The implications of a changing climate on global nutrition security

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Abstract

Climate change is perhaps the most transformative force shaping the trajectory of global development. The changes in precipitation patterns, global temperatures, the frequency and severity of extreme weather events, and the overall viability of ecosystems that accompany climatic change are already impacting food systems and are poised to undermine progress toward achieving food and nutrition security, especially in low-income countries. We aim to identify the principal linkages between climate change and nutrition, and to elaborate mitigation and adaptation options for addressing the threat of climate change to nutrition security. Warmer average temperatures, rainfall volatility, extreme seasonal heat and more frequent and severe droughts that are predicted to accompany climate change have the potential to impact nutrition outcomes through three principal intermediate outcomes: 1) the quality and quantity of crop and livestock production, 2) the stability of ecosystems, and 3) the distribution and survival of disease vectors. These intermediate impacts could have profound consequences for human nutrition via threats to food security, disruptions to and loss of livelihoods, increased vulnerability to infectious disease, and risk of regional conflicts. The actions of governments, industry, and civil society to mitigate and adapt to changing physical, economic, and social environments under climate change will be critical to ensuring the forward progress of human development efforts.

Introduction

On November 8, 2013, a 600-kilometer wide typhoon tore across the central Philippines with wind speeds peaking well above 300 kilometers per hour. One of the strongest storms in recorded history, Typhoon Haiyan killed thousands and displaced hundreds of thousands more. In 2012, a devastating drought in the United States swept over nearly two-thirds of the country, affecting crop production and river commerce. It was widely considered the worst drought incident since the Dust Bowl of the 1930s. In July 2010, unusually heavy monsoon rains submerged one-fifth of Pakistan, inundating hundreds of thousands of hectares of agricultural land, killing 2,000 people and 1.2 million livestock, and causing USD 10 billion in damages (Thomas Reuters Foundation, 2013). In that same year, hundreds of wildfires broke out across Russia on the heels of the hottest recorded summer in Russian history. The fires caused billions of dollars in damages.

Though it is difficult to directly attribute the cause of these events to the phenomenon of rising global temperatures commonly referred to as climate change, events like these may be increasingly common on a hotter planet. Beginning primarily during the industrial era, anthropogenic emissions from the burning of fossil fuels have driven increases in atmospheric concentrations of greenhouse gases (GHG) which have in turn led to positive radiative forcing (i.e. a positive net change in the Earth's energy balance) and an increase in global mean temperatures (IPCC, 2013). The statement made by the Intergovernmental Panel on Climate Change (IPCC) in its most recent working group report (AR5) that the "warming of the climate is unequivocal" (IPCC, 2013; p. 1-39), is perhaps the most trivial statement in a gamut of bleak observations and predictions made by climate scientists (see **Box 1**). Among the four climate scenarios, or Representative Concentration Pathways (RCPs) identified by the working group, the most severe, RCP8.5, represents continued high global greenhouse gas (GHG) emissions. Under this scenario, the predicted change in global mean surface temperatures will likely exceed 2°C above pre-industrial climate by the end of the century and could result in temperature increases more than double that. Hansen et al. (2007) estimate that warming even above 1.7°C relative to the pre-industrial era could result in potentially irreversible ice sheet and species loss.

The changes in surface and ocean temperatures, extreme weather events, precipitation patterns, and sea levels that are occurring and are predicted to intensify in coming decades will pose significant challenges to global development efforts to improve the health and well-being of human populations. Improving and safeguarding the nutritional status of populations is the arguably the cornerstone of such efforts.

In September 2000, a summit of world leaders committed to a set of eight Millennium Development Goals (MDGs) aimed at achieving broad progress by 2015 across a number of development sectors including health, education, and the environment. Nutrition was explicitly recognized in the first of these MDGs, and was strongly interwoven with several of the other goals. While considerable progress has been achieved, the goal to reduce by half the proportion of people who suffer from hunger has not yet been met and there are considerable disparities in the distribution of hunger throughout the globe.

Recent estimates indicate that one in eight people, or 842 million individuals were unable to meet their dietary energy requirements in 2011-2013 (Food and Agriculture Organization, 2013). The large majority of these people live in low-income countries. In sub-Saharan Africa in particular, one in four individuals are not able to meet energy requirements (Food and Agriculture Organization, 2013). Chronic undernourishment is especially detrimental to the development of young children. In 2011, 165 million children worldwide younger than five years of age were stunted (Black et al., 2013). Child stunting is caused in part by chronic nutritional deficiencies and can lead to deficits in cognitive development, work and reproductive capacity, and susceptibility to adult chronic disease (Kuklina et al., 2006; Walker et al., 2011). At the same time, in 2008, 1.4 billion adults were overweight and 500 million obese, more than double the prevalence in 1980 (World Health Organization, 2013). Child overweight has also increased by 54% since 1990 with 43 million children younger than 5 years of age overweight in 2011 (United Nations Children's Fund, WHO, World Bank, 2012). The basic causes of these varying manifestations of malnutrition are rooted in disparities in sustainable access to productive resources including information, technology, capital, institutions, and most notably, natural resources (Lakerveld et al., 2012; United Nations, 1990). The far-reaching influence of climate change on Earth’s underlying biological and physical systems has the potential to directly or indirectly affect access to all of these resources, and therefore, the health and nutrition of the global population. It is critical then, to understand the potential pathways by which climate change will impact global public health and nutrition and the possible avenues of action that might be pursued to mitigate harmful effects and successfully adapt to the changing global environment.

In this paper, we aim to identify the principal linkages between climate change and nutrition, and to elaborate mitigation and adaptation options for addressing the threat of climate change to nutrition security. Rather than structure the discussion based on the nutrition outcomes that may be impacted by climate change, we instead emphasize the intermediate consequences of climate change as the organizing constructs and follow the pathways from these environmental exposures to the plausible impacts on nutrition. As we will explore, given the global scale at which positive radiative forcing operates, any given event or exposure may influence nutrition through multiple, simultaneous pathways. We highlight three principal intermediate outcomes which climate change may impact: 1) the quality and quantity of crop and livestock production, 2) the stability of ecosystems, and 3) the distribution and survival of disease vectors. **Figure 1** summarizes each of these intermediate outcomes, the climate change-associated determinants of them, and their potential nutritional consequences.

Climate change consequences and their pathways of impact on human nutrition

Agricultural production and food security

Food security is a multi-faceted concept that encompasses the availability of, access to, and utilization of food, as well as the stability of these factors over time. Though food security is commonly used to refer only to access to sufficient quantities of food, the definition of the term explicitly states that access to safe and nutritious food is a necessary criterion for achieving food security (Food and Agriculture Organization, 1996). Our use of the term therefore, refers to access to sufficient quantities of food as well as the nutritional quality of diets. Food security is clearly intimately connected to the global system of food production. Agricultural production depends on stable local temperatures and patterns of precipitation. To the extent that changes in climate introduce volatility into these patterns, or alter the biophysical conditions to which crops are adapted, agricultural production, and therefore food security, may be impacted. We discuss below the potential impacts of climate change on crop and livestock production and the pathways by which these impacts may affect food security.

Warming surface temperatures

Climate change has the potential to impact agricultural production in several different ways with varying impacts across world regions. Warmer temperatures alter the rate of plant development by reducing critical growth periods. Though crop phenology responds approximately linearly to temperatures changes (Gate & Brisson, 2010), exceeding certain temperature limits could result in more precipitous, non-linear shortening of developmental stages (Schär et al., 2004). Accelerated crop ripening and shorter periods for grain filling can decrease yields (Craufurd & Wheeler, 2009). Heat stress can also damage plant reproductive tissues and increase pollen sterility (Thornton and Cramer, 2012). Warming temperatures may also promote plant disease and pest outbreaks (Alig et al., 2002; Gan, 2004; Tubiello et al., 2007), increasing both insect pest numbers and their range (USDA, 2008). Changes in crop phenology associated with warmer temperatures may allow increased pest damage to crops at sensitive early stages of crop development (Rosenzweig et al., 2001). Globally, and at mid- to high latitudes, crop productivity will likely increase slightly under increases in temperatures of 1°C to 3°C (IPCC, 2007), due in part to lengthened growing seasons, reduced frost damage, and enlarged root surface areas under warmer soil temperatures that may facilitate increased nutrient uptake (St Clair & Lynch, 2010). These relationships show threshold effects, however. Temperature increases above 3°C would have negative impacts on crop production even at high latitudes (IPCC, 2007). In seasonally dry and tropical regions at lower latitudes, even small increases in local temperatures are projected to deleteriously affect crop productivity (IPCC, 2007).

Warmer mean global surface temperatures are projected to have heterogeneous impacts on crop productivity not only at different latitudes, but for different staple crops as well. Together with rice, wheat and maize provide nearly a third of all food calories consumed by the more than 4.5 billion people in the Global South (Thornton & Cramer, 2012). It is estimated that warming temperatures will result in declines in wheat and maize yields, though declines in wheat may be less severe than declines in maize. Deryng et al. (2011) predict that between 2000 and 2050 wheat and maize yields will decline by 14-25% and 19-34%, respectively, under warming conditions of 2.2°C to 3.2°C above preindustrial temperatures with no adaptation. Under a more favorable emissions scenario (i.e. SRES A1B), gains in wheat yields of 1.6% (95% probability interval (PI): -4.1%, 6.7%) have been estimated while maize yields are expected to decline by 14.1% (95% PI: -28%, -4.3%) (Tebaldi & Lobell, 2008). Again, these impacts may be felt differently across regions. In a meta-analysis of the mean change in crop yields across a range of general circulation models, mean yield changes of -17% by 2050 were calculated for wheat in Africa, though no significant changes in wheat yields were found in South Asia (Knox et al., 2012). Mean declines in maize yields were calculated at -11%, -7%, -13%, and -18% in southern Africa, West Africa, the Sahel and South Asia, respectively. There is less evidence on the effects of global climate change on horticultural crops (Peet & Wolfe, 2000). Vegetables and fruits are vulnerable to environmental extremes, such as high temperatures, limited water availability, and associated low soil moisture and salinity (la Peña & Hughes, 2007). Climate change is therefore expected to impact yields of these crops and may influence farmers to adopt or abandon horticulture as an adaption strategy; however, more research is needed to understand these dynamics (Kurukulasuriya, 2008; Seo & Mendelsohn, 2007).

Livestock are similarly affected by warming temperatures and extreme heat. Animals reduce feed intake at high temperatures (by >25-30% depending on the animal species) to maintain their body temperature (Thornton & Cramer, 2012). These reductions in intake may result in substantial productivity losses (Parsons et al., 2001). Furthermore, while warmer surface temperatures may actually increase pasture productivity in highland areas, higher temperatures can reduce water availability and negatively affect pasture biomass production (Tubiello et al., 2007). Climate change could also facilitate the spread of animal diseases and pests (e.g. warmer winters may increase the range of livestock diseases such as bluetongue virus), as well as increase livestock mortality, especially under drought conditions (IPCC, 2007).

Drought and precipitation

The effect of warmer surface temperatures on crop yields depends in part on existing soil moisture and precipitation. Aridity therefore, in addition to surface temperatures is an important concern when examining the potential impact of climate change on crop yields. As aridity increases, both soil nitrogen (N) and soil organic carbon (C) concentrations may decline, becoming uncoupled from soil phosphorus (P), which could constrain plant and microbial activity and negatively affect organic matter decomposition (Delgado-Baquerizo et al.). Temperature-driven soil moisture deficits can also decrease nutrient acquisition, reduce biological nitrogen fixation, and disrupt nutrient cycling (St Clair & Lynch, 2010). Combined, these changes would yield a net negative impact on the mineral nutrition of crops far exceeding any potential beneficial effects of warming temperatures (St Clair & Lynch, 2010). The impacts of surface warming on crop productivity then could be exacerbated under drought conditions. Lobell et al. (2011) calculated that for each degree-day spent above 30°C, maize yields in Africa were reduced by 1% under optimal rain-fed conditions and by 1.7% under drought conditions.

More frequent and more severe droughts are a serious concern under future climate change scenarios. These may be meteorological droughts caused by long-term declines in precipitation, hydrological droughts resulting from long-term declines in surface runoff and groundwater levels, or agronomic droughts evidenced by reductions in soil moisture availability during the crop growing season (St Clair & Lynch, 2010). Warming of the lower atmosphere strengthens the hydrologic cycle (i.e. warm air holds more water vapor than cool air), causing dry regions to become drier and wet regions to become wetter (World Bank, 2012; Trenberth, 2011). In dry regions, droughts may be intensified by enhanced surface drying through increased evaporation and evapotranspiration that accompanies warming temperatures (Trenberth, 2011). Given that millions of smallholder farmers around the world are already farming on rainfed marginal lands, especially drylands, and that future gains in food production will rely increasingly on expansion of production onto drylands (Reynolds et al., 2007), drought intensification under climate change scenarios poses considerable challenges to future food production and food security. Even farmers with access to irrigation may face increasing challenges managing water stress (i.e. the ratio of irrigation withdrawals to renewable water resources). Irrigation water requirements are likely to substantially increase under most climate change scenarios, perhaps disproportionately in southeast Asia and the Middle East (Döll, 2002; Fischer et al., 2007)

On the opposing end of the spectrum, wet regions may experience amplified precipitation under increased atmospheric water vapor loading (World Bank, 2012). The IPCC (2013) predicts that extreme precipitation events over mid-latitude land masses and wet tropical regions will intensify and become more frequent in the coming decades. Increases in annual runoff though, may be unevenly distributed across seasons such that during the rainy season, excessive precipitation leads to flooding while water stress during the low-flow season is not abated (World Bank, 2012). Excessive precipitation can reduce crop yields, erode sloped soils, contribute to soil nutrient loss, and, in poorly drained soils that become waterlogged, create conditions of hypoxia that promote elemental toxicities, impaired root growth, and reduced nutrient uptake (Kawano et al., 2009; St Clair & Lynch, 2010; Zougmoré et al., 2013). These extreme conditions, together with volatility in the onset and ending or rains that may disrupt germination and require farmers to sow crops multiple times (Mary & Majule, 2009), present challenges to agricultural production even in regions where water stress is not a common concern.

A potential benefit of increased atmospheric concentrations of CO_2 on crop yields is a phenomenon known as "CO_2 fertilization." CO_2 fertilization refers to the sequestration of CO_2 by photosynthetic plants under conditions of increased ambient CO_2 concentrations such that plant growth is actually enhanced. However, the potential for this phenomenon to occur outside of controlled settings is uncertain. A recent review of so-called FACE (Free Air CO2 Enrichment) experiments revealed that grain crop yields, especially C4 species (e.g. maize) increased far less than anticipated under elevated CO_2 concentrations (Ainsworth & Long, 2005). Even if the CO_2 fertilization effect were to yield benefits to crop yields in controlled settings, in actual farmers' fields, the potential for this phenomenon to yield production gains would be determined by the presence of other potentially limiting soil nutrients such as phosphorus and nitrogen (W.orld Bank, 2012). As noted earlier, under arid conditions and conditions of low soil moisture which may be common under warming surface temperatures, it is not at all clear that these nutrients would be sufficiently available.

Food security consequences of changes in agricultural production

Taken together, the manifestations of climate change described above including warmer surface temperatures, more frequent extreme temperatures, increasing droughts in some regions, and extreme precipitation in other regions, present serious challenges to the stability of global food supplies and food security. The populations of low-income countries will disproportionately bear the burden of food insecurity brought about by these climatic changes (Wheeler & Braun, 2013). Food insecurity is already widespread in low-income countries. The FAO estimates that the total number of undernourished individuals in high-income and low-income countries in the period 2011-2013 was 16 million and 830 million, respectively (FAO, 2013). As we have seen, the negative consequences of climate change on agricultural production may be greatest in the low-latitude tropical regions of the globe, precisely where the vast majority of the world's poor already live. With so many individuals already enduring seasonal or chronic food insecurity in low-income countries, and many more balancing on the edge of that precipice, the potential is great that warming temperatures and climate-related shocks will deepen food insecurity to levels from which it may be difficult to rebound. This situation could have clear negative effects for the nutritional status of populations, especially vulnerable groups like young children. Perhaps not surprisingly, the overwhelming majority of the world's stunted children live in these same low-income countries where the prevalence of food insecurity is highest (Black et al., 2008). Even accounting for economic growth, climate change may increase by one-quarter and nearly two-thirds, the prevalence of severe stunting in sub-Saharan Africa and South Asia, respectively (Lloyd et al., 2011).

For poor subsistence households whose consumption depends in large part on their own agricultural production, climate change-induced declines in agricultural productivity may have direct negative consequences on their food and nutrition security. However, most poor households, in both urban and rural areas, are net purchasers of food (Byerlee et al., 2006; Ivanic & Martin, 2008). This means that, more than the availability of food produced from their own production, the rural and urban poor are concerned with the price of food. The poor spend a large proportion of their income on food (56-78%) (Banerjee & Duflo, 2007). Increases in food prices then, will disproportionately affect the poor, exacerbating among these households not only access to sufficient quantities of food (World Food Programme, 2008), but also the quality of diets (i.e. micronutrient intakes) (Iannotti et al., 2012). Global cereal prices are expected to increase under most climate change scenarios, even those that account for farmer adaptation (Parry et al., 2004; Rosenzweig & Parry, 1994). These price increases will arise from climate change-related reductions in agricultural productivity, but also growing urban populations with increasing incomes and demand for food (Nelson et al., 2010). In the next thirty years, nearly all of the world’s population growth is expected to occur in urban areas of low-income countries (Cohen, 2006). Therefore, the pressures of climate change, population growth, and urbanization will likely concentrate in the most vulnerable regions of the globe.

Declines in agricultural productivity resulting from warming global temperatures and population-driven increases in food demand certainly have the potential to negatively impact food sufficiency, one component of food security. Food security though, encompasses not only access to sufficient quantities of food, but also food that is safe and nutritious. Climate change may have direct negative consequences on the nutritional quality of food crops (e.g. reduced grain filling capacity, impaired soil nutrient acquisition), and may indirectly affect diet quality at a macro scale by reinforcing historical emphases on staple crop production. The technological advances of the Green Revolution propelled massive increases in the yields of staples like maize, wheat and rice (Hafner, 2003). Much less investment has been targeted at improving production of pulse crops, and fruits and vegetables, all of which provide incredibly important complementary nutrients and phytochemicals to diets. As a result, for the past five decades, cereal grain and oilseed production has far outpaced global production of pulses, fruits and vegetables (FAOSTAT, 2013). Though output of fruits and vegetables has increased in recent years (FAOSTAT, 2013), with production of cereal grains and oilseed crops threatened by warming temperatures, it is possible that agricultural research efforts will be redoubled toward further enhancing production of these crops at the expense of pulses, fruits and vegetables. Providing diverse, nutrient-dense diets is clearly important for preventing and alleviating chronic undernutrition. However, it is also of paramount importance for addressing the rising global burden of overweight and non-communicable diseases. Especially among the poor, overconsumption of calories is often achieved by consuming energy-dense, nutrient-poor foods. These foods may be the most economically accessible. Perhaps not surprisingly then, micronutrient deficiencies are in fact common among overweight and obese individuals (Garcia et al., 2009). Maintaining production diversity under a changing climate then, alongside efforts to improve yields of staple grains, is an important goal for addressing the entire spectrum of malnutrition.

Food safety, another component of food security, may also be threatened by climate change. Though many food safety-related concerns may be exacerbated with warming temperatures (e.g. warming seas may contribute to increases in human shellfish and reef-fish poisoning and salmonellosis (Schmidhuber & Tubiello, 2007), the threat of mycotoxins stands out because of the scale at which it may affect populations. It is estimated that mycotoxins, the toxic secondary metabolites of fungi from the genera *Aspergillus*, *Fusarium* and *Penicillium*, may contaminate as much as one-quarter of all agricultural crops worldwide (Smith et al., 1994). This proportion would likely climb under climate change scenarios. Many staple crops including maize and groundnut, but also nuts and fruits, are susceptible to colonization and infection by mycotoxins (Fung & Clark, 2004). *Aspergillus* may infect crops before harvest and during storage, especially under conditions of prolonged exposure to high humidity or drought—precisely the kinds of extreme conditions warming global temperatures may exacerbate. Aflatoxins, a group of mycotoxins produced by *Aspergillus flavus* and *Aspergillus parasiticus*, are potent carcinogens (Fung & Clark, 2004) and are associated with child growth stunting (Gong et al., 2004; 2002). Contamination of food supplies by aflatoxins and other mycotoxins is of particular concern in rural areas of low-income countries where screening and food safety controls are often absent (Lewis et al., 2005). These are the same regions, especially in sub-Saharan Africa, which may be especially vulnerable to the effects of warmer surface temperatures. Prolonged periods of high temperatures (>30°C) and drought stress could leave crops considerably more prone to mycotoxin contamination (Van der Fels-Klerx et al., 2013; Magan et al., 2011; Paterson & Lima, 2010). Increasing mean temperatures could also expand the range of latitudes at which mycotoxin-producing fungi are able to compete (Tirado et al., 2010).

The stability of natural ecosystems, human livelihoods and regional security

Human livelihoods directly or indirectly rely on the multitude of ecosystem services provided by the natural environment. These include provisioning services (i.e. food, fresh water, fuelwood, fiber, biochemical, genetic resources), regulating services (e.g. regulation of air quality, water regulation and purification, pollination), and other supporting services (e.g. soil formation, nutrient cycling and primary production) (United Nations Environment Programme, 2003). Though the potential impact of climate change on terrestrial and marine ecosystems will likely be heterogeneous across regions, warming temperatures, especially those predicted under continued high GHG emissions (i.e. RCP8.5), will alter ecosystem function across all global regions to some extent.

Biological diversity is strongly linked to ecosystem productivity and resilience (Chapin et al., 2000; Tilman et al., 2001). Destructive changes in ecosystems associated with warming global temperatures will therefore have far-reaching consequences for biodiversity. Ecosystem functioning and service provision are expected to change dramatically under warming global temperatures. Examples of these changes include: 1) widespread forest retreat and transition to lower biomass, drier ecosystems, 2) more frequent and intense forest fires from heat stress, increasing aridity, and changes in human land use, 3) expansion of ocean hypoxic zones and declines in nutrient availability to phytoplankton under warming ocean temperatures, 4) erosion or destruction of coral reefs from ocean acidification, and increased frequency and intensity of tropical cyclones, and 5) loss of mangroves from rising sea levels and increasing atmospheric CO_2 concentrations (World Bank, 2012). Furthermore, biome shifts and migration of species toward the poles and toward higher elevations could disrupt predator-prey relationships and traditional food sources (World Bank, 2010). As greater increases in temperatures lead to increasingly severe changes in ecosystems, thresholds, or tipping points, are possible whereby irreversible loss of ecosystems will occur beyond certain temperature limits. Global mean temperature increases greater than 2°C will put at risk of extinction 20 to 30 percent of plant and animal species (IPCC, 2007). Temperature increases beyond 4°C could lead to more profound species loss associated with the permanent dieback of rainforests, for example (Lenton et al., 2008).

The degradation of ecosystem services and accompanying loss of biodiversity could have widespread impacts on human livelihoods. As already discussed, warming surface temperatures could lead to declines in crop and animal productivity, especially in the tropics, via several different pathways (e.g. changes in crop phenology, increased susceptibility to pests and disease, increasingly volatile and extreme rainfall events, less access to water for irrigation, and reduction in livestock feed intake). In coastal regions, rising sea levels, strong storm surges, and saltwater intrusion on coastal agricultural land will also likely make that land unusable (Wheeler & Braun, 2013). For the 80% of rural poor households who depend on agriculture as a source of livelihood, these changes could have a substantial impact on nutrition outcomes (International Fund for

Agricultural Development, 2010). Income earned from agriculture may be used not only to purchase food, but also health, education and hygiene inputs. Loss of income for any of these purchases could negatively impact nutrition outcomes in the short-term, especially for women and children, by affecting diet quality, and household health, sanitation and hygiene environments. Early nutrition deficits, lost educational opportunities, and intergenerational stunting can also translate into long-term losses to productivity, health and nutrition (Martorell & Zongrone, 2012). Especially in tropical regions, the livelihoods of households that depend on fisheries for livelihood may be negatively affected by declining fish stocks whether from the poleward migration of fish away from warming waters, or the degradation of fish habitat from acidifying oceans and increased hypoxic zones (World Bank, 2012). Households dependent on forest products for food or livelihood would face similar pressures from loss of forest habitat or the transformations of forest habitat into less biodiverse, lower biomass, more arid ecosystems. Biodiversity is also important for the discovery of new medicines (Bernstein & Ludwig, 2008) as well as the formulation of traditional medicines which are estimated to be used by 60% of the world's population (World Health Organization, 2013a). Ecosystem degradation and biodiversity loss then could also have direct impacts on human health and nutrition.

Lost or diminished livelihoods resulting from degradation of natural resources and ecosystem services under climate change may threaten economic stability and exacerbate societal inequalities. Conflict could then result as individuals compete for the allocation of increasingly scarce resources, or act out grievances over economic disparities. Food riots in response to rising food prices are one example of this phenomenon (Barrett, 2013). Hsiang et al (2013) observed that a one standard deviation increase in a location’s temperature is associated with a 13.2% increase in the rate of intergroup conflict. The effect of increasing temperatures on conflict is especially strong in regions that are temperate or warm, precisely the regions where the largest increases in mean temperature are predicted, that have the lowest interannual temperature variability, and that are already the most food insecure (Hsiang et al., 2013). Given that conflict further disrupts livelihoods (Goodhand, 2001), health systems, public institutions and infrastructure, as well as degrades productive resources and exacerbates food insecurity, nutrition outcomes are likely to be profoundly negatively impacted via multiple pathways from climate change-induced conflicts.

Disease vectors and human health and nutrition

The synergistic relationship between infection and malnutrition has been recognized for decades (Scrimshaw et al., 1968). Nutrient deficiencies can impair resistance to infection (Scrimshaw & SanGiovanni, 1997), and infection can impair absorption of nutrients. In low-income regions, a vicious circle is often present wherein lack of access to improved water and sanitation co-occurs with poor diets, food insecurity and poor access to health services, thus exacerbating both malnutrition and disease. Many studies in diverse contexts have demonstrated that access to improved water and sanitation yields benefits for the health, growth, and development of children (Checkley et al., 2004; Esrey & Habicht, 1986; Hebert, 1985). Access to these resources may improve the nutritional status of children by reducing the incidence of diarrhea (Checkley et al., 2008) or by preventing or ameliorating environmental enteropathy (Humphrey, 2009). Climate change could have direct negative impacts on water and sanitation, especially for poor populations that already lack adequate access to these resources.

Water, sanitation and hygiene

Climate change may deleteriously affect water quality, sanitation and hygiene in several important ways. Short-term, seasonal, and cyclic multi-year warming trends may lead to increased episodes of diarrhea in adults and children (Alexander et al., 2013; Checkley et al., 2000; Lama et al., 2004; Singh et al., 2001). One explanation for this trend is the warming ocean waters associated with warmer temperatures during the "El Niño-Southern Oscillation" (ENSO) which may stimulate populations of *Vibrio cholera*, the gram-negative bacteria that cause cholera (Salazar-Lindo et al., 1997). Reliance on stagnated or otherwise contaminated secondary water sources during droughts, or increases in the population density or activity of flies that carry diarrheal-disease causing organisms during periods of high temperature are other plausible mechanisms by which diarrhea may be associated with warmer temperatures (Alexander et al., 2013). To the extent that extreme rainfall events, stronger storm surges, and more frequent flooding accompany climate change, increased runoff could transfer pathogens from environmental reservoirs to ground and surface water, and cause increased diarrheal incidence (Medina et al., 2007). More frequent and intense high tides and wave damage associated with climate change could also threaten the water supplies of island communities through the intrusion of salt water into underground freshwater reserves (Singh et al., 2001) or coastal aquifers (Antonellini et al., 2008). Perhaps not surprisingly, outbreaks of water-borne diseases will likely be most severe in regions that are already environmentally degraded and lack public infrastructure for sanitation and hygiene (Schmidhuber & Tubiello, 2007).

Vector-borne diseases

Climate change may also influence the distribution and survival of other disease vectors including mosquitoes. Mosquitos may carry five different species of the *Plasmodium* parasite that causes malaria, and are also responsible for the transmission of viruses that cause various forms of encephalitis, yellow fever and dengue fever. The reach of these viruses is expected to expand under climate change (Hales et al., 2002), though the spread of malaria is perhaps of most concern given the high mortality burden associated with it. There were approximately 219 million cases of malaria in 2010 with 660,000 deaths, mostly African children (World Health Organization, 2013b). Malnourished children may have as much as a two-fold higher risk of dying from malaria than non-malnourished children (Muller et al., 2003), and malaria may lead to acute weight loss (McGregor, 1982) as well as stunting in young children (Nyakeriga et al., 2004). There is evidence that warming temperatures are allowing mosquito populations to expand into highland regions where they previously were never observed (Epstein et al., 2013). In parts of East and southern Africa, new species of mosquitoes are establishing populations (World Bank, 2012; Peterson, 2009) with one study suggesting that by 2050 more than

200 million additional individuals will be at risk for malaria because of warming temperatures (Béguin et al., 2011). Stagnant water from extreme rain events and flooding under climate change may provide additional habitat for mosquitos. Changes in temperature, precipitation and humidity that accompany climate change will likely also influence the distribution and survival of other disease vectors including those that cause leishmaniasis, Lyme disease and schistosomiasis (World Bank, 2012).

Strategies for reducing the potential harmful impacts of climate change on nutrition

Strategies for reducing the potential harmful impacts of climate change on nutrition fall under two broad categories: mitigation and adaptation. Mitigation refers to the reduction of GHG emissions to prevent greater increases in global mean temperatures than are already expected. Past and current GHG emissions are already substantial enough though that even under the most robust mitigation scenario (RCP2.6), global mean temperatures will likely still rise by 2°C (van Vurren et al., 2011). Adaptation, therefore, will be required in addition to mitigation to confront the consequences of warming temperatures that are already occurring and that will continue into the future.

Mitigation

The increase in atmospheric concentrations of CO_2, CH_4, and nitrous oxide (N_2O) has occurred primarily because of human activity (IPCC, 2013). Therefore, mitigation will necessarily require reducing anthropogenic emissions of these GHGs as well as capturing and storing carbon. In 2012, 84% of global energy consumption came from non-renewable liquids, natural gas and coal (U.S. Energy Information Administration, 2013). This percentage is predicted to decline only marginally to 78.5% by 2040, but with a 42% increase in total energy consumption from all of these sources (authors' calculations) (U.S. Energy Information Administration, 2013). If these predictions hold true, it seems unlikely that conservative emissions scenarios will be feasible.

While the burning of fossil fuels for electricity and heat is the single largest source of global GHG emissions (26%), deforestation and land clearing for agriculture, as well as other agriculture-related emissions (e.g. management of agricultural soils, livestock, rice production and biomass burning) together contribute nearly a third of all emissions (31%) (IPCC, 2007). Therefore, perhaps more than in any other sector, changes in agriculture have the potential to contribute substantially to climate change mitigation, and, in turn, may also have the greatest potential to mitigate the negative impacts on nutrition outcomes that are predicted from climate change. Changes that result in greater, more efficient, or more equitable food production could yield nutritional benefits via the food security and livelihood pathways outlined above. However, given the enormous ecological footprint of agriculture, especially animal agriculture, on water and forest resources, and ecosystem services more broadly, changes to agricultural production systems that work to mitigate GHG emissions could also facilitate improvements in nutrition and health outcomes by reducing ecosystem disruptions, stabilizing livelihoods, and reducing vulnerability to vector-borne illnesses. We therefore limit our discussion of mitigation and adaptation strategies primarily to the agriculture sector (including food, fiber and fuel production).

Various strategies for mitigating the emissions of GHGs from the agriculture sector have been proposed. These include 1) adopting cropping systems with reduced reliance on inorganic fertilizers and pesticides (e.g. using legumes in crop rotations and providing temporary vegetative cover between successive crops), 2) improving nitrogen (N) use efficiency to reduce N_2O emissions, 3) adopting reduced- or no-till agriculture to reduce soil carbon losses, 4) increasing the use, efficiency and effectiveness of irrigation to enhance carbon storage in soils (though CO_2 costs associated with water delivery would need to be minimized), and 5) using agro-forestry to increase soil carbon sequestration by planting trees on the same land used for food and livestock production (IPCC, 2007). In general, reducing fossil fuel use overall by improving energy efficiency in agriculture could result in a decrease of 770 Mt CO_2-eq/ year by 2030 (Smith et al., 2008). Furthermore, allowing sections of agricultural land to revert to native vegetation, or creating grassed waterways or shelterbelts are other effective ways of increasing carbon storage and mitigating GHG emissions from agriculture (IPCC, 2007). For poor farmers, however, who may already be cultivating small plots on marginal lands, this may not be a feasible option.

Two agricultural transformations in particular could provide multiple wins for food production and access, GHG emissions mitigation, and sustainable development: 1) reducing food waste, and 2) reducing consumption of animal-source foods (ASF). If achieved, these approaches would lessen the need for intensification of food production. However, they require overcoming enormous societal inertia from population pressures, changing preferences, and price incentives.

Approximately one-third of all food produced globally for human consumption is lost or wasted (Stuart, 2009). In low-income countries, these losses tend to occur close to the source of production in the form of post-harvest losses or spoilage between farm and market. In higher-income countries food waste is most prevalent among households, restaurants, and the food service industry. Cheap food prices are a strong incentive for food waste in high-income countries where higher income consumers spend a much lower proportion of their income on food than the poor in low-income countries. While healthy, edible food is often discarded along production lines because of perceived cosmetic imperfections, and fully stocked supermarket shelves mean that foods close to expiration are ignored by shoppers, high-income countries mainly waste food because they can afford to (Swedish Environmental Protection Agency, 2009). Per capita food waste by consumers in Europe and North-America is estimated to be 95-115 kg/year, and only 6-11 kg/year in sub-Saharan Africa and Asia (Gustavsson et al., 2011). In low-income countries, premature harvesting, poor storage facilities, food safety issues, lack of infrastructure to transport food efficiently and effectively, lack of processing facilities, and unsanitary storage and sales conditions are responsible for most food losses (Gustavsson et al., 2011). Reducing global food loss and waste would lessen the overall need for increased food production and could therefore, limit the need for agricultural intensification preventing, in part, the GHG emissions from that intensification. Investing in rural infrastructure and markets in these countries then, is a high priority for reducing food waste, as well as improving rural livelihoods more generally.

Reducing consumption of ASFs, similar to reducing loss and waste in our food system, is a strategy with enormous potential to mitigate climate change, but one that requires swimming upstream against equally powerful demographic currents, especially in emerging economies. Demand for ASFs has rapidly increased as the global population has grown, and become increasingly urban and wealthy (Delgado et al., 1999). Global meat consumption increased by at least 50% in the latter half of the 20th century and is projected to increase by another 24% by 2030 (World Health Organization, 2013c). Global meat production has likewise risen to meet the increased demand—production has tripled over the last four decades (Chang, 2011) and is projected to more than double by 2050 from 2000 production levels (Food and Agriculture Organization, 2006a). Increases in meat consumption associated with increased urbanization and rising levels of wealth will likely be the principal driver of increased global food demand in the coming decades more so than population growth (Tilman et al., 2011). Though livestock production is an especially important component of the livelihoods of the poor, it also has far-reaching negative consequences for global food production potential, environmental sustainability, and climate change. Livestock production: 1) uses more land than any other single human activity, 2) has led to massive deforestation (70% of previously forested land in the Amazon is now animal pasture and agricultural land for feed crops) and therefore reductions in biodiversity, 3) contributes to soil erosion and land degradation associated with overgrazing, 4) is responsible for 9%, 37% and 65% of anthropogenic CO_2, CH_4 and

N_2O emissions, respectively, 5) accounts for over 8 percent of all human water use, mainly from irrigation of crops that are fed to livestock, and 6) contributes greatly to water pollution from animal wastes, antibiotic and hormones, sediments from eroded pastures, and fertilizer and pesticides used for feed crops (Food and Agriculture Organization, 2006b). Shifting diets toward plant-based food like cereals and grain legumes that are much more efficient at converting energy into protein, or even transitioning consumption from beef to poultry or from grain-fed to pasture-fed beef would work to lessen these impacts (Tscharntke et al., 2012). In addition to the nutrition impacts that may occur via the climate change pathways described earlier, intensive animal production and consumption of ASFs, red meat in particular, could have direct health consequences. Prospective cohort studies have demonstrated that consumption of red meat is associated with an increased risk of total mortality, cancer mortality and type-2 diabetes (Yip et al., 2013). Furthermore, consumption of dairy products likely increases the likelihood or severity of prostate cancer (though may be protective against colorectal cancer) (Ludwig & Willett, 2013). At the same time, however, ASFs are rich in highly bioavailable nutrients such as iron and vitamin A that are often lacking in the diets of undernourished children and women. In fact, ASFs have been shown to improve early growth in infants and children (Neumann et al., 2003). Therefore, the consumption of ASFs are certainly important, albeit, the type of meat or dairy product, the amount consumed, and the lifestage at which it is consumed are all important factors.

One of the most promising approaches to creating greater efficiencies and mitigating climate change within the livestock production sector as well as other agricultural sectors is payment for ecosystem services (PES). The costs associated with the depletion of natural resource stocks and the degradation of ecosystem services are not currently reflected in the pricing of almost any goods and services, though they may contribute directly to such depletion and degradation. There are in fact real costs associated with the provision and protection of ecosystem services; however, these services are complex and poorly understood (Farley & Costanza, 2010). Therefore, the correct price for a service, its potential effectiveness, and possible negative consequences are not always clear. Payments for carbon sequestration are one example of this, wherein eucalyptus plantations that sequester carbon unfortunately also degrade biodiversity, disrupt water provision, and limit nutrient cycling (Farley & Costanza, 2010; Lohman, 2006). Nonetheless, full costing, that is, pricing goods and services such that environmental "externalities" are reflected in the price paid by consumers, will help to prevent long-term degradation of ecosystem services (Pinstrup-Andersen, 2013). Removing subsidies that promote overexploitation of natural resources and securing property rights for commons and waste sinks are also important (Food and Agriculture Organization, 2006b).

The RCP2.6 emissions scenario assumes not only a substantial reduction in GHG emissions (i.e. a reduction of 70% compared to a "business-as-usual" baseline scenario), but also assumes widespread use of bio-energy and reforestation measures (van Vurren et al., 2011). Carbon capture and storage (CCS), wherein CO_2 emissions from large carbon point sources such as coal- and gas-fired electric power generation facilities are captured, transported off-site, and injected into geological formations for long-term storage, is seen as a transition technology that may require several decades to peak (IPCC, 2005). GHG emissions from facilities incorporating CCS could be reduced by as much as 80-90%, though challenges associated with the cost of retrofitting existing facilities, distance from sequestration sites, and increased fuel needs and costs of energy production at plants suggest that this technology may be limited in its mitigation potential in the near term (IPCC, 2005). Bioenergy and carbon capture and storage (BECCS) is an approach that substitutes production of bioenergy from biomass sources for traditional fuels in combination with CCS (Rhodes & Keith, 2008). This approach has the potential to yield negative emissions, though limits to the scale of biomass production and the negative impacts of displacing food production with bioenergy production, especially in tropical regions where much of the expansion would likely need to occur, presents serious logistical and ethical concerns to this approach being adopted on a large scale (Rhodes & Keith, 2008). More ambitious geoengineering approaches (e.g. ocean fertilization) for actively removing carbon dioxide from the atmosphere to achieve net negative emissions remain controversial and unproven with unknown side effects (IPCC, 2005).

Mitigation has the potential to positively impact nutrition outcomes by reducing the harmful environmental costs associated with future increases in global temperatures. To the extent that these same strategies increase households' production and consumption of diverse foods, increase incomes through more resilient farming practices and livelihoods, and/or directly incentive shifts in diets toward healthier patterns, they may also have direct, positive nutritional impacts.

Adaptation

The negative effects of climate change including lost agricultural productivity, ecosystem degradation, biodiversity loss, and the expansion and intensification of vector-borne diseases will be felt most strongly by those populations who are already bearing the burdens of food insecurity, livelihood insecurity, environmental decline, conflict, malnutrition and ill health. The actions needed to adapt to climate change therefore are largely the same that are needed for sustainable development broadly. These include improving rural infrastructure, expanding educational opportunities, strengthening the capacity of institutions, providing greater access to information, income-earning opportunities, and productive resources, and ensuring equity in access to the benefits that accrue from these improvements (Smit, 2001). Efforts to achieve these improvements are ongoing, though climate change will make achieving success more elusive.

Agroecological intensification (AEI) is one approach within the agriculture sector to attempt to achieve these sustainable development goals while at the same time increasing the capacity of rural communities to adapt to climate change. AEI encompasses a set of agricultural practices rooted in agroecological principles and a reliance on cheap information rather than cheap fossil fuels to increase productivity in agriculture while also enhancing ecological resilience and ecosystem service provision (Dobermann & Nelson, 2013). These practices are often adapted to local and regional contexts and may include selecting well-adapted, hybrid or high-yielding seeds, planting and harvesting at suitable times, employing integrated pest management, increasing the efficiency of fertilizer and water use, applying integrated soil and nutrient management, and leveraging agro-forestry and recycling of agricultural by-products (Dobermann & Nelson, 2013).

If successful in strengthening the resilience of farm production, livelihoods, and the natural resource base, AEI practices could certainly positively impact household food and livelihood security with subsequent benefits for nutrition. Direct nutrition actions, however, are also a necessary component of an adaptive climate-sensitive nutrition strategy. Not surprisingly perhaps, this strategy will require doing "more of the same, and better" (Crahay et al., 2010) These nutrition actions include scaling up coverage of nutrition-specific actions (e.g. food and vitamin supplementation, breastfeeding promotion, disease prevention and management) (Bhutta et al., 2013), incorporating climate change resilience actions into nutrition-sensitive investments (e.g. agriculture, education, and social safety net programs) (Ruel & Alderman, 2013), strengthening health systems, and disproportionately increasing women's access to resources, education, and opportunities.

Conclusion

The contrasting burdens of undernutrition and obesity currently afflicting billions of people around the globe are a testament to the great strides that still must be made in achieving equity in our food systems, health systems, and global economy. Climate change will perhaps be the most transformative force in shaping the trajectory of these efforts. Though nutrition may seem like a distant outcome in contrast to the more proximal threats to global ecosystems posed by climate change, protecting the nutrition and health of populations must be a concurrent priority if human communities are to have the capacity to weather the coming storm. Similarly, efforts by the nutrition community to ensure the healthy growth and development of mothers, children, adolescents, the elderly, and all populations, must work to incorporate climate-sensitive actions. This will require explicitly considering ecological and social contexts in the design, planning, and implementation of programs and policies.

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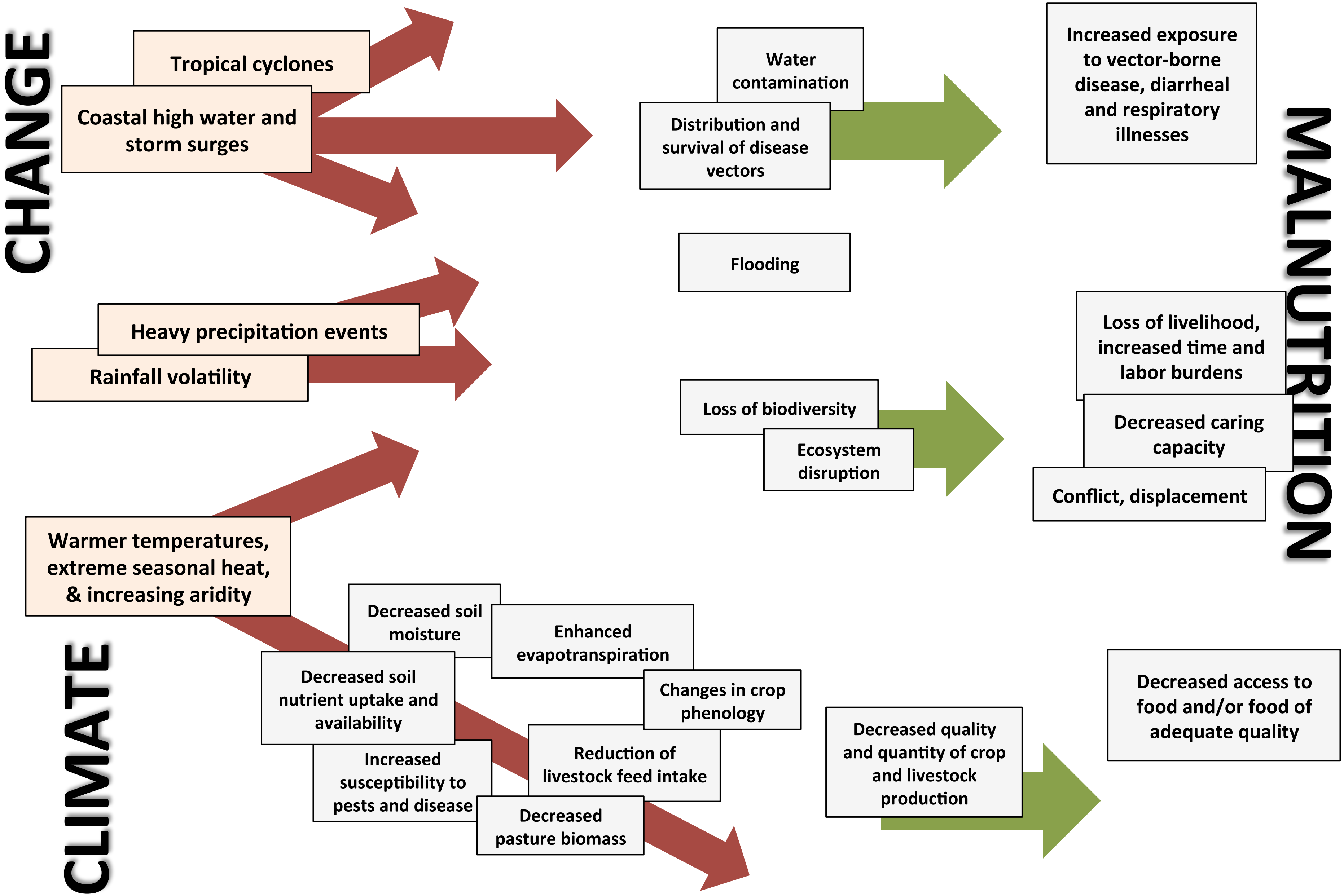

CLIMATE CHANGE

Tropical cyclones

Coastal high water and storm surges

Heavy precipitation events

Rainfall volatility

Warmer temperatures, extreme seasonal heat, & increasing aridity

Water contamination

Distribution and survival of disease vectors

Flooding

Loss of biodiversity

Ecosystem disruption

Decreased soil moisture

Enhanced evapotranspiration

Decreased soil nutrient uptake and availability

Changes in crop phenology

Increased susceptibility to pests and disease

Reduction of livestock feed intake

Decreased pasture biomass

Decreased quality and quantity of crop and livestock production

Increased exposure to vector-borne disease, diarrheal and respiratory illnesses

Loss of livelihood, increased time and labor burdens

Decreased caring capacity

Conflict, displacement

Decreased access to food and/or food of adequate quality

MALNUTRITION