Title: Climate change and global food systems: Potential impacts on food security and undernutrition

Running title: Climate change & global food security

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Abstract

Great progress has been made in addressing global undernutrition over the past several decades, in part because of large increases in food production from agricultural expansion and intensification. Food systems, however, face continued increases in demand and growing environmental pressures. Most prominently, human-caused climate change will influence the quality and quantity of food we produce and our ability to distribute it equitably. Our capacity to ensure food security and nutritional adequacy in the face of rapidly changing biophysical conditions will be a major determinant of the next century’s global burden of disease. In this paper, we review the main pathways by which climate change could potentially affect our food production systems — agriculture, fisheries, and livestock — as well as the socioeconomic forces that may influence equitable distribution.

Keywords

Planetary Health, Global Health, Climate Change, Food Security, Malnutrition, Global Environmental Change

Introduction

One of the great public health achievements in modern history is the steep acceleration in global food production over the past six decades. Despite historic growth in global food demand, rates of undernutrition have fallen. This achievement was driven in part by technological innovations, including development of higher yielding grain varieties, production of synthetic fertilizers and pesticides, and mechanization of agricultural labor. It has also required the appropriation of large shares of Earth's natural resources. Roughly 40% of Earth's ice-free land surface is used as cropland and pasture (52). Irrigation uses 66% (about 2,000 km^3) of annual water withdrawals, and is the single largest human use of water (22).

Despite our enormous successes in increasing global food availability (a key requirement for food and nutrition security), the global burden of undernutrition and micronutrient deficiencies remains staggering. It is estimated that two billion people are deficient in one or more micronutrients, 160 million children under the age of five years are too short for their age, 50 million children under the age of five years are dangerously thin for their height, and 790 million people are estimated to have insufficient daily dietary energy intake (68). The latest analysis available suggests that undernutrition is associated with 3 million child deaths annually, or almost half of the global total (18).

Looking toward the future, global food demand is expected to continue rising at the historically steep pace that began in the 1950s (Figure 1). But unlike the 1950s, we are facing growing constraints in our capacity to appropriate new land, new water, or new fisheries to meet these demands. Added to this challenge is the fact that human activity is rapidly changing the environmental conditions within which global food production operates (144). One of the great humanitarian challenges of the 21st century is to keep up with increasing human nutritional needs in this context of natural resource constraints and our rapid transformation of Earth's natural systems, including the climate system.

Climate change is associated with increasing temperatures and more extreme rainfall; it alters relationships amongst crops, pests, pathogens, and weeds; and it exacerbates trends in pollinating insect declines, water scarcity, increasing ground-level ozone concentrations, and fisheries declines. On the other side, there are yield benefits to higher concentrations of atmospheric CO_2 and potential productivity gains at higher latitudes. Some overall estimates of the potential impacts of climate change on nutrition and mortality outcomes exist (108; 140), but necessarily entail substantial uncertainty, largely because of limitations in our current understanding of the complex and interacting pathways by which climate change can affect food and nutrition security and health. Here we review the mechanisms and the estimates for how climate change may influence food production and distribution, as well as associated consequences for human food and nutrition security. Figure 2 provides a schematic for this review. We do not attempt a comprehensive review of all literature for each mechanism, but rather focus on the most recent and relevant literature and on studies that synthesize the topics at hand.

1. Agriculture

The history of agriculture has involved repeatedly overcoming constraints and achieving greater food production through increasing the amount of cultivated land and intensifying cultivation through the adoption of new agricultural technologies (46; 117; 142). Yet the quantity and nutritional quality of agricultural production ultimately depends on a dynamic balance of appropriate biophysical resources, including soil quality, water availability, sunlight, carbon dioxide, temperature suitability, and, in some cases, pollinator abundance. Production diminishes under certain weather extremes as well as from pests, pathogens, and air pollution (e.g. tropospheric ozone). In some places, production is heavily dependent on physical agricultural labor. Climate change is expected to influence each of these dimensions of agricultural production, but often in ways that remain poorly characterized.

1.1 Temperature, Water, and CO_2

Global land temperatures in the last decade, 2006-2015, were 1.0°C warmer than the 20th century average (112). Under a moderate greenhouse gas emissions scenario, referred to as RCP4.5, atmospheric CO_2 concentrations would continue their rise from a 280 ppm preindustrial baseline, beyond the present 400 ppm levels, on to values of 540 ppm by 2100 (120). Climate simulations indicate a further land warming of 1.9–4.0°C (90% CI) (36; 70; 112). Under the higher emission scenario, called RCP8.5, CO_2 concentrations would reach 940 ppm by 2100 and result in warming of 4.0–6.8°C (70). Even a moderate emissions scenario is expected to result in average summer temperatures that exceed the most extreme temperatures currently experienced in many areas of the world (10).

The availability of water resources for agriculture will be influenced by climate change in a multitude of ways, including shifting precipitation patterns, loss of glaciers and earlier seasonal snow melt, and intrusion of salt water into coastal aquifers (73). Climate model projections generally indicate less precipitation in currently arid and semi-arid regions and greater precipitation in the polar latitudes (36). Rainfall events are expected to become more intense, likely increasing runoff and flooding (36).

Crop yields are highly sensitive to changes in temperature and water availability (84). Optimal growing temperatures vary depending upon cultivars and other environmental variables (126), but air temperatures above approximately 30°C are generally associated with reduced yields for rainfed crops (28; 129). High temperatures can depress yields by accelerating crop development (4; 27) and can induce direct damage of plant cells (126). Exposure to damaging temperatures will generally increase as global temperatures rise (57), although these trends will vary regionally and can be locally tempered by irrigation or other changes in agricultural practices (19; 39; 102; 104).

Crop water stress is also a major driver of yield loss (99; 134), and is generally coupled with high temperatures both because low soil moisture leads to a decrease in evaporative cooling from the landscape (100) and high temperatures increase crop water loss (85).

Although the rising concentration of atmospheric CO_2 is the primary driver of harmful anthropogenic climate change, it can also improve crop performance by increasing rates of photosynthesis and water use efficiency (88). Crops that operate with a C_3 photosynthetic pathway, including wheat, rice, and soybean, experience greater stimulation of growth from CO_2 increases than crops with a C_4 photosynthetic pathway, such as maize, sorghum, and sugarcane (78).

There remains substantial uncertainty about the interacting consequences of changing temperature, precipitation, and CO_2 concentrations, particularly in the context of largely management-driven yield increases that are still occurring across the majority of croplands (58; 80; 121). Climatic shifts may either provide a drag or a boost to ongoing yield trends. Existing estimates suggest that climate trends since 1980 have reduced global production by approximately 5% for maize and wheat relative to a counterfactual scenario with no climate shift, while net global production of soybeans and rice has remained unaffected by climate change, though there are regional gains and losses (86).

Considering future scenarios of climate change, estimates generally indicate that warming will depress yields for maize and wheat, with stronger yield losses expected in tropical regions, whereas rice yields appear to be less sensitive to anticipated changes (30; 123). Crop growth models that incorporate the effects of CO_2 concentrations along with effects of temperature, water availability, and nitrogen limitation indicate 25% average yield losses for low-latitude maize and 15% losses for low-latitude wheat in a scenario where global temperatures warm by 4ºC by 2100 (123). There is considerable variation across individual model results, however, with some models predicting roughly twice the losses and others even suggesting small gains in yield at low latitudes. Furthermore, these models do not explicitly represent adaptation or attempt to represent phenomena such as changes in ground level ozone, pests, pollinators, or agricultural labor.

Farmer adaptation to new climate conditions holds promise for mitigating losses in agricultural production, although the magnitude of adaptation potential remains a topic of ongoing debate (26; 30; 41; 82; 96). Within a particular crop management system, farmers may alter planting and harvest dates, change crop varieties, or adjust irrigation practices. A recent meta-analysis quantifying the benefits of such changes found that simulated adaptation led to crop yields that were 7–15% higher than yields in the absence of adaptation. Gains from adaptation tended to be largest in temperate areas, whereas the mitigation opportunity from adaptation was minimal for tropical maize and wheat production (30). Farmers may also adapt to new climate conditions by switching to entirely different crops or reallocating land from crop production to grazing (93).

1.2 Ground Level Ozone

Ground-level ozone is primarily derived from chemical reactions of anthropogenic emissions (2). Ozone formation increases with rising temperature, particularly above 32°C (13). In addition to being a human cardiorespiratory toxin, ground-level ozone is also a plant toxin, hindering crop photosynthesis and growth, as well as reducing grain weight and yields (3; 49; 53). Open-air experiments indicate that the ozone concentrations of 54–75 ppb found currently in polluted regions decrease yields by 8–25% in rice, soybean, and wheat (97; 133; 146). Globally, current levels of ozone pollution are estimated to have suppressed maize, wheat, and soybean yields by 6–9% (5). While increased government regulation should lower ozone levels over the coming decades in developed countries, many developing countries, especially in Africa and Asia, can anticipate increased ozone levels due to greater emissions and warming (138).

1.3 Pests

Insects, pathogens, fungi, and weeds are estimated to be responsible for reducing production of major crops by roughly 25-40% (51), although systematic global data are limited. Annual losses due to fungal infestation alone are estimated to reduce global dietary energy availability by 8.5% (50). Warming temperatures increase winter survival of insect pests and rates of herbivory (6). Changing temperature also drives shifts in the latitudinal range of crop pests and pathogens. Among 612 species of pests and pathogens, investigators observed an average poleward shift of 2.7 kilometers per year since 1960 (12). Crops often lack defenses against non-native pests and pathogens (11), requiring ongoing breeding and management efforts to face new threats. Spatial mismatches between pests and natural predators can also undermine biological control systems (131).

Extreme weather events can destabilize agricultural systems, compromising crop defenses and creating niches that allow pests and weeds to establish (124); however, weather extremes may also pose threats to pests and invasive plants, sometimes actually boosting the competitive ability of crops (145).

In addition to the effects of a changing climate, agronomists anticipate that increasing CO_2 concentrations will lead to complex changes in the composition of weeds and the strength of plant defenses against pests and pathogens (32; 150). Moreover, herbicides are less effective at controlling weed biomass increases induced by elevated CO_2 concentrations (147; 148).

1.4 Pollinators

Climate change will also affect food production of flowering species by reducing the abundance of pollinating insects and shifting their regional distributions (1; 61; 69; 92). Warming affects the timing of flowering and will generally cause plant communities to migrate poleward (114), and these changes may result in mismatches between mutualistic plant-pollinator pairs, thereby disrupting interactions and ecosystem functionality. Furthermore, reduced overlap between timing of plant flowering and pollinator emergence may reduce the breadth of diet for pollinators, resulting in decreased pollinator abundance and increased extinctions of both plants and pollinators. Finally, increasing CO_2 concentrations are also changing the nutritional value of important forage for pollinator species, with undetermined consequences for pollinator health. A recent study showed that, since 1842, there has been a one-third reduction in the protein content of goldenrod pollen, a late-blooming plant that plays an important nutritional role for over-wintering pollinators (149). Chamber experiments indicate further declines with increased atmospheric CO_2 concentrations (149). The impact of significantly reduced dietary protein for bees and other pollinators is currently unknown.

Though the net effect of climate change on pollinators remains uncertain, studies indicate that a reduction in animal pollinationwould decrease yields of numerous pollinator-dependent food crops that play important roles in providing human food and micronutrients (31; 45). Recent modeling indicates that global pollinator declines would increase child mortality and birth defects from increased vitamin A and folate deficiency, respectively, and also increase risk of heart disease, stroke, diabetes, and certain cancers in adults as a result of reduced dietary intake of fruits, vegetables, and nuts and seeds (136).

1.5 Agricultural Labor

Physical human labor is an important determinant of food production, especially in less developed regions not relying on mechanization. Such labor can, however, be limited by the need to regulate body temperature under conditions of high ambient temperature, high radiation and humidity and low wind. Heat already limits agricultural labor in tropical and sub-tropical regions at certain times of the day and year, and climate change is expected to impose further constraints on human performance (76).

Historical meteorological estimates and model predictions can be used to assess how climate change would influence human capacity for labor (42). Under the moderate RCP4.5 emissions scenario heavy outdoor labor would be restricted to 50% of the workday during the hottest month in much of India and portions of sub-Saharan Africa and Australia by the end of the century. Under the high-emissions RCP8.5 scenario, such restrictions on labor during the hottest month become widespread across tropical and sub-tropical regions by the end of the century (42).

Labor in temperate regions is expected to be less affected by warming, but an economic assessment found that United States labor productivity in agricultural and other sectors involving intense outdoor activity would still decline by 0.6–3.2% by the end of the century given a high emission scenario (65). Increased mechanization may help replace human work capacity that is lost to heat stress, though some agricultural communities will have restricted economic potential for such substitution, particularly in the developing world (76). How the direct effect of climate change on human capability will manifest in terms of changes in agricultural practices and overall production is still unclear, but there exists the concerning prospect of substantial and disproportionate impacts in the tropics on account of higher baseline heat stress, physical labor playing a more central role in productivity, and lower potential for adaptation.

1.6 Nutrient Losses

Beyond its influence on yields, increasing CO_2 is also changing the nutritional composition of crops. Experiments in which food crops are grown at elevated CO_2 levels, both in chambers and in open-field conditions using free air carbon dioxide enrichment (FACE) methods, show reductions in protein content in the edible portion of these crops. C_3 grains and tubers including rice, wheat, barley, and potatoes experience 7-15% reductions in protein content while C_3 legumes and C_4 crops show either very small or insignificant reductions (106). When these nutrient changes are modeled across current diets, over 200 million people are expected to fall below thresholds of recommended protein intake, and protein deficiency among those already below this threshold will worsen (91).

Crops grown at elevated CO_2 also exhibit lower concentrations of important minerals. CO_2 concentrations of 550 ppm can lead to 3-11% decreases of Zn and Fe concentrations in cereal grains and legumes (106), and 5-10% reductions in the concentration of P, K, Ca, S, Mg, Fe, Zn, Cu, and Mn across a wide range of crops under more extreme conditions of 690 ppm CO_2 (87). These declines in zinc content are expected to place 150-200 million people at new risk for zinc deficiency and will exacerbate existing deficiencies in over a billion people (105). In addition, roughly 1.4 billion children aged 1-5 and women of child bearing age, or 59% of the world total in these groups, live in countries where current anemia rates exceed 20% of the population and where dietary iron intake is expected to decrease by 3.8% or more as a result of these CO_2-mediated nutrient changes (137). Overall, hundreds of millions of people are expected to be placed at risk of zinc, iron, and/or protein deficiencies as a result of rising CO_2 concentrations while the estimated two billion people already experiencing zinc or iron deficiency will likely see those deficiencies exacerbated by this effect.

2. Fisheries

Although agriculture dominates global food production with respect to total dietary energy, seafood is important in the supply of protein, minerals, vitamins, and fatty acids for many populations around the world (14; 17; 56; 74). Recent estimates suggest that declining fish harvests will leave 845 million people vulnerable to deficiencies of iron, zinc, and vitamin A, and 1.4 billion people vulnerable to deficiencies of vitamin B12 and omega-3 long-chain polyunsaturated fatty acids (56). The global poor are particularly at risk of nutrient deficiencies because of their limited access to dietary alternatives, such as other livestock and fish products, vitamin supplements, and nutritionally-fortified foods.

Independent of climate change, the current trajectory of marine fish catch is concerning. Recent analyses from the Sea Around Us project indicate that global fish catch peaked in 1996 and has been falling by 1.22 million metric tons (nearly 1% of total global catch) per year since, a decline three times faster than that reported by the United Nations Food and Agriculture Organization (115). An analysis of nearly 5,000 fisheries worldwide representing 78% of global reported fish catch showed that 68% of global fish stocks have fallen below biomass targets to support maximum sustainable yield, and 88% are expected to fall below targets by 2050, indicating that decreases in exploitation rate are needed to rebuild fish stocks (38).

2.1 Sea Temperature Rise

Climate change is predicted to warm, deoxygenate, and acidify the oceans (55; 119), thereby altering net primary production (20; 81) and generally displacing habitats poleward (34; 54). Warming may lead to increased stratification of oceanic layers, and reduce the upward flux of nutrients into the euphotic zone, or the surface layer of water where photosynthesis can occur, leading to spatiotemporal variations in net primary productivity of phytoplankton (21; 33; 43; 81). One recent study suggests that the response of plankton communities to increases in sea surface temperature will be variable depending on location and nutrient richness (79). These changes in abundance and distribution of plankton communities are important because plankton forms the foundation of the marine food web.

A recent study indicates that, as a result of these changes in size and distribution of plankton communities, under a high-emission RCP8.5 scenario, global fish catch potential would decrease by 3-13% by 2050 relative to recent decades (34). Another study indicates that that the biomass of tropical fish communities will also be smaller by about 20% in 2050, given a high emission scenario, on account of ocean warming and associated reductions in oxygen content (35). Declines of 30–60% have been suggested for some tropical shelf and upwelling areas including, most notably, in the eastern Indo-Pacific, the northern Humboldt, and the North Canary Current.

For aquaculture, the net impacts of a changing climate are incompletely characterized and likely to be quite heterogeneous. Aquaculture systems are likely to experience some benefits from climate effects through increased food conversion efficiencies and growth rates of fish under higher water temperatures, an extended growing season, and a larger potential range for aquaculture operations at higher latitudes due to reductions in sea and lake ice cover (7; 116).

However, higher temperatures may also increase the spread of infectious disease among fish, increase the risk of harmful algal blooms, expand the range of aggressive invasive species such as the Pacific oyster and their associated pathogens, and accelerate the uptake of toxins and heavy metals in freshwater shellfish (40).

2.2 Ocean Acidification.

Current understanding of how acidification impacts ocean productivity is limited, often to single species responses. Characterization of larger food web dynamics and systemic responses remains a major challenge (125). However, it is clear that coral reefs—ecosystems critical for many coastal tropical fisheries—will be heavily degraded by warming and ocean acidification (37). One study estimates a 92% reduction in coral reef habitat by 2100 (139).

2.3 Nutrient Quality

Climate change may also influence the nutrient content of seafood through changing the nutritional composition of phytoplankton communities (15), with consequent effects up the food chain (89). Warming leads to reduced long-chain polyunsaturated fatty acid content in phytoplankton (63) and in cold-water pelagic fish, such as sprat and anchovy (111). Another study suggests that uptake of minerals such as iron becomes more limited in warmer and more acidic waters (33), though further examination of impacts on micronutrient composition is needed.

Similar to agriculture, the direct effects of CO_2 emissions combined with attendant changes in climate lead to substantial uncertainties regarding the implications for the availability of food and nutrition, though for fisheries the compounding complexity of how the entire marine food chain will alter leads to perhaps even greater uncertainty.

Animal Husbandry

Heat stress is a major determinant of livestock productivity. Studies document in cattle and pigs that increased heat stress — both with regard to individual extreme events and accumulated excessive heat over time —decreases productivity, food intake and weight, chance of survival, and fertility (16; 95; 107; 128). For poultry, heat stress reduces growth, egg yield and quality, and meat quality (77). However, much uncertainty remains regarding the ability to adapt livestock systems. Livestock systems are generally regarded as more adaptable than crop systems, especially with regard to the less industrialized livestock systems of developing countries (141). On the other hand, the main response of livestock to heat stress is higher water consumption, which can be jeopardized by drought, especially in areas with rudimentary water systems, such as in portions of South Asia and Sub-Saharan Africa (118).

As with agriculture, how climate change will influence forage depends on local interactions between CO_2 levels, temperature, and precipitation. Increasing global CO_2 levels are predicted to improve productivity of pasturelands, whereas higher temperatures can have a positive or negative effect, depending on uncertain changes in precipitation and soil water availability, whether temperatures exceed tolerable ranges for certain species, and nutrient availability (72). Higher CO_2 conditions may also have competing effects on the protein available for grazing animals by shifting species compositions toward more protein rich C_3 plants (44) but also causing reductions in the protein content of those plants through altering carbon to nitrogen ratios (94). It is difficult to generalize climate impacts on livestock production systems, and more research is needed to characterize localized impacts with respect to particular systems (e.g. dryland pastoralists) (141).

3. Effects on Food Security and Nutrition

In sum, global food production is likely to be altered through several climate changerelated pathways affecting the quantity and quality of food produced in agricultural, fishery, and livestock sectors. Although precise quantification of the net impacts of these environmental changes is beyond the reach of our current understanding, there exists the troubling prospect of disruption of our capacity to maintain adequate supply of nutritious foods. If we cannot do that, the purchasing power of wealthier populations will ensure that food flows towards the wealthy, leaving the poor with insufficient supply. Of course, nutrition and food security are determined not only by aggregate supply, but also the ability of people to access, afford, and use food (9; 132).

3.1 Conflict

Political and economic forces dictate food access. Discrimination, especially on the basis of gender, ethnicity, caste, and wealth, impedes participation in markets, legal recognition of land and asset ownership, and other rights critical to attaining food security (90). Climate change may exacerbate social exclusion by increasing competition for scarce natural resources and forcing mass migration (8), factors that played important roles over the past few decades in severely restricting food access during civil conflicts in Sub-Saharan Africa and the Middle East (25; 62; 75). The hypothesized linkage between climate change and violence is controversial (23; 67), but the evidence base is growing. A recent review of 60 primary studies identified a strong and significant historical relationship between the two phenomena (66), suggesting that projected increases in temperature were associated with higher levels of intergroup violence (e.g. civil wars), with the hardest-hit regions precisely those at greatest risk of undernutrition—Sub-Saharan Africa and South Asia. Such high-intensity conflict and associated population displacement would likely lead to more acute undernutrition, in addition to other health burdens.

3.2 Increases in prices of staple foods

Climate change will also intensify economic pressures on food access. Simulations run using the International Food Policy Research Institute's (IFPRI) IMPACT model suggest that inflation-adjusted prices of the three most important staple grains in the world—wheat, rice, and maize—would increase 31-106% by 2050, with assumptions about climate change mitigation, population growth, and income growth determining the exact values within that range (109). For some smallholder farmers, the benefits of greater income may outweigh the costs of more expensive food (135), and landless laborers working on these farms may also see wage increases. Most multi-country analyses, however, suggest that higher food prices will generally increase poverty and food insecurity, not only for the urban poor (for whom the effect is unambiguous), but also for rural people, the majority of whom are net food consumers (71). Recent reviews of price elasticities of food demand in low-income countries found that price increases were associated with steep declines in consumption of all food groups, suggesting that, at least at the scale of national economies, higher prices are likely to reduce nutrient intake (59). However, the magnitude of impacts will vary depending on wealth across and within countries, as well as by food group. The overarching lesson of the literature is that localized analyses are necessary: the impact of food price increases on food security depends on the structure of the economy—including the ability of farmers to adapt to volatile ecological and economic conditions (98)—and the relative magnitude of price changes across foods.

3.3 GDP Growth

The influence of food prices on consumption may, however, be swamped by the rate of growth in gross domestic product (GDP)(130). Projecting growth trajectories is difficult, even without considering the additional variable of climate change. One recent study takes an innovative approach by looking at the historical association between macroeconomic productivity and temperature within countries, a relationship largely driven by the effect of extreme and/or persistent heat on labor supply, labor productivity, and crop production. The authors find that unmitigated climate change may result in 75% lower income, relative to a temperature-neutral scenario, in the poorest nations by 2100. In a low economic growth/rapid climate change (RCP8.5) scenario, 43% of all countries in the world would be poorer in absolute terms by the end of the century than they are now (24).

Despite the sensitivity of the above study to underlying assumptions, the qualitative message of all the scenarios is clear: unmitigated climate change has the potential to lead to immense economic losses, which may translate to greatly weakened consumer purchasing power to obtain food in the developing world. Even if improved crop yields raise the level of aggregate global production, markets and food systems in poor countries may continue to struggle to access the foods available on the global market. The dis-connect between where food is produced (and able to be purchased) and where food is needed may grow wider due to the expected impacts of climate change on low-latitude agricultural systems. These dangers combine with the demographic reality that most of the world’s anticipated population growth of 2.5-3.0 billion people over the coming decades is expected to occur in cities in the developing world.

3.4 Food Utilization and Disease

Food security extends beyond the supply and demand dynamics of markets. Utilization of food also matters: protecting food stocks against spoilage and pests (64; 113), cooking safe and nutritious meals, and being healthy enough to absorb and retain the nutrients consumed. This last point is critical; when safe water and sanitation systems are absent, precipitation extremes—both increased rainfall and prolonged drought—lead to increased exposure to pathogenic bacteria, parasites, mycotoxins, and a host of viruses (122). The resulting enteric infections and diarrheal diseases have profound impacts on child nutritional status, growth, and development (60; 110). An ecological analysis of 171 nationally representative demographic and health surveys from 70 countries across the world between 1986-2007 found that access to improved sanitation and water were significantly associated with reduced levels of stunting in children under 5 years of age (48).

3.5 Volatility

Future projections of food availability, access, and utilization are usually spoken of in terms of mean trends: levels of production, prices, income, disease, etc. as they change over time. Also important, however, is lack of volatility, or stability. As climate change increases spatial and temporal variability in food production patterns, prices may also fluctuate more greatly. The uncertainty bounds for projecting the impact of climate change on any of the determinants of food security are large—and much work remains to be done especially with respect to volatility of food access and utilization—but most biophysical and economic models share the conclusion that the future world will contain more volatile food prices.

4. Future Directions and Conclusions

This review focuses on the anticipated effects of climate change on global food security. There are substantial uncertainties regarding the degree to which environmental conditions will change; the response of plants, animals, and farm labor; and potential adaptations to these changes. Although these uncertainties render predicting future changes in food production difficult, the evidence base strongly implies the need to prepare for a larger range of possible outcomes. Furthermore, our review of the evidence indicates that environmental changes are generally tilted against environments that are already hot and have the least resources for adaptation.

In most instances, further research will reduce these uncertainties. We have highlighted some research priorities in this review. One area not already mentioned is the importance of better describing what people in different populations eat. Estimates of food availability derived from the Food and Agriculture Organization (FAO) have previously been used to model health impacts of pollinator declines (136), reduced fish catch (56), and nutrition and health impacts stemming from elevated atmospheric CO_2 levels (105). However, these estimates of food availability have several flaws: they focus on availability rather than actual intake; they lack information about how different foods are distributed across age, sex, and income groups, as well as how foods are distributed across sub-national populations; and they inadequately account for wild harvested foods, including fish and bushmeat. In addition, our knowledge about the nutrient composition of these foods is limited to several regional food composition databases, many of which have not been updated for decades and are incomplete. The result is a large gap in our understanding of what people are eating, where their nutrients are coming from, and what the relative impact of altered nutrient intakes from changing environmental conditions might be for their overall health.

Policy and programmatic action to improve current and future food security is critical. Many regions still have large gaps between current and practically attainable crop yields (83; 103). Agricultural development through Green Revolution techniques lifted yields in many countries through adopting modern crop varieties, increased use of agronomic inputs, and greater irrigation (117; 142). Yet these gains are distributed unequally. Areas of Sub-Saharan Africa suffer severe food insecurity, relatively low-yielding croplands, and the potential for large relative yield gains (127). Closing yield gaps requires addressing a host of interacting agronomic and socio-economic constraints (83; 101; 143). The joint evolution of agricultural development and global environmental change will together determine future levels of crop productivity.

Reducing food loss and waste would also help meet future demand. Nearly one third (1.3 billion metric tons annually) of global food production is either lost or wasted. Most of the food waste in developed countries takes place in consumer households, whereas loss occurs primarily from pests and fungi prior to reaching markets in developing regions (47). Producing crops for direct human consumption, as opposed to animal feed, could also increase global available dietary energy (29), though animals can be important for nutrition and economic welfare for smallholder farmers.

Better management of environmental change—especially reducing greenhouse gas emissions and other pollutants, more sustainably managing fisheries, and improving efficiency in the agricultural use of land, water, and chemicals—would alleviate the stress placed on many food systems. Striking the correct balance and scope of action between these many policy priorities requires more complete understanding and precise accounting of how environmental transformations determine food production and global health.

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Figure Captions

Figure 1. Since the start of the green revolution, total dietary energy produced by the global food system has been increasing rapidly, with demand projected to continue rising at historic levels. At the same time, the global climate upon which our food system relies has been changing rapidly, and is projected to continue on its current course unless significant interventions are made. Panel a): *Global dietary energy supply*. Historical dietary energy supply estimates were calculated by multiplying daily per capita calorie supplies from FAO food balance sheets [48] by global population estimates from the UN Population Division [147]. Projections of future energy supplies were estimated by multiplying estimates of global daily per capita supplies through 2050 from Alexandratos [109] by median population projections from the UN [147].

Panel b): *Atmospheric CO2 concentration*. Historical data are taken from annually averaged Mauna Loa observations [41]. Future projections are taken from representative concentration pathway (RCP) climate scenarios used in the most recent Intergovernmental Panel on Climate Change report [124]. Panel c): *Global average temperature change*. Historical data are annually and globally averaged land and ocean temperature anomalies relative to average temperature of 1900-2000 [116]. Projected temperature estimates represent the median of four RCP model ensembles standardized to the same 1900-2000 standard level, as well as 95% confidence interval for 2050, as reported by the IPCC [71] and aggregated by the KNMI Climate Explorer (https://climexp.knmi.nl). Panel d): *Global population*. Historical and future estimates (with 95% CI for forecasted data) for global population are estimated by the UN [147].

Figure 2**.** Anthropogenic greenhouse gas emissions are likely to impact human nutritional status through a cascading set of biophysical and socioeconomic changes. Details for the mechanisms and impact of each cause may be found in its corresponding section, labeled in parentheses.