has more than kept pace with population growth over the last 50 years, with cereal production per capita increasing from 0.29 to 0.39 tonnes per person between 1961 and 2014, even while human populations more than doubled from 3 billion in 1961 to 7 billion in 2014. However, many questions for the future remain unanswered: Will agriculture be able to keep pace with future population demand? Will we reach peak cropland? And where might we expect future productivity gains to come from?

4.1. Projections of Future Production and Demand

With rising human populations and increasing per capita wealth, the demand for food, feed, and other agricultural products is expected to increase in the future. Two major studies have projected future demand to 2050. Alexandratos & Bruinsma (5) from the Food and Agriculture Organization (FAO) projected that aggregate agricultural production (of all crop and livestock products) will increase 60% by 2050 compared with a 2005–2007 baseline. But this aggregate is difficult to interpret because it includes multiple dissimilar products that are weighted by international prices (5, 159). Alexandratos & Bruinsma also estimated demand for different commodity groups on a tonnage basis and found that between 2005–2007 and 2050, global demand for meat production and sugarcane and sugarbeet production will increase by 76%, oil crop production will increase by 90%, and cereal production will increase by 50%.

Tilman and colleagues (153, 155) also projected future food demand to 2050 using future projections of population growth and GDP coupled with income-dependent estimates of per capita crop demand. Their analysis projected a 100% increase in global demand for calories and a 110% increase in protein by 2050 (153). It is difficult to compare the aggregate figures from Tilman and colleagues with those from Alexandratos & Bruinsma because of the different units (calories versus value-weighted production) used by these studies.

Total factor productivity (TFP): the ratio of total output (crop and/or livestock) to total input (including land, labor, capital, and material resources)

However, as we discuss in Section 7.1, several recent studies challenge these estimates of future food demand. Current trends should not necessarily be a guide to the future. Diets heavy in meat, oils, and sugars are a major contributor to the global health burdens of diabetes, cancer, and heart disease (155), and future realization of these negative impacts may cause demand to be much lower than projected. Policies that promote greater dietary reliance on grains, fruits, vegetables, and dairy would in turn also alter future demand on global agriculture.

4.2. Will We Reach Peak Cropland?

Peak cropland is a term used to describe a time when humanity might reach its most extensive use of Earth's land surface area for agriculture. A recent study (8) suggested this might occur soon. Analyzing historical trends, the authors showed a reduction in rates of cropland expansion over 1961–2010, with expansions of 0.24% per year over the whole of 1961–2010 but only 0.04% per year during 1995–2010. They showed that this was a result of rising yields and relatively slower growth in consumption (than expected based on changing affluence) countering increased pressure on croplands from growth in population and affluence. Projecting forward, they showed possible scenarios whereby cropland areas would peak and then decline. This projection of peak cropland requires slower diet shifts toward meat consumption and the abandonment of biofuels or other nonfood uses of crops (8). It is debatable whether these projections are realistic.

But whether or not cropland actually peaks, Alexandratos & Bruinsma's (5) FAO study supports the slowdown of cropland expansion. Recent historical trends suggest that 77% of increased production over the 1961–2005 period came from increased yields, 14% from expansion of croplands, and 9% from increases in cropping intensity (5). Looking forward into 2050, they projected that 80% of future production growth will come from yield growth and 10% each will come from cropland expansion and increases in cropping intensity (5). This suggests that the contribution of cropland expansion to production growth is expected to reduce by ~4% in the future.

Notwithstanding projections of future cropland, for environmental reasons we must slow cropland expansion, as most of the new lands available for clearing are in the tropics and of high carbon and biodiversity value (119). The threat of climate change is an especially important reason to avoid deforestation for agriculture (50).

4.3. Future Growth Through Improvements in Efficiency

Increases in crop productivity since the Green Revolution have been driven in part by increases in external inputs (e.g., water and nutrients). However, increasingly, some of the improvements in productivity are being driven by improvements in the efficiency of input use. Agricultural economists use the concept of total factor productivity (TFP) to examine the efficiency of input use. A recent study (57) estimated that since 1990, overall contributions to global agricultural output have switched from input intensification (growth owing to, e.g., addition of new land, irrigation, labor, or machinery) to improvements in TFP (more output per input).

Future increases in TFP can be sustained by further increases in input efficiency—getting more crop per drop of fertilizers or water. Economists argue that past successes have resulted from high investments in research and development in agricultural technology, such as witnessed in Brazil and China in recent decades (57). Precision agriculture and variable rate applications of inputs can increase efficiencies by applying nutrients and inputs where they are required to achieve the best productivity gains on a given piece of land (99). However, the cost of obtaining information to enable TFP increases through precision agriculture is high (23) and has slowed adoption (19). Other potential opportunities to increase TFP exist through ecological intensification (e.g., 69), conventional breeding, or genetic engineering approaches, although economic gains from these advances are not always clear (e.g., 127).

Gigatonne (Gt): 10^9 tonnes; 1 Gt = 1 Pg

CO_2eq: the equivalent concentration of CO_2 that would cause the same net radiative impact as another greenhouse gas (e.g., methane)

5. IMPLICATIONS FOR ENVIRONMENTAL HEALTH

5.1. Forest Loss and Fragmentation

Agriculture is responsible for converting ~30% of forests worldwide (117). From 1980 to 2000, more than half of new agricultural land in the tropics came from deforestation of intact forests, and just under a third from disturbed forest (62). Globally, between 2000 and 2010, it is thought that 80% of deforestation resulted from conversion to agriculture and grazing lands (85). Just two countries, Indonesia and Brazil, were responsible for over 50% of tropical forest loss (10). Agriculture also has massively fragmented forests, with large stretches of natural habitat, such as the Brazilian Atlantic Forest, now existing in degraded fragments of <1,000 ha in size, all within 1 km of the forest edge (70).

5.2. Greenhouse Gas Emissions

Agriculture, including deforestation and land use change, currently contributes ~22% of global GHGe (139). Approximately 9% of GHGe (4.3–5.5 GtCO_2eq/y) comes from ongoing deforestation and land conversion (139). The conversion of tropical forests to cropland releases approximately three times more carbon into the atmosphere compared with temperate forests (174). GHGe from agriculture have changed over time and space as a result of land use regime shifts. For example, in the Great Plains of North America, conversion of prairie habitat and plowing were the greatest contributors to GHGe in earlier times, but livestock are now the largest emitters (110). Globally today, agricultural management on already-converted lands is thought to make up ~13% of GHGe (5.0–5.8 GtCO_2eq/y). Over one-third of this results from CH_4 from enteric fermentation, ~15% from N_2O emissions from manure and synthetic fertilizer application, and ~12% from CH_4 in rice paddies (139). Like carbon losses from deforestation, management-based emissions are concentrated geographically in particular hotspots: CH_4 enteric fermentation largely occurs in India, sub-Saharan Africa, Brazil, and Western Europe (73), whereas more than 50% of all N_2O emissions from nutrient application are from China, India, and the United States (173), and ~60% of CH_4 from rice is emitted by India, China, and Vietnam (26).

5.3. Biodiversity Loss

Agriculture affects biodiversity through habitat replacement and management choices on converted lands. Across biomes and taxonomic groups, conversion to pasture and cropland results in losses of ~20–30% of local species richness (106). Biodiversity loss is nonrandom, with marked declines in functionally important species in ecosystems, such as large-bodied pollinators (91). In the tropics, species losses have been shown to be persistent after abandonment of agricultural lands (63). Fragmentation breaks down essential plant–animal interactions required for regeneration and persistence of native vegetation (105) and causes erosion of species diversity over time beyond initial disturbance events (70).

In addition to habitat loss and fragmentation, agricultural management impacts biodiversity through management choices, such as use of pesticides, fertilizers, and crop choice. Fertilization, from nitrogen-fixing legumes and application of manure and synthetic fertilizers, has contributed to a global increase in nitrogen (N) flow (170). This results in species loss in terrestrial (145) and freshwater (103) environments. The longest-running experiment of N addition at Rothamsted Research Station in the United Kingdom shows that plant diversity rebounds after reductions in N application, although it is unclear if recovery is possible in other systems (148). Intense management, which includes tillage and short rotations, also negatively affects soil biodiversity and food web structure (160).

Petagram (Pg): 10^{15} grams

Pesticide application has also been linked to declines in populations of nontarget plants and insects (20) and to the development, foraging patterns, and effectiveness of bees and natural enemies of crop pests (37, 142). Conversely, management options to increase the diversity of cropping systems have been shown to improve both the abundance of natural enemies (94) and species diversity and yield contributions of pollinators (59). Organic agriculture typically has higher species richness than conventional systems across a range of taxonomic groups (161), but lower yields make it less efficient for local species richness on a per-unit product basis than conventional systems (134). However, crop diversification closes the yield gap between organic and conventional systems (114), suggesting that this trade-off is dependent on management of crop choice and scheduling of rotations.

5.4. Soil Health

The impact of agriculture on soils is tightly linked to land use change and agricultural management. The alteration of vegetative cover, through replacement of forests or grasslands with annual crops, influences infiltration, erosion, and organic matter inputs. Three major soil erosion–linked agricultural transitions have occurred: the expansion of river-based populations up forested slopes around 2000 BCE, the invention of sharp plough and deep tillage from the sixteenth to the nineteenth century, and crop expansion into tropical biomes after World War II (101). It is estimated that by 1990 ~15% of the world's soils were in some way degraded (108). Current rates of erosion on agricultural land are estimated to be ~35 Pg/y (28 Pg/y from water, ~5 Pg/y from tillage, and ~2 Pg/y from wind) (116)—rates that are an order of magnitude higher than that of natural erosion or soil formation processes (150). Land clearing for agriculture has also led to soil degradation through other means, with vegetation removal in semiarid Western Australia resulting in recharging of ground water at two orders of magnitude above the background rate, causing water tables to rise, and salinization of ~10% of agricultural lands in the region (61).

The management of soils, through fertilization, tillage, grazing, crop type, and rotation planning, also has had marked influence on soil health. The loss of soil organic matter, which results from replenishing soil nutrients with synthetic mineral fertilizers (N-P-K) without replenishing organic material, has pushed agricultural systems into a state of rapid nutrient cycling with high rates of nutrient loss (98). This, in combination with shorter rotations and loss of cover crops, has led to increases in soil-borne pathogens (169), increases in crop susceptibility to droughts (34), and crop yield declines (15).

5.5. Water Use and Quality

Agricultural production accounts for 92% of the human water footprint, ~77% of which can be attributed to rain-fed agricultural systems (77). Of the agricultural water footprint, 12% is in freshwater, with irrigation accounting for ~64% of withdrawals worldwide (42). Agricultural water use has had catastrophic impacts on freshwater resources, for example, the complete loss of the 68,000 km^2 of the Aral Sea at the end of the last century (102) and groundwater depletion crises in North West India (126).

Importantly, water use in production systems is concentrated in space and by crop type. China, India, Pakistan, and the United States account for ~68% of irrigated water used, half by India alone, with rice and wheat covering ~69% of irrigated area and consuming ~54% of irrigated water globally (173).

In addition to effects on quantity used, loading of nutrients (27), pesticides (4), and livestock antibiotics (84) from agriculture all have negative effects on water quality and pose public health problems for humans. Phosphorous and nitrogen fertilizer pollution in particular is notorious for forcing algal blooms and anoxic dead zones in both freshwater (27) and coastal marine systems (40), which kill fish and reduce the palatability of drinking water for human consumption.

Safe operating space: the condition in which Earth system processes are maintained within hospitable boundaries for human life

5.6. Summary of Environmental Impacts

GHGe, biodiversity loss, soil degradation, and water impacts of agriculture all negatively feed back and reduce the benefits that can be received from the food system. For example, agricultural GHGe contribute to an increase in extreme events (41) and global crop production losses (93), soil erosion is leading to declines in crop productivity (150), and pollinator declines threaten yields of increasingly pollination-dependent cropping choices (115). These negative feedbacks within agriculture represent significant long-term financial and business risks. While humans have become more environmentally efficient on a per capita basis at producing food (e.g., 16), in aggregate these negative effects of agriculture are a major concern both for the future of agriculture and for the safe operating space for humanity on our planet (143).

6. IMPLICATIONS FOR FOOD SECURITY

6.1. More Production, More Calories, but Less Nutrition

The Green Revolution was a massive success in terms of producing calories for humanity. Average available calories per person from crop and livestock production increased from 2,196 kcal/day per person in 1961 to 2,884 kcal/day per person in 2013. There was more than enough energy available in 2013 to supply every person on the planet (**http://www.fao.org/faostat/en/#home**).

However, this energy is not distributed evenly and is not as nutritious as it could be. Whereas the United States had ~3,680 kcal/day per person available in 2013, the Central African Republic had only half, ~1,880 kcal/day per person. The number of undernourished in the world remains unacceptably high, with ~795 million people still lacking sufficient calories today (54). Furthermore, 2 billion suffer from iron deficiencies (162). Deficiencies in iron and other micronutrients, such as iodine, folate, vitamin A, and zinc, are particularly detrimental to human growth and are together associated with a range of pathologies, including cognitive impairment, anemia, blindness, and pregnancy complications (162).

A new problem exists today. From 1975 to 2014, the world transitioned from a state in which the prevalence of underweight was double that of obesity to one in which more people are obese than underweight (39). Currently approximately 37% of the world's population is overweight or obese (107), carrying a heavy burden of noncommunicable diseases, such as diabetes, heart disease, and morbidity (149).

The global reliance on very few crops for energy, with some 84% of calories globally coming from just 17 crops (173), is a primary reason for the human nutrition gap. This is most clearly demonstrated by the South/Southeast Asian regions, which have micronutrient deficiency prevalence of ~30% owing to the dominance of white rice in the diet (13). Moreover, in some regions, marked declines in micronutrient density in diets have taken place in recent decades, with shifts away from fruits, nuts, and pulses toward calorie-dense but nutrient-poor foods (e.g., maize, rice, wheat, vegetable oils), such as in sub-Saharan Africa during 1979–1993 (13). Worryingly, there have also been downward trends in the nutritional quality of crops, with declines for some items observed in the United States between 1950 and 1999, owing to optimization for increased yield (32). The world produces 22% less fruits and vegetables than required to meet the World Health Organization recommendation to consume five portions of fruits and vegetables per day to achieve a healthy diet (136).

Ecosystem services: the benefits that human societies obtain from ecosystems

Agroecological: bringing ecological principles to bear in the management of agricultural systems

6.2. More Production, More Calories, but Access Remains the Bottleneck

A recent study found that improvements in caloric supply were not the main cause of improvements in child nutritional status from 1970 to 2012 (138); instead, dietary diversity, sanitation, clean water, and women's education were equally or more important drivers. The prevalence of malnutrition despite sufficient caloric availability at the national and global levels led the FAO to revise their definition of food insecurity in 1996 to include availability, access, utilization, and stability (53). Purchasing power is a central component of access, and reliable cash-transfer programs have been shown to increase the quality and quantity of food in diets of the poor (157). Similarly, off-farm income plays an important role in increasing the food security of smallholders (56). Globally there is an inverse relationship between GDP and the proportion of labor force in agriculture (177)—and this lack of purchasing power means that countries whose workforces consist predominantly of farmers are typically food insecure. Currently 69% of the world's farms exist in Southeast Asia, South Asia, and sub-Saharan Africa (97), with 30% of their produce coming from holdings <2 ha in size (75). Economists have suggested that the solution to economic development is agricultural development, but the directionality of this relationship on the national level is widely context dependent (9). The urban environment brings new access opportunities (133), but malnutrition remains prevalent in populations of the urban poor (131). It has been widely documented that populations that exist in perpetual states of caloric and nutritional food insecurity from poverty-limited access are also often those that are most at risk for acute food insecurity from extreme climate events or political disasters (12).

6.3. More Production, but Less Stability

Intensive crop production systems might be more fragile than less-intensive systems (93). Some evidence exists at the regional scale that maize yields (but not wheat or rice) follow Taylor's power law, with the variance in crop yields increasing nonlinearly with increases in yield (14). However, maize cultivar trials do not support the existence of a trade-off between yield and stability (158). High-input systems, with nutrient and water additions, also provide a fundamental means to decouple growth from external stressors and protect, at least in the short term, against environmental water stress (24) or nutrient exhaustion (104). Pollinator-dependent plants typically display higher production instability than nonpollination-dependent crops (60), which suggests stability benefits for agricultural systems owing to decoupling from nature. The increase in pollination dependency (3) could therefore be destabilizing production. However, the benefits of decoupling from nature may fail when systems are pushed to their limits, such as under extreme weather events (95) or, over the long term, when intensified practices lead to ecosystem degradation (154), which negatively feeds back onto crops.

An alternative perspective is that diversified farming systems have more stable production because they rely on a diversity of ecosystem service providers (86, 88). Ecological theory and experiments suggest that it is possible to obtain high yields and reduce production variability simultaneously (81). Although diversification practices have remained at the sidelines of agricultural development, the few local-scale tests of diversified agroecological systems suggest stability benefits, with evidence that polycultures increase the temporal stability of yields (65), increase pollination (59), and decrease losses to pests (82). Facilitation between plants is maximized under environmental stress (22), suggesting that diversified systems might actually increase their adaptive capacity under extreme shocks (88, 95). Nevertheless, although there is some evidence that polycultures may increase supply stability by providing portfolio effects and increasing nutrient- and water-use efficiencies (21, 81), widespread adoption on large-scale farms has not yet taken place. Links between crop biodiversity and stability at higher levels of organization (e.g., national, regional, or global levels) have not yet been made empirically.

Agricultural intensification: increasing agricultural output per unit land area with increased inputs (in contrast to extensification, where production increases through expanding land)

7. CURRENT DEBATES

In this section, we review some of the major ongoing debates in the agricultural, food security, and environmental literature.

7.1. Challenging the Doubling Narrative

In Section 4.1, we reviewed two future projections of crop production to 2050: a 60% growth in aggregate production in dollar-weighted terms from a 2005/2007 baseline and a 100–110% increase in calories/protein demand from a 2005 baseline. These studies have resulted in a general tendency in the literature to suggest that a doubling of food production is needed by 2050 (52, 122, 152).

Several recent papers have challenged this narrative. Tomlinson (159), referring to an older FAO estimate of a 70% increase by 2050, pointed out that it was not a normative estimate (desirable production in 2050) but rather a projection of the most likely future according to the authors. Moreover, she pointed out that the FAO estimate is not of production or calories but of dollar-weighted aggregate production (also excluding fruit and vegetables). Alexandratos & Bruinsma take pains to make the same point in their updated 2012 report (5). Another recent study also critiqued the doubling narrative for ignoring baselines (78), pointing out that the baseline for both the FAO and Tilman studies was ~2005 and that production growth experienced since then actually suggests that only a 25–70% increase is needed between 2014 and 2050.

7.2. Land Sparing Versus Land Sharing

Land sparing is the idea that intensifying agricultural production, and thereby growing the same amount of food on less agricultural land, can spare land for nature. The idea goes back to Norman Borlaug, the Father of the Green Revolution, who estimated in an editorial (18) that 1.2 billion ha of land had been spared from cultivation between 1950 and 2000 because of yield increases over that period. Waggoner (171, 172) also had proposed the same idea in the 1990s in an article titled, "How Much Land Can Ten Billion People Spare for Nature?"

Although the idea that agricultural intensification could promote nature conservation by land sparing originally came from agricultural scientists, it was picked up by conservation biologists in the 2000s. In a widely known article (67), Rhys Green, Andrew Balmford, and colleagues proposed a theoretical model to examine the tradeoffs between food production and biodiversity conservation. Their model suggested that the nature of the tradeoff is determined by how the densities of wild species and crop yields respond to intensification. Their proposal has been widely criticized since (51, 66, 168).

One major criticism of land sparing is that agricultural intensification does not actually result in land sparing in practice, because intensification generally results in more farmers adopting the practice, resulting in increased (and not decreased) clearing for cropland (7). Two studies

(48, 129) conducted global empirical assessments and found no evidence for land sparing in practice. However, neither study constructed a proper counterfactual to examine what might have happened in the absence of the Green Revolution (76). Two recent studies that used an economic modeling framework to construct a counterfactual concluded that the historical Green Revolution did result in land sparing (76, 146). However, whether the spared land actually resulted in nature conservation remains an open question (87, 112). Land sparing initiatives need to be coupled with appropriate policies to ensure that conservation actually takes place (87, 112).

7.3. Genetic Engineering Versus Organic Farming

Another widespread and passionate debate in the scientific community is on the role of genetically modified (GM) foods versus organic farming in navigating pathways to sustainable food systems (55). Because labeling of GM foods is still not common in most countries, "organic," by expressly prohibiting GM, has set itself up as the only product that ensures that consumers can have non-GM food. There is an especially wide gap between scientific and public perceptions of GM foods (58). Although both approaches could have important roles to play in different circumstances (128), the two communities have continuously clashed.

7.4. Sustainable Diets

Until recently, the predominant focus of agricultural science was on supply-side solutions to meeting the sustainable food security challenge. But a spate of recent papers have pointed to the necessity and enormous leverage of demand-side solutions (e.g., 28, 44, 52, 144, 155). For example, Erb et al. (44) explored 500 different future scenarios for feeding the world in 2050 that would also avoid further deforestation. They found feasible or probably feasible biophysical options in nearly two-thirds of their scenarios, but all required either cropland intensification or a shift to plant-based diets. No scenario permitted low-yielding agriculture along with meat-based diets. Cassidy et al. (28) estimated that shifting the current mix of crops away from biofuels and animal feed would itself increase global calories by 70%. They also calculated that this is roughly equivalent to all the yield gains seen in maize, wheat, and rice from 1965 to 2009; in other words, shifting to vegan diets would be as powerful for increasing food availability as was the historical Green Revolution. Relative to scenarios, less-extreme shifts toward reducing meat consumption, waste, and the demand for nonfood agricultural products (e.g., cotton) could greatly reduce the environmental impacts of the food system (52).

8. CONCLUSIONS: IMPLICATIONS FOR PLANT BIOLOGY

Humans have fundamentally transformed global landscapes and shaped the distribution of plant life on Earth through agriculture. Although advances in production of food over recent decades have kept pace with human population growth, these advances have come at a cost to both the environment and human health. Direct negative feedbacks to agricultural systems from environmental degradation now threaten long-term agricultural productivity. Coordinated research programs are needed to steer humanity into a safe operating space for agriculture. This will require conjoined efforts across many different disciplines within plant biology and collaborations between subject areas that have to date remained pedagogically and ideologically separate.

A major challenge facing plant biologists is the joining of modern breeding approaches (including genomic selection and genomic engineering) with agroecological farming practices. The package deal of seeds, fertilizers, and energy that enabled the Green Revolution was a massive success for increasing production of a few key crops. New modern varieties from industry have been successful in increasing shelf life and catering to consumer tastes and preferences. We now need a new package deal for the future, one that is optimized across different environmental, social, and health outcomes. This will require investment into understanding how diversified farming systems can be made financially competitive with the current monocultures that dominate large swaths of the planet, not only by developing plant materials that assist in sustainable agriculture but also by developing appropriate policies that promote positive environmental, social, and health outcomes.

Breeding for agroecological farming practices, including intercropping, perennial systems, and increased soil biodiversity, should be directed toward multifunctionality in cropping systems (e.g., simultaneous yield stability, microclimate control, erosion control, water- and nutrient-use efficiency, reduced pollution, and increased pest control). There is a further need to join these efforts with modern innovations in breeding of climate smart seeds, improving photosynthetic efficiency (introducing C_4 metabolism into C_3 crops) and nitrogen fixation, and increasing nutritional content (i.e., for improved protein and micronutrient supply to humans and livestock) and disease resistance. Such innovations can help avert yield stagnation, adapt to changes in the growing season and extreme weather events, close the micronutrient gap, and decrease food waste.

Coordinated efforts are required to bring together diverse research programs in agroecology and plant breeding; reduce agriculture's negative impacts on the environment; and ensure food security at local, national, regional, and global levels. This will require reorientation of public and private funding to support the research and development needed for sustainable agriculture. It will also require input from farmers and consumers to design systems to be socially relevant for effective knowledge transfer and adoption and maximum impact. History provides the proof that this is possible: The Green Revolution brought coordinated international efforts across governments and research institutes to increase productivity, fundamentally shaping human civilizations and the functioning of the planet as we know it. It is time plant biologists use the lessons learned from the historical trends and outcomes of agricultural land use to design the next wave of research geared toward developing both productive and sustainable agricultural systems in the future.

SUMMARY POINTS

1. Agriculture is a major cause of global environmental degradation, and its impacts are expected to increase even further with rising future demand for agricultural products due to human population growth and increasing per capita consumption.
2. Although tropical deforestation for agriculture continues today, on a global scale agricultural expansion has slowed down and production increases are being achieved mainly through agricultural intensification (commonly called the Green Revolution).
3. Agricultural landscapes are increasingly under monocultures dominated by a few types of crops (cereals and oil crops), causing valid concerns about the erosion of crop diversity and crop genetic resources and the resilience of future agricultural systems.
4. Following the Green Revolution has been a livestock revolution, particularly in the developing world, driven by increasing consumption of livestock products with rising wealth.
5. Although the world has produced more calories per capita on average over the last 50 years, undernourishment and micronutrient deficiencies remain in many parts of the world, and increasing obesity is posing new human health challenges.

6. Providing adequate nutrition to the world population without further harming the Earth's environment is a grand challenge and presents numerous contentious issues. Do we need to produce more food to achieve global food security, or would reducing waste and shifting diets allow current production to be sufficient? Can we intensify production without causing further environmental harms? What is the role of genetic engineering technologies and of methods such as diversified agroecological farming in enhancing sustainable food production and security? Ongoing debates on these issues have taken entrenched positions, but solutions to complex food system problems will most likely need to take advantage of a wide array of methodologies and systems and be adapted to specific contexts.
7. New coordinated efforts are required to bring together diverse research programs in agroecology and plant breeding. Addressing food system challenges is not simply about developing higher-yielding crops—plant biologists developing crops for the future must optimize for multiple goals including production, nutritional value, environmental and social impacts, and resilience to climate change and other stressors, in addition to consideration of the local contexts.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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Errata

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