Climate Change and Food Systems

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Abstract

Food systems contribute 19%–29% of global anthropogenic greenhouse gas (GHG) emissions, releasing 9,800–16,900 megatonnes of carbon dioxide equivalent ($MtCO_2e$) in 2008. Agricultural production, including indirect emissions associated with land-cover change, contributes 80%–86% of total food system emissions, with significant regional variation. The impacts of global climate change on food systems are expected to be widespread, complex, geographically and temporally variable, and profoundly influenced by socioeconomic conditions. Historical statistical studies and integrated assessment models provide evidence that climate change will affect agricultural yields and earnings, food prices, reliability of delivery, food quality, and, notably, food safety. Low-income producers and consumers of food will be more vulnerable to climate change owing to their comparatively limited ability to invest in adaptive institutions and technologies under increasing climatic risks. Some synergies among food security, adaptation, and mitigation are feasible. But promising interventions, such as agricultural intensification or reductions in waste, will require careful management to distribute costs and benefits effectively.

Contents

1. INTRODUCTION

1.1. Purpose of the Review

During the second half of the twentieth century, global food supply and distribution developed rapidly enough to keep abreast of population growth and, for many regions, to bring gains to food security in terms of more affordable, reliable, and safe food for all sectors of society. The last decade has seen a rapid reversal of these gains. Achieving food security in the face of accelerating food demand, competition for depleting resources, and the failing ability of the environment to buffer increasing anthropogenic impacts is now widely seen as the foremost challenge of our time (1–5). Climate change is one among a set of interconnected trends and risks facing agriculture and food systems (6). Other components of global environmental change that are driving the future of food security include rapid changes in biodiversity, land cover, availability of freshwater, oceanic acidification, and the nitrogen and phosphorus cycles (7). Future food security for all will ultimately depend on management of the interacting trajectories of socioeconomic and environmental changes. Climate change, and especially increased climate variability, is, however, arguably one of the greatest challenges to food security, particularly via its effects on the livelihoods of low-income individuals and communities, which have less capacity for adaptation and depend on highly climate-sensitive activities such as agriculture (8).

The purpose of this review is to provide a critical overview of the now extensive literature on the tightly coupled relationship between climate change and food systems. In particular, it seeks to draw attention to wider issues of food systems beyond food production, to highlight the distribution of climate-related impacts on food security across sectors of global society, and to set out the opportunities and challenges in food systems for integrating the options for mitigation, adaptation, and food security.

1.2. Climate Change and Food Systems: Concepts and Relationships

The drivers and patterns of observed and predicted climate change are well reviewed (9). A useful distinction can be drawn between long-term (decadal) trends and near-term increases in variability in climate (10), though the same radiative forcing drives both. In the absence of complete mitigation, society needs, in the long term, to adapt to gradual changes in the means and distributions of temperatures and precipitation. Depending on the speed and direction of these trends, incremental or transformative adaptation is needed (10). Most immediately, climate change is being experienced as increasing temporal and spatial variability in temperature, precipitation, and winds, particularly the incidence and magnitude of extreme events. The types of extreme events that are likely to increase include the frequency and intensity of heat waves, frequency of heavy precipitation events and associated floods, intensity of tropical cyclone events, and incidence of extremely high sea levels owing to storm surges. Longer dry spells in some areas, and the area affected by drought each year, are likely to increase. Other types of extreme events, such as cold spells and frosts, will decrease in frequency and intensity (9). In the short term, therefore, increasing climate variability has more impact than longer-term change in mean values, and the appropriate focus of adaptation is climate risk management (11). The need for this focus will continue even though the need to address changes in mean values over the longer term will increase.

Food chain activities are the manufacturing and distribution of inputs (seed, animal feed, fertilizers, pest control); agricultural production (crops, livestock, fisheries, wild foods); primary and secondary processing, packaging, storage, transport and distribution; marketing and retail; catering; domestic food management; and waste disposal. In some cases, this supply is linked through a "cold chain" in which continuous refrigeration is used to extend and ensure the shelf life of fresh and processed foods. Importantly, food systems encompass not only food chain activities but also the outcomes of these activities and their governance (12, 13). All humans participate in food systems and in doing so have multiple objectives: livelihoods, profit, and environmental stewardship, as well as securing food (for nutrition, pleasure and social functions).

Food systems worldwide are in flux, owing to demand-side drivers (population growth, shifting patterns of consumption, urbanization, and income distribution) and trends in food supply, which are related to climate change, to competition (for water, energy, and land), and to the interactions between food production and other ecosystem services (4). Other important trends are changing institutional and social processes within the food system, such as trade liberalization, associated market penetration by transnational food companies, restructuring of retail toward supermarkets, food industry marketing, and consumer attitudes (to social status, health, and sustainability) (1, 14). Broadly speaking, there is no global food system but rather a set of partially linked supply chains for specific products, sometimes global in extent (e.g., soy protein) and sometimes more local (e.g., cassava and other staple food crops in much of the world).

The food industry is highly fragmented, and hence competitive, relative to other resource-based industries, such as mining and minerals. The top 50 food processors account for less than 20% of retail sales by value (15) and, by extension, an even smaller proportion of total food consumption across all formal, informal, and nonmarket channels. However, there is high market concentration for particular foodstuffs, for example, coffee, and for particular portions of the supply chain, notably the seed supply sector (16), and increasingly the retail sector. Supermarkets' share in retail food markets increased from 5%–10% in 1990 to 50%–60% in South America and South Africa, and to 20%–50% in Mexico, Central America, and Southeast Asia by 2007 (17).

Well-functioning markets do not guarantee adequate nutrition to all. Food systems are already unable to prevent widespread chronic malnutrition, as measured by the 178 million children who are stunted, predominantly in South Asia and Africa. Even in high-income countries, sizeable portions of the population are food insecure (5). Hunger and malnutrition are trenchant because, being closely linked to poverty, their underlying causes are complex (18). Governments regularly intervene in markets to guarantee sustained supplies of food that ensure stable and affordable prices for a broad spectrum of consumers to provide themselves with reliable, nutritious, and safe diets. In agricultural countries, these prices should also be sufficient to support farm livelihoods. More generally, poverty reduction initiatives, such as job creation or social welfare schemes, are essential to achieving food security for individuals and households most vulnerable to chronic and acute disruptions to food availability, access, and utilization (19–21). As discussed below, the impacts of climate change

MtCO$_2$e: megatonnes of carbon dioxide equivalent

on livelihoods are likely to be just as important, if not more important at least in the short term, than the impacts on total crop production in determining future outcomes for food security.

2. IMPACTS OF FOOD SYSTEMS ON CLIMATE CHANGE

Many food system activities give rise to production of greenhouse gases (GHGs) and other climate change forcings, such as aerosols and changes in albedo (22). The exceptions are some agricultural practices, such as certain agroforestry systems, that can have a net carbon sequestration effect, especially if used to restore degraded land. GHG emissions vary markedly across the different activities of the food chain at the global level (**Table 1**), but there are important differences in this pattern among countries. In high-income countries, the postproduction stages tend to have a greater role, while in other countries, specific economic subsectors are important, such as the United Kingdom, or to do with country-specific economic subsectors, such as the high contribution from fertilizer manufacture in China (**Figure 1**). Adding the figures across the aggregate global food chain, and assuming a growth in emissions of 3% per year, gives the total global GHG emissions for the year 2008 in the range of 9,800 to 16,900 megatonnes of carbon dioxide equivalent (MtCO$_2$e) from the food system, inclusive of indirect emissions associated with land-cover change. Thus, the food system contributes 19%–29% of total global anthropogenic GHG emissions (using data for nonfood sectors from Reference 23). Of this, agricultural production contributes 80%–86% at the global level, noting the major differences among countries (**Figure 1**), while the remainder comes from preproduction (predominantly fertilizer manufacture) and the postproduction activities of processing, packaging, refrigeration, transport, retail, catering, domestic food management, and waste disposal (landfills). The caveat

Table 1 Estimates of the relative contributions of different stages of the food chain to global greenhouse gas emissions

Stage of food chain[a]		Emissions (MtCO$_2$e)[b]	Year of estimate	References
Preproduction	Fertilizer manufacture	282–575	2007	24
	Energy use in animal feed production	60	2005	25
	Pesticide production	3–140	2007	24
Production	Direct emissions from agriculture	5,120–6,116	2005	26
	Indirect emissions from agriculture	2,198–6,567	2008	Emissions from the supplementary material for Reference 23 combined with proportion due to agriculture from Reference 28
Postproduction[c]	Primary and secondary processing	192	2007	Calculated from Reference 29
	Storage, packaging, and transport	396	2007	Calculated from Reference 29
	Refrigeration	490	2004	30
	Retail activities	224	2007	Calculated from Reference 29
	Catering and domestic food management	160	2007	Calculated from Reference 29
	Waste disposal	72	2007	Calculated from Reference 29

[a] Note that there may be some overlap among categories (for example, transporting and retailing may both involve refrigeration) and that estimates without ranges have low confidence.

[b] Abbreviation: MtCO$_2$e, megatonnes of carbon dioxide equivalent.

[c] The postproduction figures are largely multiplied up from Chinese data on the assumption that as a large middle-income country it is suitably representative of the global level.

with these figures is that they depend on extrapolation from single-country data; using the UK data rather than the China data for the postproduction stages of the food chain gives total global GHG emissions for the year 2008 in the range of 16,800 to 23,900 $MtCO_2e$, with agricultural production contributing 47%–61% of all food-related emissions. This difference may be indicative of the future trajectory of global food system emissions, toward a higher proportion associated with postproduction stages of the food chain.

2.1. Preproduction Activities

2.1.1. Fertilizers. Much food production relies on inputs to some or all tillage, seeds, fertilizers, irrigation, pest and disease control, and feed for animals. Of these, the main source of GHG emissions is fertilizer production, largely owing to its energy intensity but also to some emissions of nitrous oxide (N_2O) in the manufacture of nitrate fertilizers. Production of fertilizers emitted 284–575 $MtCO_2e$ in 2007 (24). The estimate of GHGs produced in the manufacture of synthetic nitrogen is 48 $MtCO_2e$ for India in 2006/2007 (31), and there are two estimates of GHG production for China: 393 $MtCO_2e$ in 2007 (29) and 400–840 $MtCO_2e$ and N_2O in 2005 (26) (the N_2O gases in the latter range are emissions associated with fertilizer application, which other authors allocate to the agricultural production stage of the food chain). Ammonia is the most important input in the fertilizer manufacturing process. Natural gas is the feedstock for 67% of ammonia production globally and has the lowest GHG emissions per energy output, but 27% of ammonia production still relies on coal, nearly all of which is manufactured in China (32). Information on GHG emissions from agricultural pesticide manufacture and use is scarce. A recent global estimate of emissions from crop protection gives a wide range of 3–140 $MtCO_2e\ yr^{-1}$ (24).

2.1.2. Animal feed. The production of feed for livestock and aquaculture contributes GHG emissions directly because of fossil-fuel inputs (in cultivation, transport, and the processing of feed) and indirectly through land-cover change both for grazing and for feed cultivation. Literature on this topic is also scarce, but Steinfeld et al. (25) estimate that more than half of the total energy consumed in livestock production is used in feed production. They estimate that about 20% of the 80 million tonnes of nitrogen fertilizer produced annually are used to cultivate livestock feed. Noting that regional variances are high, best estimates for 2005 show fertilizer use in global feed cultivation led to 41 $MtCO_2e$ emissions (25). Total on-farm fossil-fuel use for feed production released close to 60 $MtCO_2e$ emissions (25). In addition to fertilizer production, energy is used in seed, herbicides, pesticides, diesel for machinery, electricity for irrigation, heating, drying, and processing. Ruminants require more feed per kilogram of meat than monogastric animals (pigs and poultry), and therefore emissions per kilogram of product are higher for the former. However, ruminant production in extensive grazing systems on land unsuitable for crop cultivation will reduce emissions associated with land-cover change (33).

2.2. Production Activities

Agricultural production contributes significantly to GHG emissions, both directly, through agricultural practices, and indirectly, via land-cover change as a result of opening new agricultural lands. Despite the many reviews on the impact of agriculture on climate change, most notably those conducted through the Intergovernmental Panel on Climate Change (IPCC), there is still substantial uncertainty associated with many of the estimates (26).

2.2.1. Direct emissions. Of global anthropogenic emissions, direct emissions from agricultural production accounted for about 60% of N_2O emissions and about 50% of methane (CH_4) in 2005, with a wide range of uncertainty on agricultural and total emissions

(26). The net flux of CO_2 is small, with agricultural soils acting as a sink or source. Overall, for the IPCC, Barker et al. (27) estimated total direct emissions from agriculture to be 14% of global anthropogenic emissions in 2004, whereas Smith et al. (26) estimated direct emissions to be 10%–12% of total global anthropogenic emissions or 5,120–6,116 $MtCO_2e$ at 2005 levels. The sources of these direct emissions are N_2O emissions from soils (38%), CH_4 from enteric fermentation (32%), biomass burning (12%), rice production (11%), and manure management (7%).

2.2.2. Indirect emissions. In 2005, agriculture covered 37% of the earth's terrestrial surface (26). About 80% of the new land for crops and pastures comes from replacing forests, particularly in the tropics (34). Land-cover change is a major source of CO_2 to the atmosphere. For the IPCC, Barker et al. (27) estimated that land-cover change contributed 17% of global GHG emissions. Van der Werf et al. (23) revised the estimate downward, calculating that deforestation, forest degradation, and peat land degradation accounted for 12% (with a range of 6%–18%) of total anthropogenic emissions in 2008. Emissions from peat land degradation are considerable, about a quarter of that for deforestation and degradation. In one of the few quantitative studies, using compiled data from various sources, Blaser & Robledo (28) estimated that globally three-quarters of deforestation and degradation can be attributed to agriculture, with just over half of this due to smallholder agriculture, while the remainder is attributed to ranching and commercial crops. More recent work, on the basis of a meta-analysis of case studies, suggests that, although small farmers were important agents of change from 1960 to 1980, subsequently agribusiness (cattle ranching, soybean farming, and plantation agriculture) has become more important as a driver, especially in the vast forested lands of Brazil and Indonesia (35). In much of Africa and South Asia, smallholders continue to account for substantial land-cover change, but further globalization and urbanization are expected to intensify the trend that agribusiness becomes the chief driver (36).

2.2.3. Total agricultural emissions and regional variation. Combining what is known about direct and indirect emissions, assuming three-quarters of deforestation, forest degradation, and peat land degradation is due to agriculture (28), and using lower and upper estimates reported above, agricultural production contributes 15%–25% of total global anthropogenic emissions. The different lines of evidence suggest that the magnitude of indirect and direct emissions varies among world regions (**Figure 2**). In sub-Saharan Africa, agricultural emissions are about 1,500 $MtCO_2e\ yr^{-1}$ of which just under half comes from indirect emissions. Total agricultural emissions are about 3,000 $MtCO_2e\ yr^{-1}$ in South and Southeast Asia, and similar in Latin America, in both cases with half or slightly more than half coming from indirect emissions. In other parts of the world, sequestration from forest growth and expansion exceeds emissions from agriculturally driven deforestation. Total agricultural emissions in the United States and Canada are just under 500 $MtCO_2e\ yr^{-1}$. In North America and China, there is no indirect contribution from land-cover change, although the food systems of these countries are associated with land-cover change in other regions via imports. The relative importance of different sources of direct emissions also varies among regions (**Figure 2**). For example, direct emissions in South and Southeast Asia come mostly from rice cultivation, N_2O emissions from soils, and enteric fermentation, but in sub-Saharan Africa, a high proportion derives from biomass burning.

2.3. Postproduction Activities

2.3.1. Processing. GHG emissions from food processing include CO_2 (from combustion in cookers, boilers, and furnaces) and CH_4 and N_2O (from wastewater systems). Food processing was responsible for 48 $MtCO_2e$ of emissions in China in 2007 (29). Processing of sugar, palm oil, starch, and corn drives most of the total GHG emissions caused by global food processing. Corn wet milling is the most energy-intensive process, requiring 15% of total US food industry energy. Energy intensities of most primary processing activities are not high: Edible oils require about 11 GJ per tonne (t^{-1}), sugar 5 GJ t^{-1}, and canning operations 10 GJ t^{-1}(39). Secondary processing activities are variable; for example, bread making requires 2–5 GJ t^{-1} and manufacture of breakfast cereals, 19–66 GJ t^{-1}(40).

2.3.2. Packaging. Information on GHG emissions from food packaging is scarce and difficult to interpret, as it may include manufacture of packaging materials, the process of packaging, and a portion of refrigeration costs associated with the cold chain. Jungbluth et al. (41) state that, for both vegetables and meat, packaging is of minor importance in terms of total food emissions. Garnett (22) finds that packaging accounts for 7% of UK food-related GHG emissions.

2.3.3. Transportation. Transporting food makes a large direct contribution to GHG emissions, and the notion of "food miles" receives considerable attention in the scientific and more general media. Food transport for the United Kingdom, for example, produced 19 $MtCO_2e$ in 2002 of which 10 Mt were emitted in the United Kingdom, almost all from road transport (42). Brodt (43) estimates that the same amount of fuel can transport 5 kg of food only 1 km by car, 43 km by air, 740 km by truck, 2,400 km by rail, and 3,800 km by ship.

2.3.4. Refrigeration. Pelletier et al. (44) report that refrigeration (not transport or food miles) is the major energy-intensive component of the food chain. For example, Coca Cola calculates that 71% of its total carbon footprint, including indirect impacts, is the result of refrigeration in sales and marketing equipment (45). James & James (30) bring together the limited data available to estimate that the cold chain accounts for approximately 1% of total global GHG emissions or about 490 $MtCO_2e$ at 2004 levels. The percentage is considerably higher in high-income countries. For example, about 2.4% of the United Kingdom's GHG emissions are due to food refrigeration; "embedded" refrigeration in imported foods could increase this figure to 3%–3.5% of national emissions (46). Refrigeration causes GHG emissions from energy use and from the manufacture and direct loss of refrigerants used in the refrigeration systems. Coulomb (47) estimates that 15% of the electricity consumed worldwide is used for refrigeration. Leakage of chlorofluorocarbon (CFC) refrigerants accounted for 30% of supermarkets' direct GHG emissions in the United Kingdom in 2009. Major retailers are now converting to non-CFC refrigerants in Europe, but CFCs may continue to be a major contributor to GHG emissions in other countries. James & James (30) point out that use of refrigeration is likely to increase with rises in mean ambient temperatures, and this will increase associated GHG emissions.

2.3.5. Retail activities. Energy consumption of modern retail food outlets contributes significantly to GHG emissions. Tassou et al. (48) estimate that the total annual emissions associated with major retail food outlets in the United Kingdom amount to ~4 $MtCO_2e$. The energy consumption of supermarkets depends on business practices, store format, product mix, shopping activity, and the equipment used for in-store food preparation, preservation, and display. Electrical energy consumption can vary widely from ~700 kWh m^{-2} sales area yr^{-1} in hypermarkets to over 2,000 kWh m^{-2} in convenience stores. Refrigeration is responsible for a major percentage of the electrical energy consumption of retail food stores ranging from ~25%–30% for hypermarkets to over 60% for food-dominant convenience stores (48).

2.3.6. Catering and domestic food management. Preparing food contributes to GHG emissions via energy use associated particularly with cooking and refrigeration. Garnett (22) calculates that catering accounts for 6% of direct UK food chain emissions, and home-related food cooking, storage, and preparation account for 9%. These figures are largely not available for low-income and middle-income countries. An estimated 60% of energy consumption by small-scale enterprises across Africa is used for cooking and baking, and cooking is a much greater proportion of total household energy use in low-income households and countries than in high-income contexts (49). An important factor is likely to be the rise in emissions associated with the switching of domestic cooking fuels as household incomes increase. In China, for example, the switch from biomass fuels to commercial fuels, particularly coal-based electricity, increased CO_2 emissions from rural residential energy consumption from 152 Mt in 2001 to 284 Mt in 2008 (50).

2.3.7. Consumer waste. Food waste contributes to GHG emissions directly through CH_4 emissions from landfills. Rates of emissions from landfills differ enormously depending on the composition of waste going to landfill and associated management practices; for the United Kingdom, the food component of landfills is estimated to emit 2–13 $MtCO_2e\ yr^{-1}$ of CH_4 (22, 51). However, the more important role of waste in GHG emissions is generally understood to be through its indirect contribution via the embedded emissions in the production, distribution, and refrigeration of the wasted food itself. In the United Kingdom, avoidable food waste produced estimated emissions of 20 $MtCO_2e$ in 2011 (51). US food waste is estimated to have risen from 30% of total food supply in 1974 to 40% in 2003 (52). Venkat (53) calculates that avoidable food waste in the United States in the postproduction food chain results in GHG emissions of more than 113 $MtCO_2e\ yr^{-1}$, which is 13% of total national food-related emissions and 2% of total US GHG emissions. Consumers account for 60% of this waste. Estimates of waste across countries or across food systems tend to rely on questionnaire data rather than actual measurements (54). There has been little data collection in medium- and low-income countries over the past 30 years (55).

3. IMPACTS OF CLIMATE CHANGE ON FOOD SYSTEMS

The impacts of global climate change on food systems are expected to be widespread, complex, geographically and temporally variable, and profoundly influenced by preexisting and emerging social and economic conditions. The main sources of scientific knowledge on food systems under climate change are (*a*) historical statistical studies of impacts of weather anomalies and climatic trends on food systems (56–58); and (*b*) integrated assessment models that link the direct impacts of weather on plant and animal physiology and on yields with downstream impacts on prices, reliability of delivery, food quality, and food safety, and sometimes with further extrapolation to human welfare outcomes, such as the prevalence of malnutrition (59–61). A third, less common, approach is Ricardian (hedonic) analyses of land values, which account for farmers' allocations of activities across time and across landscapes. Hertel & Rosch (62) and Challinor et al. (63) provide explanations of the various approaches.

Major uncertainties within these integrated assessment models include uncertainty about the direction and rate of climate change at subglobal levels and about the extent to which mitigation and adaptation actions and their feedbacks are included. A drawback of both statistical and hedonic studies is the limited possibility for extrapolation beyond climatic conditions already experienced historically. There is also considerable difficulty in distinguishing climate change from other key drivers of change in food systems (6, 64). Nonetheless, there is sufficient evidence that climate change will affect not only food yields but also food quality and safety, and the reliability of its delivery, as discussed in the subsections below. In particular, management of food safety is emerging as a major area of concern for future food systems under climate change.

3.1. Production Activities

The scientific consensus established by the IPCC (9) is that, generally, up to 2050, temperate regions will experience increased crop yields associated with anticipated mean temperature rises of 1–3°C, whereas water-constrained tropical regions will undergo yield decreases. With higher mean temperatures beyond 2050, all regions will be susceptible to yield losses, but impacts on global food availability would be small owing to compensatory institutional factors, such as enhanced global markets. Beyond 2050, major changes in food production are anticipated. Battisti & Naylor (65) show that, by the end of the 21st century, mean growing season temperatures are highly likely to equal current extremes in temperate areas and to exceed them in the tropics and subtropics, resulting in major impacts on food production.

More recent work intimates that the projections of the IPCC up to 2050 may be overoptimistic for a variety of reasons: The observed climate change is faster than predicted (66); particular climatic variables, such as temperature extremes, may play a greater role than previously anticipated (57, 67); certain fishing and farming systems are unexpectedly sensitive (68, 69); food markets are suboptimally integrated at the global level (70); and interactions between climate change and other variables, such as poverty, population growth, and dietary changes, are profound (4). Furthermore, there is little information on some food systems, such as wild foods, on which there is likely to be greater dependence in times of climate-related crop and livestock failure. By contrast, most models do not account for adaptation actions and socioeconomic development, which might overcome many of the projected impacts of climate change. For example, emerging approaches in fisheries science that couple biophysical and social models suggest that the impact of societal responses to climate change may outweigh the direct climatic effects on fish meal production (71).

3.1.1. Crops. Climate change affects the growth of crops both positively and negatively through multiple mechanisms, including changing phenology, heat stress, water stress, waterlogging, and increases or reductions in pests and diseases (63, 72, 73). A small number of attempts have been made to provide global estimates of crop production under climate change. Funk & Brown (74) use a set of general circulation models to predict that climate change will result in declining per capita food production at the global level. Nelson et al. (59) use two general circulation models to forecast yield changes to 2050 of −27% to +9% across all developing countries and −9% to +23% across all developed countries for the three key staples (maize, rice, and wheat), assuming a carbon fertilization effect (59). A more cautious position is that, owing to the many uncertainties, it is not possible at the present time to make global-scale predictions over any time frame (8, 67). Historical statistical data indicate that six major crops have experienced significant climate-associated yield reductions of 40 Mt yr^{-1} between 1981 and 2002 at the global level, but these losses have been outstripped by technological improvements (56). There is much variation among countries and crops because of differences in trends of both yields and climate. A recent comprehensive statistical study shows wide geographic variation in the extent to which rice, wheat, maize, and soy yields have responded to measurable climate trends over the past 30 years; except for rice, which has largely fared better at higher latitudes, there is no apparent correlation with geographic regions or the development status of individual countries (58).

Much work on single crops focuses on particular regions, which have greater homogeneity in agro-ecosystems, climate, farming practices, and markets than those at the global level. Knox et al. (75) provide a systematic review of model-based studies of future crop yields in South Asia and Africa. Under high GHG emission (IPCC A1) scenarios, there are no impacts on timescales prior to 2050; beyond 2050, crops with significant yield variation are maize (−16%) and sorghum (−11%) in South Asia and wheat (−17%), maize (−5%), sorghum (−15%), and millet (−10%) in Africa. Statistical studies provide empirical evidence and greater detail. For example, data from historical maize trials in Africa show the importance of both water and heat to rain-fed maize; each day above 30°C reduces yield by 1% on average and by 1.7% under drought conditions (57).

The impacts of climate change not only on yields but also on food quality may be critical to future food security. A meta-analysis of 228 experiments found that elevated CO_2 (540–958 ppm) reduced the protein concentration of wheat, barley, rice, and potato by 10%–15% and of soy by a smaller but still statistically significant 1.4% (76). Other effects of climate change on food quality during crop production include the greater risk associated with flooding, contamination of agricultural land, groundwater and surface water, heavy metals, agricultural residues, and hazardous wastes (including dioxins and polychlorinated biphenyls), as experienced during the European flood events of 2002 and in the United States following Hurricane Katrina in 2005 (77).

3.1.2. Livestock. Global projections of the impact of climate change on livestock production are not available. Precision is difficult owing to the complexity of livestock production systems, the difficulties in isolating and integrating climatic and nonclimatic effects, the range of possible adaptive responses at technical and social levels, and the problem of separating the impacts on the animal per se from the impacts due to changes in feed. Thornton et al. (78) provide a thorough review of livestock and climate change in low-income and middle-income countries, noting the paucity of system-wide approaches as a major gap in scientific knowledge (78). It is expected that in the future climate change will primarily affect livestock production directly via impacts on pasture and feed supplies, water, diseases, and genetic diversity. Recent modeling work demonstrates that the emergence and spread of bluetongue, a viral disease of ruminants, is associated in Europe with climatic trends (79). Regarding availability of graze in rangeland systems, there is general agreement that changes in the variance will in the future have as much impact as, or more impact than, trends in average conditions (9, 78). Poorer livestock keepers will be particularly susceptible to mortality of livestock in arid and semiarid regions where drought events are projected to become more frequent.

3.1.3. Fisheries. Efforts to model future climatic impacts on global productivity are more advanced for marine fisheries than for livestock or crops. Historical data show that climate-related changes have already occurred in ocean productivity, with a 1% decline in primary productivity per year in eight of the ten world's ocean regions (80). A multispecies model of marine capture fisheries projects less than 1% change in maximum catch potential between 2005 and 2055 under high GHG emissions (IPCC scenario A1B), but with major spatial differences, notably increases of 18%–45% across Nordic fishing zones and a decline of more than 20% in Indonesian zones (81). Equivalent models have not yet been developed for aquaculture. Inland aquaculture comprises a growing proportion of total fish consumption and may be sensitive to water scarcity or to increasing frequency and intensity of flooding (69). Rising ambient temperatures are associated with increasing incidence of harmful algal blooms that result in lethal toxins, particularly in shellfish (82). Longer-term changes in algal communities have wide-ranging impacts on marine communities and hence food availability and food safety for human populations (77).

3.1.4. Food safety. Diarrheal diseases cause about 1.9 million deaths per year, mainly among children in poor households in low-income countries, and most are caused by food-borne pathogens, such as *Salmonella* and *Campylobacter*, transmitted in animal-derived foods, such as milk, meat, and shellfish (83). The scientific consensus is that, although individual pathogens will differ widely in epidemiological responses, the net impact of climate change will be a large increase in the burden of infectious diseases (84). For plant-derived foods, mycotoxins are considered the key issue for food safety under climate change (85). Roughly a quarter of the global annual maize crop is contaminated with mycotoxins, by-products of fungi, which are dangerous to human health even at low doses and are responsible for high fatality rates during acute outbreaks, such as in Kenya in 2004 (86). Historically, acute mycotoxicoses have been diseases of the poor, especially during shortages of food (77). Aside from the health risks, there are also substantial losses to harvests and to food security, which fall disproportionately on poorer households dependent on locally grown maize. The impacts of climate change on mycotoxins in the longer term are complex and region specific; temperatures may increase sufficiently to eliminate certain mycotoxin-producing species from parts of the tropics, but in colder tropical regions and temperate zones, infections may increase (87). For example, models project that mycotoxin levels associated with cereal diseases, such as *Fusarium* head blight in wheat, will exceed EU limits by 2050 (72). A further risk is that new plant fungal diseases will arise under climate change, and hence, there will be additional mycotoxin risk factors to humans (77). Scientists have expressed concern that rising incidence of disease will lead to overuse or misuse of pesticides and veterinary medicines, particularly in fisheries (9, 77, 85).

3.1.5. Overall agricultural systems. A recent set of reviews considers the impacts of climate change on the entire agricultural system for a particular country or region, providing an integrative analysis. China provides a good example of the complexity involved (88). Precipitation patterns have changed and heat waves have increased over the past 50 years. Runoff has increased in the Pearl River, associated with higher precipitation, but declined in the Yangtze and Yellow Rivers; future changes in water availability for agriculture cannot be ascertained owing to current uncertainties in models of precipitation under climate change. Increasing withdrawals for agriculture in arid regions outweigh the additional water flows from melting glaciers, which moreover will only be an additional source of water for a limited time. The rice-growing area has expanded northward, but at the same time, wheat yields have decreased, associated with rising daytime temperatures.

Models of future yield changes predict both reductions and declines, dependent particularly on the effects of CO_2 fertilization, which is still poorly understood. Other factors that are not well understood, such as pests, diseases, surface-level ozone, and the potential for uptake of adaptation options, have not been included in the models. The strengths of country- or region-based studies are their treatment of multiple interacting factors (climatic and nonclimatic) and their detailing of spatial and social heterogeneity in outcomes. For example, Dronin & Kirilenko (89) argue that yield increases at high latitudes in Russia under high emission scenarios will not increase food availability nationally because of the greater risk of drought at lower latitudes. Integrated economic models, such as Mideksa (90) for Ethiopia, and Hassan (91) for Africa as a whole, provide insights into possible long-term accumulative impacts of climate change on agricultural economies and food systems, highlighting problems of increasing inequality and lack of reinvestment in agricultural development.

3.2. Postproduction Activities

Evidence regarding the impacts of climate change on the postproduction food chain is scattered, with a small number of analyses of historical responses to climate and some modeling studies. Nonetheless, there is an emerging understanding of how increasing climate variability and longer-term trends in climate will affect the many stages of storage, primary processing, secondary processing, transport, retail, and consumption. Increasing frequency and severity of extreme weather events can affect volume, quality, safety, and delivery of food in the postproduction stages of the food chain via (*a*) amplifications of climate change impacts on agricultural production (e.g., storage methods that increase the chance of transmission of climate-related livestock diseases to human consumers) and (*b*) additional new impacts (e.g., disruption of transport owing to extreme weather events). These points are discussed in the subsections below.

3.2.1. Harvests. Recent data for eastern and southern Africa show that in these contexts the highest proportion of food waste is as postharvest losses on or near the farm, with yield losses averaging 5%–35% for different cereals (maize being the highest) and an aggregate 15% of production value lost each year (54). In extreme cases, for example, those associated with severe weather conditions, postharvest losses may be as high as 80% for rice in Vietnam and 50% for fresh vegetables in Indonesia (55). For many crops, the scheduling of harvest is critical, particularly to avoid wet spells or hot spells that can reduce yields and efficiency, potentially with major economic consequences to the industry and transmission of high prices to consumers. For example, historic wet spells during harvest in the Australian sugar cane industry have caused multimillion-dollar losses with knock-on effects for subsequent years (92). From a food security and human health perspective, the impacts of wet spells and hot spells at harvest time are of special concern, as mycotoxins are known to increase in concentration under such conditions at harvest time (93).

3.2.2. Storage. Food storage infrastructure can clearly be damaged or destroyed completely by extreme weather events, but there appears to be little research to date on the impacts of increasing climate variability and longer-term climatic trends on major food storage facilities or on the performance of more traditional food storage systems, such as home-built granaries. The Food and Agriculture Organization of the United Nations (94) notes that increasing temperatures lead to strains on electricity grids, air conditioning, and refrigeration, so storage costs will likely rise. Higher temperatures will clearly affect the perishability and safety of fresh foods. Bacterial growth rates approximately double with every 10°C rise in temperature above 10°C; below 10°C, temperature change has a stronger effect, with storage life halved for each 2–3°C rise in temperature (30). Research in Kenya has demonstrated that stored maize that reaches unsafe levels of aflatoxin can cause widespread and prolonged exposure to the surrounding community, as farmers sell maize to and buy it back from local markets through the season (86).

3.2.3. Transportation. Although the effects of weather on transport are visibly evident, there have not been many integrated assessments at either national or global levels of the impacts on transportation of changes in frequency, severity, and seasonality of extreme weather events (95). Impacts will be region specific, and net impacts across all modes of transport cannot be ascertained (96). In colder latitudes, for example, climate change will mean reduced winter maintenance costs and opening of sea and river routes for longer periods of the year, but there will also be a loss of infrastructure and roads that depend on permafrost (95). In countries with inadequate infrastructure (roads and bridges and their maintenance), the higher risk of floods is likely to pose significant threats to the distribution of food in rural areas (13). In low-income countries where transport infrastructure already limits efficient food distribution, impacts are likely to be exacerbated (94). Similarly, highly sophisticated, low-inventory food chains that work to a just-in-time mode of delivery are highly susceptible to disruption by weather (97).

3.2.4. Marketing, retail, and consumption. Seasonal markets based on demand rather than on supply are characteristic of food chains in high-income countries; there is substantial business knowledge as well as some historical academic studies that consumer behavior is affected by weather variables, such as temperature and sunshine (98). Patterns of food consumption can reasonably be expected to respond to future trends in temperature and precipitation. In addition, extreme weather events will be a more frequent determinant of food purchase and consumption, either by limiting consumers' access to food or by determining food preferences. Disaster preparedness and disaster relief both place specific demands on food systems and, furthermore, can instigate lasting changes in food security. For example, research in Thailand shows how relocation of vulnerable populations following floods can undermine their access to food via subsistence and purchase (99).

3.3. Broader Effects on Food Systems and Food Security

Perhaps the principal concern for food systems under climate change is their reduced capacity to assure food security to poor populations vulnerable to hunger and malnutrition (100). Climate change is likely to affect all four of the recognized components of food security: availability, access, utilization, and stability over time (8, 13, 20). Greatest attention is given in the literature on climate change and food systems to impacts on agricultural yields and hence food availability. Nonetheless, the impacts on incomes and livelihoods, and therefore access to food, are likely to be equally important to food security. Vulnerability to climate change—measured, for example, by the IPCC in terms of the interdependent factors of exposure, sensitivity, and adaptive capacity—is not evenly distributed (101–103). There is some evidence to date that higher exposure to climate variability, shocks, and long-term trends and higher sensitivity of food systems are correlated with weaker adaptive capacity, such as the higher risks anticipated in tropical drylands (104), but that global analysis does not show any discernible historical correlation between country gross domestic product (the usual measure of adaptive capacity) and sensitivity of crop yields to climate change (58). Likewise. the mapping of food security vulnerability in tropical regions reveals very different geographic distributions depending on the specific climate exposure (103).

Regardless of strong or weak correlations among the components of vulnerability, the major heterogeneities in wealth—and hence in adaptive capacity and access to food—arguably outweigh any distribution of climate risks. A review of integrated modeling studies concludes that climate change will slow, but not reverse, the rate of poverty reduction globally; in general, the impacts of climate change fall disproportionately on the poor, thereby increasing inequality over time (102). Poor people are expected to be more vulnerable to the following impacts of climate change on agriculture: reduced consumption because they spend a greater percentage of their incomes on food and are therefore be more strongly affected by food price increases, reduced income generation because they are more likely to depend on the climate-sensitive sectors of agriculture and ecosystems, and reduced adaptive capacity because they have fewer assets (62).

An estimated 2.3 billion people reside in rural areas dominated by smallholder agriculture (105). In many countries, the majority of poor rural households, which sell and buy different foods at different times, are marginal net food purchasers (106). Repeated extreme weather events can undermine a household's ability to maintain its asset base or to reinvest in agriculture, leading for some to chronic food insecurity, poor health, and lack of economic productivity (1, 107). Longitudinal household survey research in Malawi shows that climate shocks can impact on how households secure food through labor, trade, and transfers from family and social networks, as well as on their agricultural production (108). Impacts of climate variability on access to food will, however, always be context specific, depending, for example, on the geographic extent of a climate shock and the functioning of food markets (62). Even in high-income countries, differences in socioeconomic factors, such as farm size (109), will be major determinants of impacts of climate change on farm incomes.

An additional source of vulnerability, not well covered in the literature, is that food systems on which low-income households depend may be especially sensitive to climate shocks and trends. Parallel food chains for different socioeconomic groups exist in many countries, particularly for fresh foods such as vegetables, fruits, fish, meat, and dairy (110). Food chains for the rural poor are likely to be characterized by low use of refrigeration but high use of secondary processing, long-distance transport, and formalized quality control. Price transmission between international commodity markets and isolated rural food markets is weak and idiosyncratic (111). The implication of these factors under conditions of increasing climate variability is particular sensitivity to any sudden decreases in food quality, safety, and availability at the local level. These will be compounded by weak access to public services and humanitarian assistance in times of need and, in the longer term, isolation from market signals that can helpfully inform farming decisions. However, the future is likely to bring greater integration of poor farmers into global markets. Some will take advantage of rising prices for agricultural produce, whereas for nonagricultural rural households in parts of Africa and Asia, the rates of poverty may rise as much as 50% (61).

Although climate change impacts on rural farming communities are of major concern, over half of the world's population now dwells in urban areas (112), so the impacts on affordability are paramount. Poor urban consumers are also affected by rising food prices, but their vulnerability to high food prices is generally lower than for rural consumers, as they typically spend a smaller proportion of income on food and have better access to food markets (106). Evidence indicates that the negative impacts of climate change on agricultural yields generally translate to much smaller increases in the prevalence of poverty at the national level (102). Regardless of these complexities, the direct impacts on human health and well-being as a result of rising food prices since 2007 (111, 113), and associated social unrest (114), demonstrate the gravity of future challenges of climate change to food availability and access. Nelson et al. (59) estimate that unchecked climate change will result in a 20% increase in child malnutrition by 2050, particularly in Africa and Asia (**Figure 3**). The negative impacts of climate change on human health are again expected to fall disproportionately on poor people, owing to their limited access to clean water, food quality control, medical services, and public health services, such as mosquito control (84, 115).

4. INTERVENTIONS TO MANAGE THE INTERACTIONS BETWEEN FOOD SYSTEMS AND CLIMATE CHANGE

Coordinated actions are required for climate change adaptation and mitigation in food systems. Improved food security under climate change requires policies and actions both to make food systems more resilient to climatic variability and change and to mitigate GHG emissions and other climate forcing. Synergistic accomplishment of the goals of food security, adaptation, and mitigation in food systems, illustrated in **Figure 4**, is currently the focus of major global learning processes, for example, under the rubric of climate-smart agriculture (116). But major trade-offs must also be navigated, most importantly the capacity of agriculture to mitigate its substantial contribution to global GHG emissions versus its capacity to supply a growing demand for food (5). As described below for both adaptation and mitigation, specific technical and policy interventions must be situated within a broader holistic approach to agricultural and food system management. For instance, net mitigation effects only occur if greater on-farm efficiency does not displace emissions to other parts of the landscape or food chain. Likewise, mitigation and adaptation actions need to be balanced against other environmental and social services, such as water-use efficiency or equitable access to wild resources held in common property.

Sustained investment in institutions needs to underpin any technical interventions to manage the interactions between food systems and climate change (117). Key areas for investment include management and extension of knowledge and information at all levels (11, 20), intellectual property rights over emerging technologies (16), financial services (107, 118), and input and product markets, including markets for

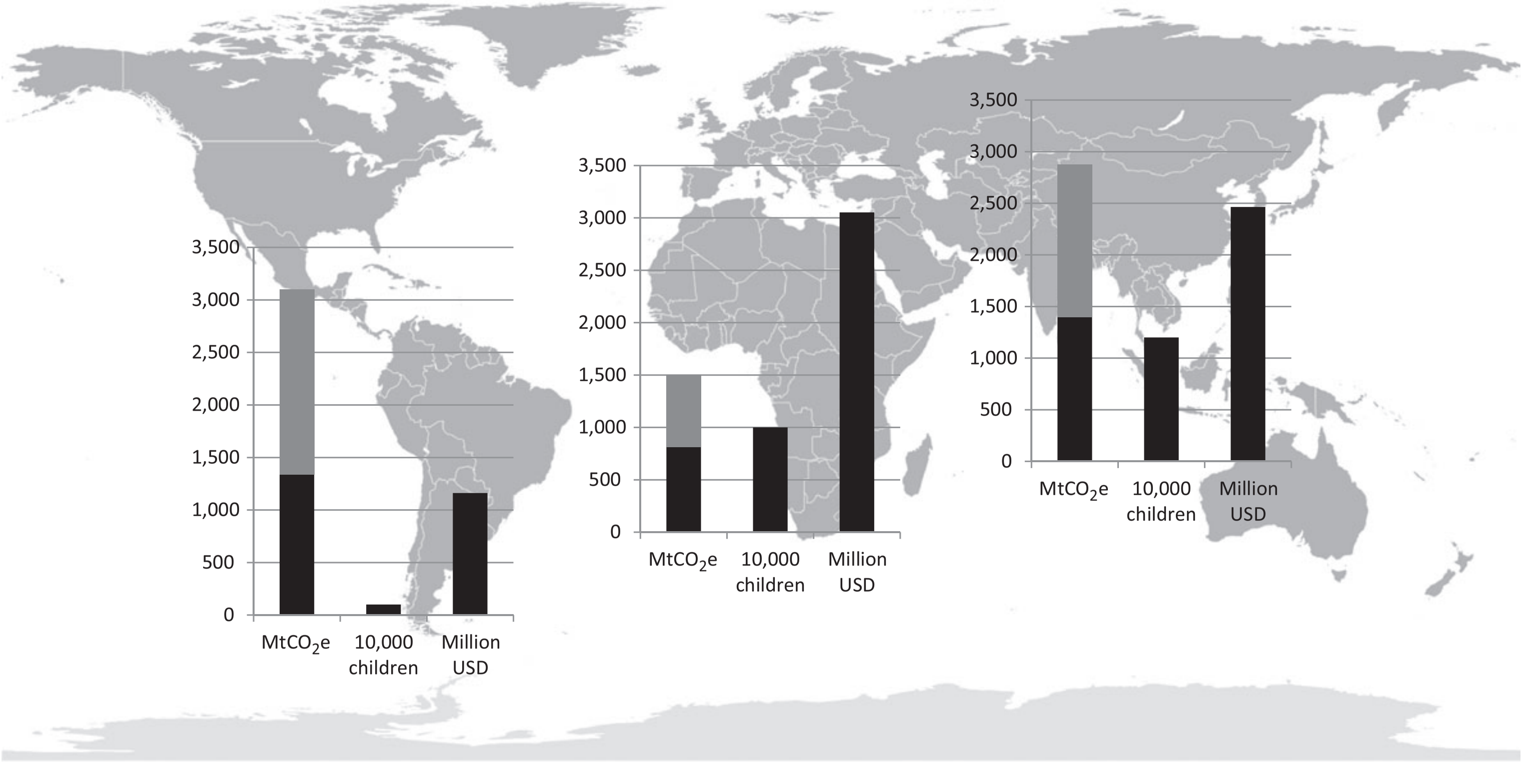

Figure 3

Regional differences in estimated direct greenhouse gas (GHG) emissions from agricultural production (*black*) and indirect GHG emissions from agriculture-driven land-use change (*gray*) for the year 2005, impacts on child malnourishment (additional children malnourished in 2050 owing to climate change in absence of adaptation), and cost of adaptation in agriculture to avoid additional numbers of malnourished children, for low-income and medium-income countries in Asia, sub-Saharan Africa, and South and Central America. Data were obtained from Reference 37 for direct emissions; these are updated data prepared for the Intergovernmental Panel on Climate Change, combined by countries that match Houghton's regions used for indirect emissions (hence, Europe is excluded, and Mexico is included in Latin America). Data from Reference 38 were used for indirect emissions in conjunction with Reference 28 for agriculture's share as a driver of deforestation and degradation.

carbon and other environmental services (118). How to achieve global food security under climate change is a political question (20) where equitable access to rights, resources, technologies, services, and governance by different social groups is a primary concern (119, 120). Mitigation and adaptation are more than a set of technological and institutional innovations; they constitute social learning processes that must address differences among people's values, capacities, and vulnerabilities (121). National policies on climate change are moving away from sectoral approaches, and there is a clear distinction between adaptation and mitigation toward highly integrative low-carbon development pathways (122). Integrative approaches have a better likelihood of avoiding unintended indirect impacts of climate change policies (117), such as the incentive for land clearance associated with biofuels mandates (123).

4.1. Adaptation and Food Security

Any estimate of the adaptation potential of a food system, or of the costs associated with adaptation, are limited by the uncertainties of climate change and other environmental or social changes. Nonetheless, the prevailing scientific view is that adaptation to the level that fully mitigates global climate-related losses in food availability is technically possible, although at a sizable environmental and social cost for particular regions (59, 104, 124). Financial costs are not, however, high. Nelson et al. (59) estimate global costs of agricultural adaptation to 2050 to be in the order of $7 billion per annum, with the most substantial investments being infrastructure, notably rural roads in Africa, and agricultural research (**Figure 3**). Similarly, Wheeler & Tiffin (124) review a number of estimates and broadly support the United Nations Framework Convention on Climate Change figure of ~$12 billion for the year 2030, including fisheries. These estimates will be improved by the future use of bottom-up methodologies, which will probably indicate higher total costs (124).

Technical options for adaptation have been more clearly framed for crops and livestock than for fisheries (104). At the farm level, to manage risks associated with increasing climate variability, these include better use of seasonal climate forecasting (11), greater deployment of water conservation technologies (64), and diversification of on-farm activities (10). Extending into the longer term, when both climate variation and trends in mean climates will have impacts on agriculture, the recommended options include development and adoption of different varieties and species more suited to emerging climatic conditions, improved management of pests and diseases, and adjustments in cropping and management practices (10, 104). Perhaps the primary limitation to planning for adaptation to climate change at the farm level and subnational level is that current climate scenarios are at coarser spatial and temporal scales than needed for local decision making (125).

Direct conflicts between adaptation in the longer term and food security in the shorter term are possible (**Figure 4**). Examples include (*a*) practices that increase the likelihood of yield but reduce total potential yield and (*b*) technologies that have high capital costs and so reduce farmers' short-term household budget. Also of concern are trade-offs with other desired outcomes from agriculture, such as biodiversity (126). Nonetheless, many of the recommended interventions build on well-established technologies and constitute good practices even without climate change, and as such are "no regrets" options (100), like those examples given in the center of **Figure 4**. Key to achieving these multiple gains at the global level will be ongoing investment to close the yield gap between what is currently produced and what is achievable at only slightly higher resource-use intensity, particularly among smallholder farmers in low-income countries (4).

However, there are limits to specific options in terms of adoption potential and costs for different social groups, particularly resource-constrained producers, but also in high-income countries (109). Wealth, gender,

Table 2 Differences in adaptation strategies, capacities, and access among social groups in household surveys in Africa

Country and sample size	Adaptation strategies recorded	Differences and determinants among social groups in strategies, capacities, and access	References
Uganda (n = >5,000)	Technology based, e.g., water harvesting Changes in labor allocation Cashing in assets and savings Reducing consumption	Complex strategy portfolios dependent on age of household head, access to credit and extension services, security of land tenure Gender not important except for drought response when women are more likely to reduce consumption and men to cash in assets and savings	127
South Africa (n = 800) Ethiopia (n = 1,000)	Switching varieties Planting trees Soil management Sowing dates Irrigation	Main barriers are lack of access to credit in South Africa and lack of access to land, information, and credit in Ethiopia Likelihood of adoption increases if household experienced a flood in the past five years and with household wealth, size, and access to credit	118
Cameroon (n = 800)	Reallocation of labor Use of wild resources Soil, crop, and water management Migration Ceremonies and prayers	Study investigated gender only: Women are more likely to favor diversified portfolios of low-cost adaptation options	128
Nigeria (n = 200)	Drought-resistant maize	Likelihood of adoption increases with wealth, off-farm income, access to technology, inputs (fertilizer), extension services, and access to climate information	129

age, and relative access to services all affect how agricultural households deal with climatic shocks and adopt adaptation strategies (**Table 2**). Autonomous adaptation actions at the farm level will need to be framed and supported by planned adaptation at higher levels (104). For example, policy incentives for diversification of types of farms across a region could enhance society's adaptive capacity in much the same way as on-farm diversification strengthens a farmer's adaptive capacity (109). In some regions, adaptation will entail substantial transitions in farming and food systems over entire agro-ecosystems, such as anticipated needs to shift from crops to livestock in certain parts of semiarid Africa (68), or even for some farmers to exit from agriculture.

Research on the options and costs for adaptation in the postproduction food system activities is less well developed than for agricultural production. In theory, adaptations that reduce levels of waste in the food chain could, if brought to scale, compensate in a large part for reductions and variability in harvests (5). There is major technical scope for improved postharvest technologies in low-income countries (130). Renewed investment in systems of grain reserves has been proposed as an adaptation that has direct benefits to food security; there is potential both for large-scale internationally coordinated reserves and for more localized networks of granaries and traders (131). Tirado et al. (77) describe some of the adaptation options available for managing food safety in the food chain, drawing particular attention to improved systems of forecasting and monitoring, plus better coordination between public health authorities and their counterparts in veterinary, crop health, and food safety offices. Refrigeration clearly has a role in avoiding the waste of fresh foods at higher ambient temperatures under climate change, and wider access to this technology could benefit public health (47). From a system-wide perspective, however, foodstuffs and food chains that do not rely on continuous cold chains will be better able to adapt to climate change.

The most important adaptations to improve food security under climate change may well be at the system-wide level or even beyond the food sector. Food systems, increasingly connected by trade, do not experience climate impacts in isolation. A small number of studies have combined models of climate, crop yields, and global trade (59–61, 132) chiefly to ascertain impacts on incomes and food security more accurately, and these have important lessons for adaptation. Hertel et al. (61) show that the impacts of climate change on national and household welfare will depend not only on direct productivity shocks, but also on changes to the relative terms of trade. Policies to manage local and international trade will be important in dampening the effects of localized climate shocks on food prices (102). Both Fischer et al. (132) and Nelson et al. (60) note that the abilities of countries to reduce levels of malnourishment under climate change depend heavily on gross domestic product and economic growth trajectories; one conclusion is that broad-based economic development is a more effective adaptation strategy for food security than sector-specific interventions. Finally, it is worth noting that consumption patterns are widely discussed as a mitigation measure (see below) but barely mentioned for adaptation, although there would appear to be much opportunity to match future diets more appropriately to the foods available, locally or globally, under climate change.

Safety nets to offset the acute impacts on food security of the most vulnerable populations are likely to be an essential component of any successful adaptation program to achieve food security under climate change. Empirical evidence demonstrates that discrete climatic shocks can give rise to chronic negative impacts, for example, on health, education, and economic productivity (107). Approaches to the management of increasing climate risks will need to address acute hazards but also the impacts of cumulative losses, particularly for poor producers and consumers (119). Institutional support to adaptation that will deliver food security requires attention to the wider contexts of food access, utilization, and stability—and hence to livelihoods, public services, markets, and patterns of consumption (20, 120). Although this area of study is not yet well developed, lessons can be drawn from experience to date with interventions in rural development, risk management, and disaster relief (20). Provision of publicly funded social safety nets is a preferred policy intervention to protect vulnerable individuals and households from chronic food insecurity (19, 107). Safety nets can take many forms, including food price subsidies (107), supplementary food or food vouchers (107), subsidized insurance (133), direct cash transfers (19), and labor guarantee schemes (21). Many of these interventions can be linked directly to the current and emerging understanding of climate change, for example, crop insurance linked to weather indices rather than the actual measurement of production failures (11, 133).

4.2. Mitigation and Food Security

Technical options for mitigation in the agricultural sector are well understood. Not including fisheries, for which understanding of mitigation potentials is in an earlier stage of development (134), the total global mitigation potential in emissions from changes in agricultural production technologies is calculated to be 6,000 $\mathrm{MtCO_2e\ yr^{-1}}$, which at a price of US$20 per tonne $\mathrm{CO_2e}$ would lead to implementation of 1,500–1,600 $\mathrm{MtCO_2e\ yr^{-1}}$, with greater implementation at higher carbon prices (26, 135). About 70% of this potential is in low-income and middle-income countries (135), although the global figure conceals wide variation in the potentials among regions and among farming systems. For example, in Japan, Vietnam, North Korea, Pakistan, and the United States, the mitigating effect of seasonal draining of paddy rice is greater than 40% of annual emissions because these countries either have a large proportion of continuously flooded rice fields or plant rice only once a year. By contrast, there is hardly any potential in Bangladesh, India, and Indonesia, which all have a relatively high proportion of rain-fed rice (136). Furthermore, the practical potential of different options remains in debate. For example, sequestration of carbon in the soil is cited as having the largest potential for agricultural mitigation at a sufficiently high carbon price, but in practice, this will be limited by the total soil carbon stock, reversibility of the flux, and induced changes in fluxes of CH_4 and N_2O (137). Appropriate and cost-effective options will need to be tailored to the specific agro-ecological and institutional contexts of specific farming systems (26).

Agricultural intensification (productivity increases per unit of land and other resources) is widely recognized as a means of maintaining or increasing food production while freeing up land for carbon storage under forests, grasslands, and wetlands (3, 4, 138, 139). Higher yields are calculated to have already avoided emissions of up to 590,000 $MtCO_2e$ since 1961 (140). Palm et al. (141) demonstrate for Tanzania and Kenya how increased use of mineral fertilizers can increase productivity sufficiently to provide total local calorific needs while reducing area-based GHG emissions through land sparing; at low population densities, green manure and tree fallows can achieve even greater emissions reductions while fulfilling local food demand. But the scope for trade-offs is also high. For example, in Vietnam, intensified production of rice and pigs reduces GHG emissions in the short term through land sparing, but after two decades, the emissions associated with higher inputs are likely to outweigh the savings from land sparing (142). There are challenges too in providing incentives for the desired land-sparing effect. In practice, local yield increases tend to increase returns to farming and hence, perversely, to stimulate extensification of agricultural land (139). Intensified agriculture drives up opportunity costs for reducing emissions from deforestation and forest degradation (143). Additionally, intensification may be associated with increases in indirect emissions in other segments of the food chain (22). Owing to these externalities and the potential for spiraling incentives, policies to achieve agricultural intensification need to be situated within broader plans for adaptation, low-carbon development pathways, and comprehensive climate change action plans (122, 144).

More generally, all of the approaches proposed for mitigation in the agricultural sector, with the possible exception of improved energy efficiency, have been subject to critique on wider environmental, social, economic, and ethical grounds (22). To give one example, improving productivity in livestock systems has clear technical benefits for mitigation of GHG emissions, but this raises concerns around increases in soil and water pollution and the costs to animal health and welfare. Additionally, there may be limited economic feasibility for smallholder farmers, who account for a majority of global production but may not have the capital to adopt new practices and technologies for feed or husbandry (78). At the broader level of global food systems and land use, there is the more fundamental question of the relative efficiency of using land, water, energy, and other inputs to produce feed for livestock instead of using these resources for direct human consumption (33). Such concerns are balanced against the value of livestock products to nutrition, particularly for low-income consumers who may have difficulty fulfilling recommended intakes of protein and micronutrients (145). Similarly, biofuel production, to substitute for fossil fuels and thereby reduce GHG emissions, has synergies and trade-offs with multiple aspects of food security, including farmers' incomes, trade, food prices at levels from local to global, human nutrition and health, and the governance of land and resource use (146). There are clearly mismatches between the contribution of agriculture to climate change in different regions and the expected vulnerability and costs of adaptation in some regions (**Figure 3**), leading to ethical considerations of where mitigation actions should be focused and how they should be funded.

The global technical potential for mitigation of GHG emissions in the postproduction stages of the food chain has not yet been estimated. Garnett (22) summarizes the major areas for intervention as improving energy efficiency, switching to cleaner and renewable fuels, and improving nonenergy resource efficiency, such as through recycling and reuse. Practical options for mitigation vary considerably among products and modes of production, as life-cycle analyses attest. A detailed analysis in Sweden found that yogurt has a larger mitigation potential than other milk products, predominantly through lowering energy use by retailers and reducing waste in households (147). Refrigeration, as the major contributor of GHG emissions in the postproduction food chain in high-income countries, is an important target for reductions. Studies have estimated that emissions related to energy use can be reduced 20%–50% through correct specification and use of equipment (46), and emissions related to CFCs by 80%–90% using existing and emerging technologies (148). There is substantial potential for multiplier benefits from mitigating GHG emissions from food chains. For example, CH_4 from wastewater treatment could potentially be recaptured for energy generation, and the palm oil industry in Malaysia could generate an additional 2.25 GWh of electricity through this process, avoiding a significant portion of the sector's current emissions of 5.17 $MtCO_2e$ per year (39). There are also potential trade-offs; for example, individual portions can minimize food waste, but create increased packaging.

Literature explicitly concerned with the wider range of possible synergies and trade-offs between food security and mitigation remains scarce with regard to the postproduction stages of food chains. More efficient use of energy and resources in food processing, distribution, and retail has the potential to reduce emissions and simultaneously improve availability and affordability of food, but there are clear trade-offs between, for example, reducing refrigeration costs and maintaining food safety (30). Although individual technical and managerial interventions are promising, their global potential for efficiency gains depends on factors in wider food systems. Garnett (22) uses the example of refrigeration to show how efficiency gains may be offset by growing dependence on cold-chain-based food supplies, which not only increases emissions directly but can also promote consumer behaviors that multiply the effect, such as consumption of more GHG-intensive fresh foods, demand for ever wider choice in processed foods, and greater household waste.

Even more importantly, rising consumption will lead to growing emissions from food systems despite greater GHG efficiency. New analyses support the forecast that demand for crop calories will double from 2005 to 2050 (138). Therefore, meaningful mitigation benefits will require reductions and changes in patterns of consumption in terms of the amounts and the types of foods eaten and discarded (22, 33), although social and policy mechanisms to manage demand remain poorly understood. The considerable consumption gap between poorer and wealthier consumers, in both calorie and nutritional terms (33, 138), raises questions of social equity in distributing the burden of consumption reductions.

SUMMARY POINTS

1. There are major uncertainties regarding the impacts of food systems on climate change and the impacts of climate change on food systems. The wide ranges in some of our estimates illustrate the level of uncertainty. For instance, direct and indirect GHG emissions from food systems account for between 19% and 29% of the total global anthropogenic emissions.

2. The postproduction stages of the food chain collectively emit GHG emissions equal to the production stages in high-income countries (**Figure 1**), although in middle-income and low-income countries, and hence globally, agriculture is by far the dominant source of emissions (**Table 1**). Indirect and direct emissions from agriculture differ markedly in their contribution by region (**Figure 2**).
3. The net effect of climate change on the global aggregate food system is anticipated to be significant if we do not adapt at a sufficient pace. Both models and empirical data suggest that there will be significant differences in impacts on food systems among different regions and between poorer and wealthier populations (**Figure 2**). Interactions between climate change and other trajectories of global environmental, demographic, and economic change mean that it remains very difficult to generate precise long-term predictions of adaptation needs.
4. Direct impacts of climate on food availability will occur throughout the food chain but will generally be strongest for agriculture, given its sensitivity to climate and its primary role in food supply and in the provision of livelihoods to poor people. Indirect impacts on nutrition, health, livelihoods, and poverty will be more complex and highly differentiated. Most research has focused on impacts on crop yields and, to a lesser extent, prices, but other key food security outcomes, including food safety, may be affected strongly by climate change.
5. Despite the many uncertainties and the potential for trade-offs among the goals of food security and mitigation, a range of actions can deliver simultaneously on food production, adaptation, and mitigation (**Figure 4**). Most of the promising options tackle either resource-use efficiency or risk management in agriculture and the postproduction food supply chain. Many are low-cost, based on current practices, and constitute good practice even without climate change; information and institutional support remain barriers to wider implementation.
6. Individuals' and societies' abilities to adapt to climate change, and to mitigate the GHG emissions associated with their livelihoods and basic needs, will differ tremendously, even at local levels (**Table 2**). Moreover, concerns around national and regional mismatches between responsibility for, and vulnerability to, climate change (**Figure 3**) mean that governance of integrated adaptation and mitigation options to achieve food security must emphasize mechanisms to reduce the disproportionate costs that fall on poor producers and consumers in all countries.

FUTURE ISSUES

1. How can we downscale forecasts in time and space, with clearer expressions of variability and uncertainty, to enable decision making at local, national, and regional levels?
2. In more precise empirical terms than we have today, what are the mitigation and adaptation potentials of different farming and food systems, taking into account both their technical potentials and the economic and institutional conditions required for implementation?

3. How can integrated assessment models be iteratively improved as tools to guide adaptation actions and decisions, particularly by incorporating development trajectories and adaptation actions into forecasts of the impacts of climate change on food and welfare?
4. What are the options for both mitigation and adaption in the postproduction phases of the food system? In particular, what types of incentives and regulations might effectively shift consumption and waste behaviors?
5. What policy mechanisms will be effective and cost-efficient in reducing the burden of climate change, and the burden of societal responses to climate change, on poor producers and consumers?

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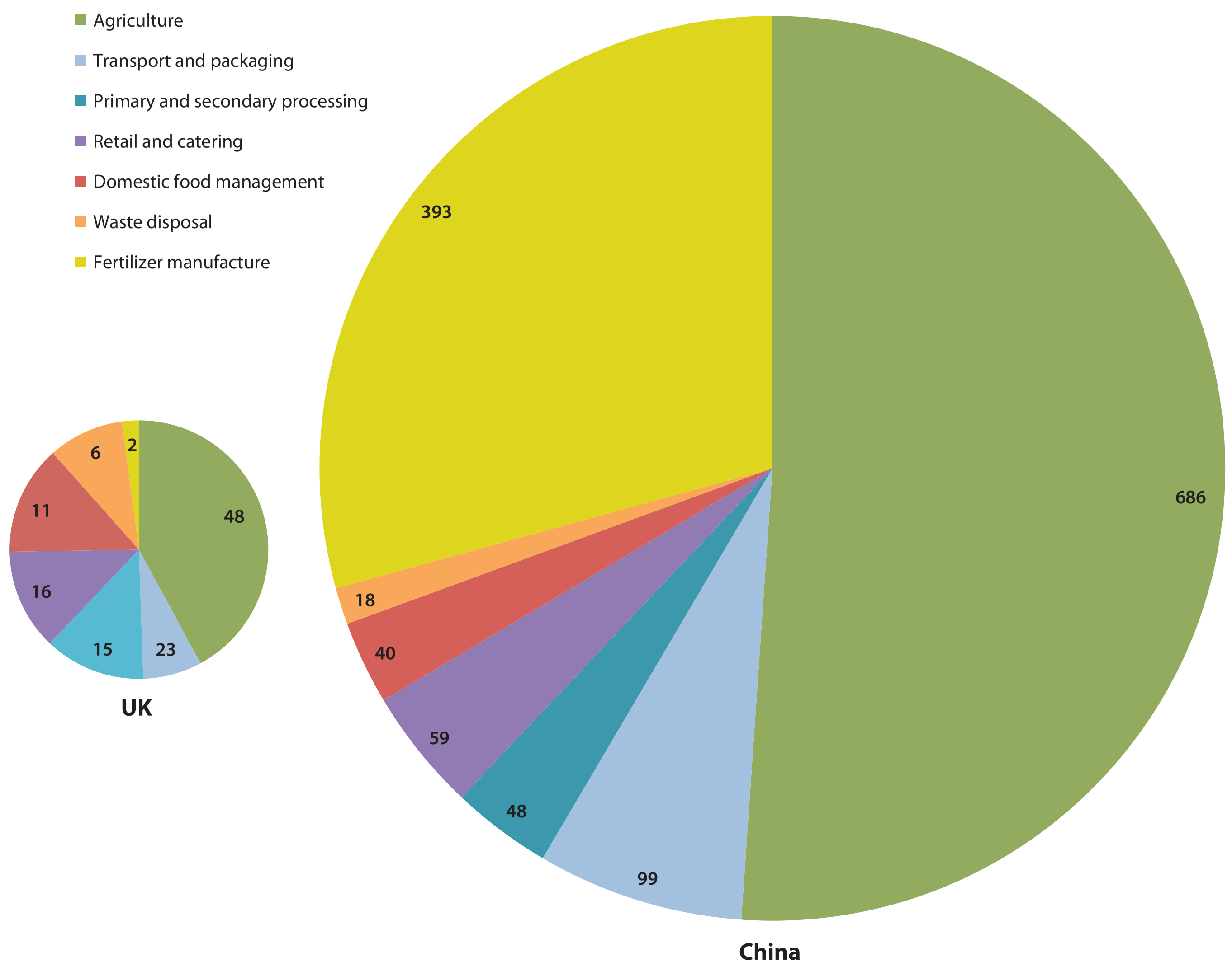


Figure 1

Partitioning of production-based food chain greenhouse gas emissions, excluding land-use change, for China and United Kingdom. The estimated megatonnes of carbon dioxide equivalent for 2007 are indicated. Data from Reference 29 were used for China (note that these data are not based on full life-cycle analysis and the categories may overlap), and data from Reference 22 were used for the United Kingdom.

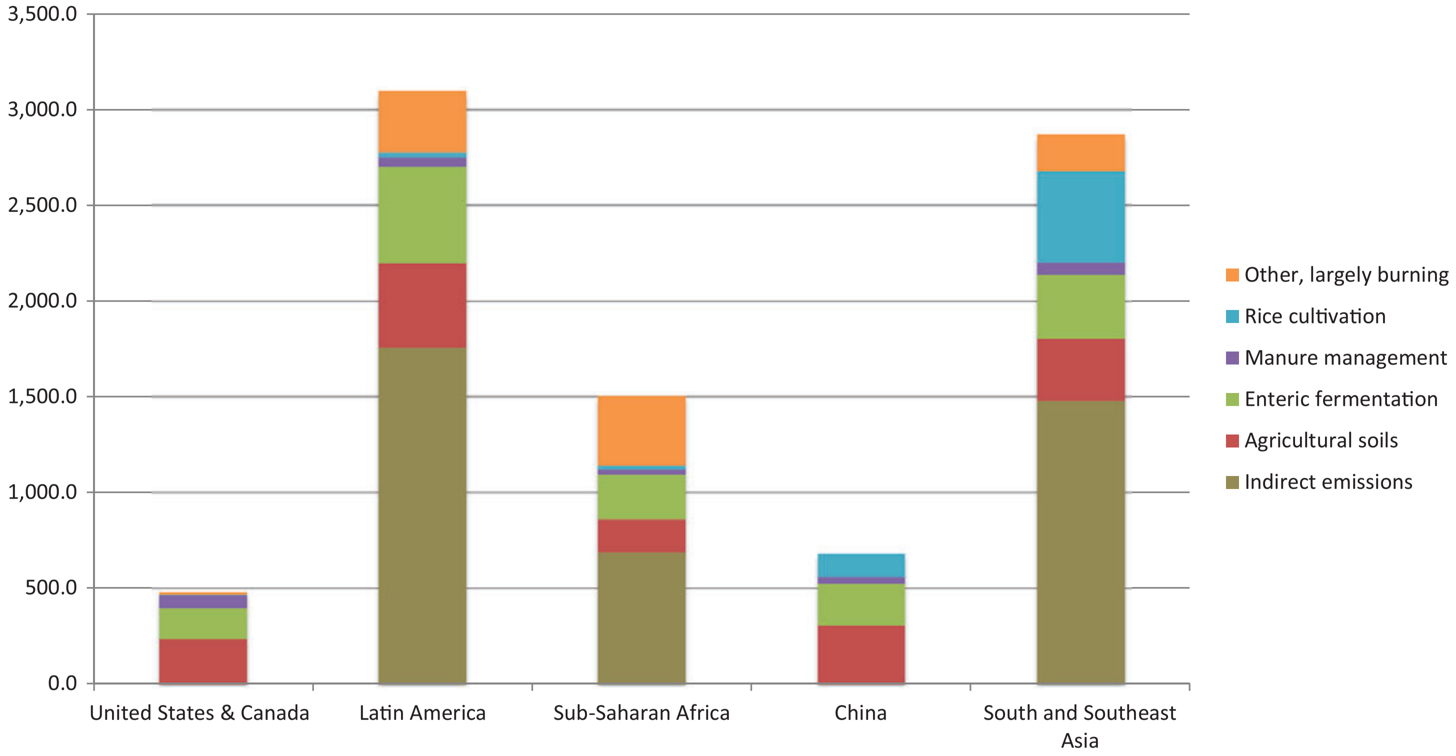
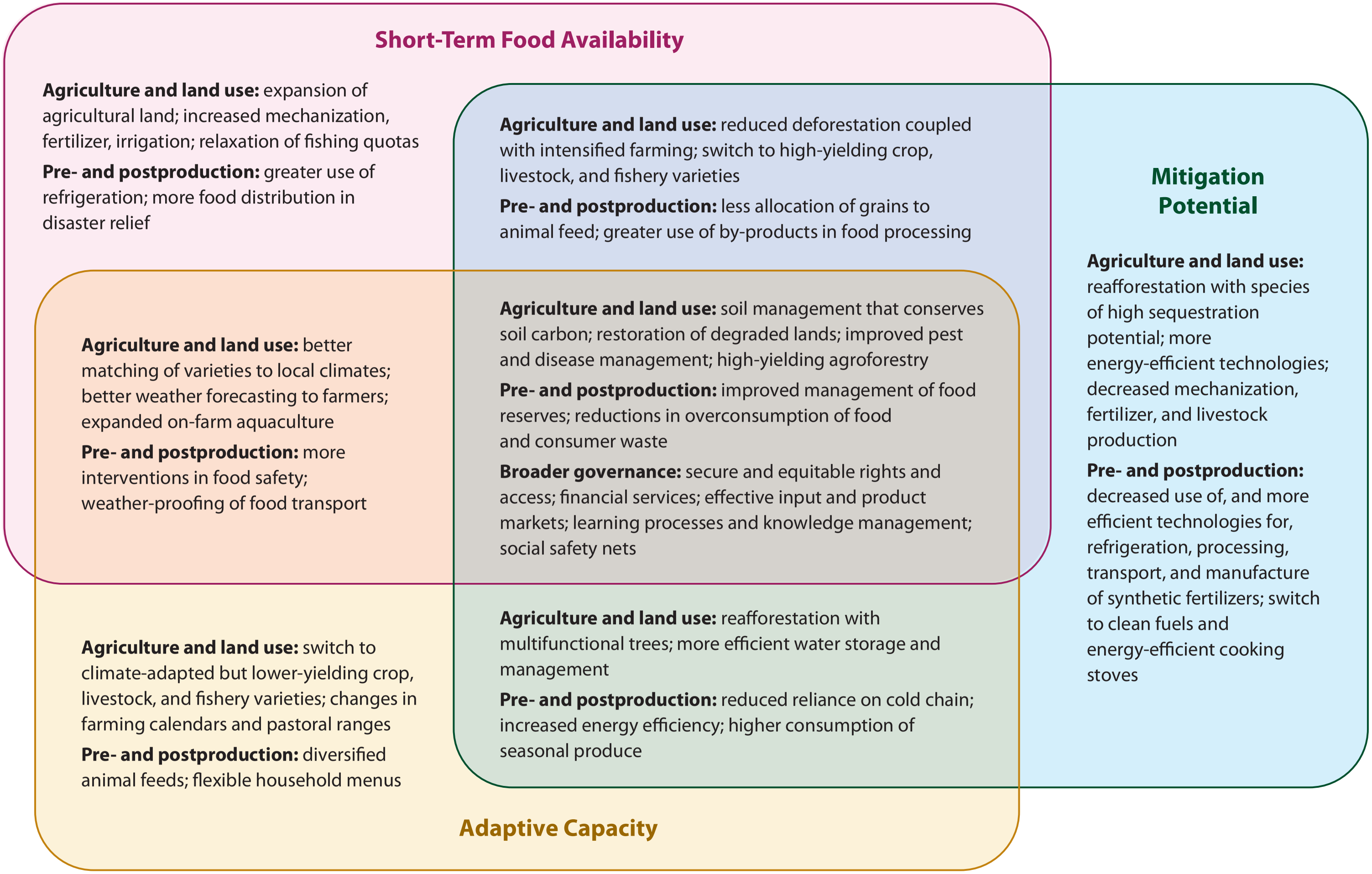


Figure 2

Regional differences in the composition of emissions from direct and indirect emissions from agricultural production for the year 2005 in megatonnes of carbon dioxide equivalent. No indirect emissions are shown for the United States, Canada, and China because forest-based sequestration exceeds emissions in those countries. Data obtained from Reference 37 for direct emissions, which are updated data prepared for the Intergovernmental Panel on Climate Change combined by countries that match Houghton's regions used for indirect emissions (hence, Europe is excluded, and Mexico is included in Latin America), and from Reference 38 for indirect emissions in conjunction with Reference 28 for agriculture's share as a driver of deforestation and degradation.



Agriculture and land use: expansion of agricultural land; increased mechanization, fertilizer, irrigation; relaxation of fishing quotas

Pre- and postproduction: greater use of refrigeration; more food distribution in disaster relief

Agriculture and land use: reduced deforestation coupled with intensified farming; switch to high-yielding crop, livestock, and fishery varieties

Pre- and postproduction: less allocation of grains to animal feed; greater use of by-products in food processing

Agriculture and land use: reafforestation with species of high sequestration potential; more energy-efficient technologies; decreased mechanization, fertilizer, and livestock production

Pre- and postproduction: decreased use of, and more efficient technologies for, refrigeration, processing, transport, and manufacture of synthetic fertilizers; switch to clean fuels and energy-efficient cooking stoves

Agriculture and land use: better matching of varieties to local climates; better weather forecasting to farmers; expanded on-farm aquaculture

Pre- and postproduction: more interventions in food safety; weather-proofing of food transport

Agriculture and land use: soil management that conserves soil carbon; restoration of degraded lands; improved pest and disease management; high-yielding agroforestry

Pre- and postproduction: improved management of food reserves; reductions in overconsumption of food and consumer waste

Broader governance: secure and equitable rights and access; financial services; effective input and product markets; learning processes and knowledge management; social safety nets

Agriculture and land use: switch to climate-adapted but lower-yielding crop, livestock, and fishery varieties; changes in farming calendars and pastoral ranges

Pre- and postproduction: diversified animal feeds; flexible household menus

Agriculture and land use: reafforestation with multifunctional trees; more efficient water storage and management

Pre- and postproduction: reduced reliance on cold chain; increased energy efficiency; higher consumption of seasonal produce

Figure 4

Examples of actions in food systems that achieve different synergies and trade-offs for adaptation, mitigation, and food security (near-term food availability). Actions must be situated in broader governance frameworks, indicated in the central box where three-way synergies are achieved.

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