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REVIEW ARTICLE

The Consequences of Climate Change for Food Security Across the Globe: A Comprehensive Review

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ABSTRACT

Agriculture is expected to face significant challenges in the 21st century in connection with the need to increase global food, timber, and bioenergy supplies to a world of 10 billion people, given limited soil and water resources and increasing threats from climate change. Increased land competition between bioenergy and food crops, climate extremes in key food exporting regions, rapidly shifting diets in large emerging economies, and a degree of financial speculation has resulted in instability in the world's food production systems. If these pressures increase further in coming decades, the world's poor are particularly vulnerable, especially those located in low-income, food importing countries, where a large share of income is already devoted to purchasing basic food staples. However, the climate-driven challenges also offer the potential to develop and promote food and livelihood systems that have greater environmental, economic and social resilience to risk. It is clear that success in meeting these challenges will require both the integrated application of current multidisciplinary knowledge and the development of a range of technical and institutional innovations. This paper aims to provide an overview of the effects of climate change on global food security and to explore ways to reduce negative impacts through adaptation and resilience.

KEYWORDS

• Agriculture • Adaptation • Climate Change • Food security • Resilience • Resources.

INTRODUCTION

Climate change denotes a long-term alteration in the statistical distribution of weather patterns, occurring over periods that can span decades to millions of years. It encompasses changes in average weather conditions as well as fluctuations in weather variability

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around these averages, potentially leading to an increase or decrease in extreme weather occurrences. The impacts of climate change are evident in the rising global average temperature, increasing sea levels, shifts in precipitation, ocean acidification, changes in salinity, uncertain water supply, and a greater incidence of storms, cyclones, and tsunamis. These developments significantly affect various living species, including crops, pollinators, pests, diseases, and their vectors.

Agriculture plays a crucial role in human society but faces significant threats from climate change in the coming decades. It is also a key contributor to environmental and climate change on local, regional, and global scales, primarily due to its extensive use of land resources. Approximately 1.4 billion hectares, or 10% of the world's ice-free land, are dedicated to crop production, while 2.5 billion hectares are utilized for grazing. Additionally, over 4 billion hectares are covered by forests, with 5% allocated for plantation forestry. Annually, more than 2 billion metric tons of grains are produced for human consumption and animal feed, accounting for two-thirds of the protein intake for people worldwide. To achieve such high production levels, significant amounts of chemical inputs are employed, with around 100 million metric tons of nitrogen applied each year, leading to considerable leaching and subsequent pollution of land, water, and air. Furthermore, agriculture is a major consumer of water resources, with over 200 million hectares of irrigated land using approximately 2,500 billion cubic meters of water annually, which represents 75% of the freshwater extracted from aquifers, lakes, and rivers. Irrigation is essential for sustaining a significant portion of the food supply, particularly cereals, which rely on it for about 40% of their production. In addition, the global consumption of fish reaches 150 million metric tons each year, with 75% of fish stocks being fully or over-exploited. Due to these extensive activities, poor management practices, and inadequate implementation, agriculture significantly contributes to land and water degradation and is a major source of greenhouse gas emissions. It releases between 13 to 15 billion metric tons of carbon dioxide equivalent (CO_2e) annually, accounting for roughly one-third of total emissions from human activities, and is responsible for 25% of carbon dioxide emissions (primarily from deforestation) and 50% of methane emissions (from rice cultivation and enteric fermentation).

In the 21st century, agriculture faces major challenges, largely due to the imperative to boost the global production of food, timber, and bioenergy to support a population surpassing 10 billion. At the same time, the sector must respond to the realities of climate change. To effectively tackle these challenges, a consistent influx of technical and institutional innovations is crucial. It is vital that strategies for adapting to climate change are harmonized with efforts to protect food security and sustain ecosystem services, including mitigation approaches that enhance carbon sequestration and promote sustainable land management (Easterling, 2007).

Physiological Changes and Agro-ecological Impacts

The impact of climate change on agriculture and forestry systems will manifest through several significant factors:

1. Rising temperatures can have detrimental effects, such as increased heat stress, particularly in low-to-mid latitude regions that are already at risk. On the other hand, there may be positive effects, including an extended growing season in high-latitude areas that are currently limited by colder temperatures.
2. Increased atmospheric CO_2 levels are expected to boost plant growth and yield, enhancing water use efficiency, especially in C_3 plants like wheat, rice, soybean, and potato. However, the effects on C_4 plants, such as maize, sugarcane, and many tropical grasses, may not be as significant due to their different photosynthetic pathways. The degree to which various agricultural crops and trees in plantation forests can benefit from elevated CO_2 remains uncertain, considering various limiting factors like pests, soil quality, and competition from weeds.
3. Projected shifts in precipitation patterns, especially concerning the expected rise in the occurrence of extreme events like droughts and floods, are anticipated to escalate in the upcoming decades, resulting in adverse impacts on land-based production systems. Additionally, a vital factor influencing plant productivity will be the interplay of temperature and precipitation changes, which will affect

soil water availability and the relationship between evaporation demands and precipitation levels.

A thorough understanding of the impact of climate change on agriculture necessitates the consideration of various factors and their interactions across different crops and regions. The current experimental data on crop and pasture responses to climate variability are largely confined to small-scale plots, which complicates the extrapolation of these results to larger field and farm scenarios. Although contemporary computer models for plant production are quite advanced in addressing soil-plant-atmospheric dynamics and crop management, they do not provide realistic representations of critical limiting factors that affect real-world agricultural operations. Consequently, the potential for unexpected challenges due to climate change remains inadequately addressed in existing regional and global projections. Some of the poorly characterized interactions in current crop and pasture models include:

i. nonlinear and threshold responses to the increased frequency of extreme climate events;
ii. alterations in the incidence of weeds, pests, and diseases, including competition between weeds and crops;
iii. the response of crops to increased CO_2 concentrations on a large scale; and
iv. the interactions between climate and management variables, particularly the effects of elevated CO_2 levels.

There is no doubt that the factors of atmospheric CO_2 concentration, temperature increases, altered precipitation and evapo-transpiration patterns, the frequency of extreme weather events, and the pressures from weeds, pests, and pathogens will significantly influence plant development, growth, yield, and the production of crop and pasture species (IPCC, 2007).

Impacts

- **Higher temperatures**

  Moderate warming, anticipated in the first half of this century, may lead to increased crop and pasture yields in temperate regions, while yields in semi-arid and tropical areas may decline. Simulation studies suggest that local mean temperature increases of 1-3°C, along with corresponding changes in CO_2 levels and rainfall, could yield slight benefits for crops in temperate regions. Conversely, models for tropical regions indicate that even moderate temperature increases (1-2°C) could negatively affect major crop yields. Furthermore, the warming projected for the end of the 21st century is expected to have increasingly adverse effects across all geographical areas.

- **Elevated atmospheric CO_2 levels**

  Numerous studies over the past four decades have demonstrated that plant biomass and yield generally increase significantly when atmospheric CO_2 levels rise above current averages. These findings are consistent across various experimental environments, including controlled closed chambers, greenhouses, and both open and closed field top chambers, as well as Free-Air CO_2 Enrichment (FACE) experiments. Higher CO_2 concentrations enhance photosynthesis, boost plant productivity, and alter water and nutrient cycles (Nowak *et al.*, 2004). Under optimal growth conditions, a doubling of atmospheric CO_2 can lead to a 30–50% increase in leaf photosynthesis for C_3 plant species and a 10–25% increase for C_4 species, despite some feedback mechanisms that may dampen this response (Ainsworth and Long, 2005). However, the increase in crop yield is generally less pronounced than the photosynthetic response. On average, when comparing current atmospheric CO_2 levels of nearly 380 ppm to 550 ppm, crop yields for C_3 crops may rise by 10-20%, while C_4 crops may see increases of 0-10% (Ainsworth and Long, 2005; Long *et al.*, 2004). For trees, above-ground biomass can increase by up to 30% at 550 ppm CO_2, particularly in younger trees, with minimal responses noted in mature natural forests (Ainsworth and Long, 2005; Nowak *et al.*, 2004). In C_3 pasture grasses and legumes, above-ground production increases are approximately 10% and 20%, respectively. Plant growth and yield simulations in major crop models align with experimental findings, indicating potential yield increases of about 5-20% at 550 ppm CO_2 (Ewert *et al.*, 2005; Tubiello *et al.*, 2007). The impact of elevated CO_2 levels, as observed in experimental settings, is well recognized by plant physiologists and crop modelers. Researchers in plant physiology and crop modelling recognize that the effects of elevated CO_2 levels, as determined in experimental environments and later applied in models, may lead to an overestimation of actual responses in agricultural fields and farms. This discrepancy arises from various limiting factors, such as pests, weeds, nutrient deficiencies, competition for resources, and the quality of soil, water, and air (Ainsworth and Fuhrer, 2003; Gifford, 2004; Long, 2005; Peng *et al.*, 2004; Tubiello and Ewert, 2002; Tubiello *et al.*, 2007). These factors are not well understood at broader scales and are often inadequately integrated into leading models. Consequently, it is essential for future crop model advancements to incorporate these additional elements to facilitate more accurate simulations of climate change impacts.

- **Interactions of elevated CO_2 with temperature and precipitation**

The relationship between elevated CO_2 and temperature and precipitation is poised to change significantly, potentially limiting the direct effects of CO_2 on crop and pasture species in the future. High temperatures during critical flowering periods can negate the positive impacts of CO_2 on crop yields by affecting grain number, size, and quality (Baker, 2004; Caldwell *et al.*, 2005; Thomas *et al.*, 2003). Rising temperatures during the growth period may indirectly lessen the impact of CO_2 by heightening water requirements. Studies show that the yield of rain-fed wheat at 450 ppm CO_2 increases with warming up to 0.8°C, but declines when temperatures exceed 1.5°C, indicating a need for additional irrigation to address these negative consequences (Centrito, 2005). In pasturelands, the combination of elevated CO_2, increased temperatures, higher precipitation, and nitrogen deposition has resulted in greater primary production, along with alterations in species distribution and litter composition (Aranjuelo *et al.*, 2005; Henry *et al.*, 2005; Shaw *et al.*, 2002; Zavaleta *et al.*, 2003). Anticipated future CO_2 concentrations may favourC_3 plants over C_4 varieties; however, the expected rise in temperatures could reverse this trend, leading to uncertain overall effects. The influence of climate on agricultural crops is significantly determined by precipitation scenarios, as water is essential for plant growth. Given that more than 80% of agricultural land and nearly all pastureland is dependent on rainfall, changes in precipitation as projected by Global Climate Models (GCMs) will often dictate the nature and scale of the impacts (Olsen and Bindi, 2002; Shaw *et al.*, 2002; Zavaleta *et al.*, 2003). Shifts in precipitation, particularly regarding the ratios of evapo-transpiration to precipitation, can alter ecosystem productivity and functionality, especially in marginal environments. Enhanced water-use efficiency due to stomatal closure and increased root density in response to elevated CO_2 may, in some cases, help alleviate or even counteract drought stress (Drinkwater *et al.*, 2005; Morgan *et al.*, 2004).

- **Interactions of elevated CO_2 with soil nutrients**

FACE experiments have established that high nitrogen levels in soil significantly amplify the response of crops to elevated atmospheric CO_2 concentrations (Nowak *et al.*, 2004). The data suggest that C_3 plant species do not show a notable yield increase under low nitrogen conditions, but their yield response improves markedly over ten years with the application of nitrogen-rich fertilizers (Schneider *et al.*, 2004). In fertile grasslands, legumes are more likely to benefit from higher atmospheric CO_2 levels compared to non-nitrogen-fixing species (Ross *et al.*, 2004). To harness the benefits of elevated CO_2, it is crucial to prevent nitrogen availability from declining through biological nitrogen fixation. However, the availability of other essential nutrients, such as phosphorus - which is vital for biological nitrogen fixation – could pose a limiting factor for legume growth in response to increased atmospheric CO_2 (Almeida *et al*., 2000).

- **Increased frequency of extreme events**

Increased climate variability is anticipated to have a more pronounced effect on agricultural production losses than previously estimated based solely on changes in average climate conditions (Porter and Semenov, 2005). For certain cereals and fruit trees, critical yield-reducing climate thresholds can occur within a matter of days, as these thresholds are tied to specific temperature levels that are essential for the development of reproductive organs, seeds, and fruits (Wheeler *et al*., 2000). Natural extremes, including storms and floods, as well as inter-annual and decadal climate variations and large-scale circulation phenomena like the El Niño Southern Oscillation (ENSO), play a significant role in affecting the productivity of crops, pastures, and forests. The occurrence of El Niño-like conditions can raise the risk of farm incomes falling below their long-term averages by as much as 75% in various cropping regions across Australia, with GDP impacts estimated to range from 0.75% to 1.6% (O'Meager, 2005). Europe faced a notably severe climate event in the summer of 2003, where temperatures exceeded long-term averages by up to 6°C, accompanied by precipitation deficits of as much as 300 millimeters. This extreme climate led to an unprecedented 36% decline in corn crop yields in Italy's Po Valley (Cialis *et al*., 2005). Likewise, in arid areas, significant soil and vegetation degradation can result in considerable reductions in the productivity of agricultural and pastoral lands. Therefore, it is essential to understand the relationships between the rising frequency of extreme climate events and ecosystem disturbances, such as fires and pest outbreaks, to better evaluate their impacts (Carroll and Taylor, 2004; Hogg and Bernier, 2005).

- **Impacts on weed and insect pests, diseases and animal production and health**

While the qualitative impacts of climate change and elevated CO_2 levels on weeds, insects, and diseases are acknowledged, there remains a significant gap in quantitative understanding. Research has sought to elucidate the competitive interactions between C_3 crops and C_4 weed species under varying climate scenarios and CO_2 concentrations. The relationship between CO_2 concentrations and temperature is increasingly acknowledged as a pivotal element in determining the extent of plant damage from pests in the future. Equally significant will be the interactions between CO_2 and precipitation (Zvereva and Kozlov, 2006). A majority of existing studies have examined pest damage in isolation, focusing either on CO_2 levels (Argall *et al*., 2004; Chakraborty and Datta, 2003; Chen *et al*., 2005) or of higher temperatures (Bale *et al*., 2002, Salinary *et al*., 2006). The rise in climate extremes is anticipated to facilitate the emergence of plant diseases and pest infestations (Alig *et al*., 2002; Gan, 2004). Investigations into the spread of animal diseases and pests from lower to mid-latitudes due to global warming reveal that notable transformations are already taking place. Forecasts indicate that bluetongue, a disease primarily affecting sheep and occasionally goats and deer, will migrate from tropical regions to mid-latitudes (IPCC, 2007). This was first evidenced by the detection of bluetongue in Northern Europe in 2006, followed by significant outbreaks in the following years and a continued presence in the area. Likewise, climate change models have shown an increased risk for the Australian beef industry concerning the cattle tick (Boophilus microplus). The lack of previous exposure to extreme weather events can lead to devastating losses in confined cattle feedlots (Mader, 2003). Between 1981 and 1999, drought conditions in Africa have been associated with mortality rates in national herds that range from 20% to 60% (IPCC, 2007). Studies on animal nutrition (Parsons *et al*., 2001) reveal that high temperatures can impose a cap on the milk yield from dairy feed intake. In tropical climates, this cap can limit production to as little as one-third to one-half of the potential yield of modern Friesian breeds. The energy deficit for this breed can exceed what is typically observed at the beginning of lactation, leading to declines in fertility, health, and longevity (King *et al.*, 2001). Furthermore, increases in temperature and humidity can adversely affect the conception rates of domestic animals that are not suited to these conditions, particularly for cattle during their main breeding season in the spring and summer (IPCC, 2001).

- **Interactions with air pollutants**

  The presence of tropospheric ozone has considerable negative implications for crop yields, forest development, and the composition of various species (IPCC, 2007). Emissions of ozone precursors, particularly mono-nitrogen oxides (NOx), are on the rise in numerous regions worldwide, with Asia experiencing significant increases. As global ozone levels are projected to rise throughout this century, the interactions with climate change and increased CO_2 will further influence plant dynamics (Booker *et al.*, 2005; Fiscus *et al.*, 2005). Although some studies suggest that higher CO_2 concentrations could alleviate some adverse effects of ozone, it is essential to acknowledge that the anticipated increase in ozone levels will likely harm plant production and may lead to greater susceptibility to pest damage, irrespective of climate change (Fuhrer, 2003). Existing risk assessment frameworks do not adequately account for these vital interactions, highlighting the need for improved modelling strategies that connect the effects of ozone, climate change, nutrient, and water availability on individual plants, species interactions, and ecosystem functions (Felzer *et al.*, 2004, 2005). Furthermore, the harmful effects of Ultra-Violet (UV)-B exposure on plant growth are well-documented, yet our understanding of its interactions with elevated CO_2 is still lacking.

- **Vulnerability of carbon pools**

  Climate change is poised to have significant repercussions on land managed for agricultural and livestock purposes, potentially disrupting the global terrestrial carbon sink and altering atmospheric CO_2 levels (Cialis *et al.*, 2005). The vulnerability of organic carbon reservoirs to climate change presents critical challenges for land sustainability and climate mitigation efforts. The future dynamics of carbon stocks and net fluxes will be heavily influenced by land use planning, policy decisions, afforestation and reforestation activities, as well as management practices like nitrogen fertilization, irrigation, and tillage, in conjunction with plant responses to elevated CO_2 levels (IPCC, 2001). While elevated CO_2 can enhance carbon storage in soil organic matter pools, particularly in the short term (Allard *et al.*, 2005), the overall soil carbon sink may become saturated at high CO_2 concentrations, especially under low nutrient conditions (Gill *et al.*, 2002). The relationship between air pollution and plant functions can indirectly impact carbon storage, as evidenced by the negative influence of ozone on biomass productivity and changes in litter chemistry (Booker *et al.*, 2005). While forecasts suggest a rise in carbon storage on global croplands due to climate change by 2100, the detrimental effects of ozone on crops could significantly undermine these projections (Felzer *et al.*, 2005). Recent studies underscore the importance of identifying potential synergies between land-based adaptation and mitigation strategies, linking carbon sequestration, greenhouse gas emissions, land use changes, and the long-term sustainability of production within effective climate policy systems frameworks (Antle *et al.*, 2004).

Impact Assessments

Research conducted through crop model simulations and integrated assessments over the last 20 to 25 years indicates that the overall effects of climate change on global food systems may be minimal in the first half of the 21st century. However, these effects are expected to become increasingly detrimental as average temperatures rise above 2.5-3°C on both regional and global levels. While the predicted minor global impacts may obscure the reality, it is crucial to recognize that climate change is anticipated to disproportionately affect agricultural production in low-latitude, tropical developing countries, while some high-latitude, developed nations may see benefits. This imbalance is likely to be exacerbated by the differences in adaptation capacities between developed and developing countries (IPCC, 2007). Simulation outcomes from crop models and integrated assessments have highlighted several uncertainties that could greatly affect crop yield impacts. Key areas of concern include the determination of the strength and saturation point of crops' responses to increased CO_2 levels, the quality and availability of water, and irrigation methods. Additionally, the interactions of crops with air pollutants, weeds, pathogens, and diseases, as well as the frequency of climate extremes in relation to average climate changes, are significant factors. Challenges also arise in implementing CO_2 effects in models, including scale and validation issues, as well as the interactions between socioeconomic and climate scenarios within integrated assessments. Recent studies have begun to address the effects of climate change under different mitigation scenarios and to analyze the connections between adaptation and mitigation strategies.

Areas of new knowledge

While existing models indicate that the cumulative effects of climate change on food production in developed countries are likely to be minor, developing regions are expected to face substantial negative impacts (Fischer *et al.*, 2002, 2005; Parry *et al.*, 2005). There is a notable chance of various unforeseen adverse effects, such as:

1. The rising frequency of climate extremes may result in crop yields declining more significantly than the average impacts of climate change. Increased occurrences of extreme weather can directly damage crops at critical growth stages, such as exceeding temperature thresholds during flowering, or hinder the timely application of agricultural inputs, thereby reducing their overall effectiveness (Antle *et al.*, 2004; Porter and Semenov, 2005).
2. The influence of climate change on irrigation water requirements could be substantial. Excluding the effects of CO_2, it is anticipated that global net crop irrigation needs may grow by 5 to 8% by 2070, with significant regional increases, such as a 15% rise in Southeast Asia (Doll, 2002). A different study that accounted for the positive CO_2 effects on crop water efficiency projected a 20% increase in global net irrigation requirements by 2080, particularly in developed regions, driven by increased evaporative demands and longer growing seasons associated with climate change (Fischer *et al.*, 2007). Both studies also forecast a rise in water stress, defined as the ratio of irrigation withdrawals to renewable water resources, particularly in the Middle East and Southeast Asia.
3. Reducing CO_2 concentrations is essential for lessening the long-term adverse effects on crop production. Forecasts suggest that the influence of climate change on global agricultural yields will be marginally below 750 ppm CO_2 stabilization. This impact can be drastically decreased (by 70 to 100%) when lower hunger risks are taken into account (by 60 to 85%) at a stabilization threshold of 550 ppm CO_2 (Arnell *et al.*, 2002; Tubiello and Fisher, 2007). The research indicates that climate mitigation could change the landscape of beneficiaries and those at a disadvantage compared to business-as-usual scenarios. In the initial decades of this century and potentially through 2050, some regions may find themselves in a worse position due to mitigation efforts, as reduced CO_2 levels may hinder crop yield stimulation while still facing comparable climate change impacts as in scenarios without mitigation (Tubiello and Fischer, 2007). A growing body of research is focused on examining the potential synergies and conflicts between mitigation and adaptation strategies (IPCC, 2007).

Socioeconomic Interactions and Impacts on Food Security

The Interplay of Socioeconomic Factors and Food Security According to the Food and Agriculture Organization (FAO), food security is defined as a state where all individuals, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and preferences for a healthy and active life (Aizen *et al.*, 2006).

1. **Food Security, Scope, and Dimensions**

   The concept of food security includes four critical dimensions: availability, stability, access, and utilization. Availability refers to the agricultural system's overall capacity to meet food demands, which is influenced by agro-climatic conditions for crop and pasture production (Munich, 2005) and the socioeconomic and cultural factors that shape farmers' market responses. Stability focuses on the risks faced by individuals who may lose access to necessary resources for adequate food consumption, with climate variability being a key contributor. For example, landless agricultural workers in areas with inconsistent rainfall and limited savings are particularly vulnerable to food access challenges. The third dimension, access, focuses on the ability of individuals to secure adequate resources (entitlements) for obtaining appropriate foods that support a nutritious diet. Entitlements are characterized as the collection of commodity bundles that a person can command based on the legal, political, economic, and social structures within their community. A vital aspect of this is the purchasing power of consumers, as well as the changes in real incomes and food prices. It is essential to recognize that these resources can extend beyond monetary forms to include traditional rights to common resources.Additionally, utilization encompasses all safety and quality factors related to nutrition, with its sub-dimensions tied to health, including sanitary conditions throughout the food chain. The availability of an adequate food supply is of little value if individuals are unable to absorb the nutrients due to health complications. Agriculture not only provides food but also serves as a source of income. In a scenario where trade can be conducted at relatively low costs, the essential issue regarding food security is not the availability of food, but rather the adequacy of both monetary and non-monetary resources that allow individuals to obtain sufficient food. This highlights that national self-sufficiency is not a prerequisite nor a guarantee for food security at the individual level. For instance, Hong Kong and Singapore, which have negligible agricultural production, maintain food security for their populations. On the other hand, India, despite its self-sufficiency in food, has a considerable segment of its population that remains food insecure. The emphasis on trade implies that these countries could reduce their vulnerabilities to global warming by relying on agricultural imports instead of domestic production. However, it is essential to acknowledge that there are several constraints when assessing the food security situation of low-income, food-importing nations, most of which currently suffer from high undernourishment rates.These countries may face challenges related to foreign exchange and supply-side limitations that restrict their ability to increase import levels. Within the larger context of development, promoting local agricultural initiatives is a powerful means of combating poverty and ensuring food security. In many African countries, food is not easily tradable due to high transaction costs and the presence of staple foods, such as roots, tubers, and local cereals, that are not found in the global market. Improving the productivity of staple foods, along with enhanced access to international markets, is crucial for achieving regional food security and improving rural livelihoods. Numerous approaches have been utilized to measure the overall status and regional distribution of global hunger; however, none of these methods adequately address all the dimensions and aspects of food insecurity outlined above (Tubiello *et al.*, 2008).

2. Climate Change and Food Security

The relationship between climate change and food security is intricate, as it affects food production directly through shifts in agro-ecological conditions and indirectly by influencing income growth and distribution, thereby impacting the demand for agricultural goods. In the long run, climate change alters food security by modifying the economic conditions that dictate consumer purchasing power and their access to food. The evolution of these economic conditions is fraught with uncertainty, influenced by factors such as population growth, development, technological innovations, and the implementation of policies aimed at climate change adaptation or mitigation. The primary issues concerning climate change and food security involve all four dimensions: food availability and production, access, stability, and utilization. While the potential for global food production may increase with a temperature rise of up to 2°C, it is projected to decline beyond that point. This increase is characterized by significant regional disparities, with high latitude areas seeing greater production potential compared to low latitude regions, which are typically less food secure. Furthermore, changes in temperature and precipitation will affect pest and disease pressures, leading to an overall increase in both, with the most severe impacts felt in poorer, low-latitude countries. Food accessibility will remain the foremost determinant of food security, with socioeconomic developments expected to exert a much larger influence than the effects of climate change.

Projections indicate that Sub-Saharan Africa will become the leading region for food insecurity, outpacing Asia, with or without the repercussions of climate change. The IPCC has organized various pathways in the Special Report on Emissions Scenarios (SRES) that illustrate different economic growth and equity scenarios. These pathways capture essential variables that influence food access, making it important to review their key assumptions before investigating the dynamics of food production, utilization, and the overall stability of food security.

The three factors affecting agriculture are (i) changes in temperatures, (ii) changes in atmospheric CO_2 concentrations, and (iii) changes in the level and distribution of precipitation. Food security will be mainly affected by changes in the levels and distribution of incomes (access) and indirectly through food production (availability) and the levels and efficiency of agriculture production (income effects through agriculture).

3. **Impacts on the stability of food supplies**

It is projected that global and regional weather conditions will become increasingly erratic, with a notable rise in the occurrence and severity of extreme weather events, including cyclones, floods, hailstorms, and droughts (IPCC, 2001, 2007). Such changes can negatively impact food supply stability and food security, resulting in greater fluctuations in crop yields and local food availability, as well as increased risks of landslides and erosion. The challenges posed by climate change and short-term climate variability, along with the need for adaptation, are longstanding issues in agriculture. Key agricultural regions, such as the Midwest of the United States, North-eastern Argentina, Southern Africa, and Southeast Australia, have historically experienced more significant climate variability than regions like Central Africa or Europe (Fischer *et al.*, 2002). Areas prone to significant climate variability are likely to increase, and the prevalence of short-term climate fluctuations is expected to rise across all regions, potentially exceeding levels in specific areas (IPCC, 2007). As climate changes become more pronounced and widespread, the frequency and severity of droughts and floods—major contributors to short-term food production variability in semiarid and sub-humid regions—are likely to escalate. In semiarid regions, drought can lead to considerable reductions in crop yields and livestock productivity (IPCC, 2001). Sub-Saharan Africa and parts of South Asia, which are among the poorest regions with the highest rates of chronic undernourishment, will be at the greatest risk of instability in food production (Bruinsma *et al.*, 2003).

4. **Impacts on Food Prices**

The various development trajectories outlined by SRES indicate a future marked by substantial economic growth, with agriculture's role expected to decline significantly over time. This pattern has been ongoing for many years in numerous developing regions. In this scenario, income growth will empower a large segment of the global population to counteract potential local food production deficits through imports, while also finding solutions to ensure the safety and stability of food supplies (Fischer *et al.*, 2002). Additionally, as real incomes increase more swiftly than real food prices, it is likely that the percentage of income spent on food will decrease, suggesting that rising food prices will not severely impact the food budgets of the impoverished. Conversely, in areas with low income levels and high food expenditure shares, escalating food prices may still lead to or intensify food security issues. Several studies have evaluated the anticipated impacts of climate change on food prices (Fischer *et al.*, 2002; Tubiello *et al.*, 2006). The primary conclusions drawn from these studies regarding climate change's effects on food prices are:

1. Food prices are projected to experience a moderate increase in correlation with gradual temperature rises until 2050, with some research suggesting a slight decrease in real prices during this period. However, post-2050, as temperatures continue to rise, a more significant increase in prices is anticipated.
2. For commodities such as rice and sugar, projections indicate that prices could surge by as much as 80% compared to their baseline levels in the absence of climate change.
3. The anticipated price fluctuations due to global warming are considerably less pronounced than those resulting from socioeconomic development trajectories. The most significant price hikes are expected in the future, which aligns with the likelihood of a persistently high number of undernourished individuals until 2080. Nevertheless, maintaining a constant absolute figure of undernourished people would still reflect a notable reduction in hunger prevalence; with global population estimates reaching 13.6 billion and over 11.6 billion in developing regions, this scenario suggests a dramatic decrease in hunger rates from 17% to approximately 7% by 2080.

5. Quantifying the Impacts on Food Security

Research utilizing the AEZ tools created by IIASA, along with the Decision Support System for Agro technology Transfer (DSSAT) crop models, consistently employs the IIASA-BLS economic model to evaluate economic impacts (Tubiello *et al.*, 2006). These tools, albeit with some adjustments in simulating crop yield variations, have been adopted by other researchers to conduct similar evaluations and perform sensitivity analyzes across various SRES and GCM projections. Numerous simulations have also investigated the implications of climate change, both with and without adaptation strategies (such as technological advancements, domestic policy reforms, and international trade liberalization), as well as in the context of mitigation efforts aimed at stabilizing CO_2 levels, temperature, and rainfall patterns. Many studies offer impact assessments for varying degrees of climate change (Darwin, 2004). The principal findings from these diverse studies can be summarized as follows:

1. It is highly probable that climate change will exacerbate the number of individuals at risk of hunger relative to scenarios that exclude its influence, with the precise effects being closely linked to projected socioeconomic changes. By 2080, climate change could lead to an increase in undernourished individuals by 5 to 26% (Fischer *et al.*, 2005).
2. Furthermore, it is probable that the magnitude of climate-related impacts will be minimal in comparison to those stemming from socioeconomic development (Ainsworth and Long, 2005). The rate of undernourishment is projected to decrease, as all scenarios indicate a continued growth in the global population until 2080, albeit at a slower pace. Currently, the FAO reports approximately 820 million undernourished individuals in developing nations, while various studies (Parry *et al.*, 2005) predict a reduction of over 75% by 2080, translating to a decrease of about 560 to 700 million people, with estimates suggesting that 100 to 240 million may still be undernourished by that time. Despite the anticipated decline in food insecurity, nearly all quantitative assessments indicate that advancements in reducing hunger will be uneven across the developing world, with progress expected to be gradual in the initial

decades of the forecast. As expected, whether or not climate change occurs, the Millennium Development Goal (MDG) of halving hunger prevalence by 2015 is unlikely to be achieved before 2020-2030 (Fischer *et al*., 2005).

3. Additionally, it is likely that the scale of climate impacts will be relatively minor when compared to the effects of socioeconomic development (Ainsworth and Long, 2005).
4. Furthermore, sub-Saharan Africa is projected to surpass Asia as the most food insecure area. By the year 2080, it could represent 40 to 50% of the world's undernourished population, compared to roughly 24% today (Fischer *et al*., 2005). In certain simulations, this region may account for 70 to 75% of global undernourishment by 2080. The projections for regions outside of sub-Saharan Africa vary significantly based on Global Climate Model (GCM) scenarios, leading to considerable uncertainty.
5. Additionally, there is considerable uncertainty surrounding the impact of increased CO_2 levels on crop yields and, by extension, food security. This is highlighted by the differences between climate change simulations that incorporate CO_2 fertilization and those that do not. While elevated CO_2 levels show limited influence on global hunger projections, all scenarios suggest a trend toward higher real incomes, enhanced transportation and communication infrastructure, and adequate global food production. Consequently, smaller estimates are unlikely to significantly affect global food security (Tubiello *et al*., 2006). Without CO_2 fertilization, climate change could reduce the number of undernourished individuals by only approximately 20 to 140 million by 2080 (Parry *et al*., 2005).
6. Recent research highlights that climate stabilization may yield significant benefits for the agricultural sector. Nonetheless, the positive effects of mitigation efforts may take decades to become apparent following their implementation, with enhancements in crop production expected primarily in the latter part of this century (Arnel *et al*., 2002; Tubiello *et al*., 2006).

6. Uncertainties and Limitations

The trajectories of socioeconomic development play a crucial role in shaping future food security and are likely to overshadow the impacts of climate change. Existing global assessments of climate change and food security have primarily concentrated on food availability and access, failing to evaluate the potential effects on food safety and vulnerability. These assessments do not take into account the additional challenges posed by extreme weather events such as droughts and floods (FAO, 2006), nor do they quantify the potential rise in food-borne diseases or the interactions between nutrition and health due to the spread of vector-borne diseases. Current discussions on food availability fail to account for the potential impacts of rising sea levels on agricultural production and the possible decreases in marine and freshwater fish populations. Furthermore, the assessments of global food supply have largely concentrated on the average effects of climate change, neglecting the potential for significant changes in the frequency of extreme events that could affect regional production capabilities. They also do not consider scenarios involving abrupt climate or socioeconomic changes, which could significantly worsen the already negative projections regarding climate change's effects on global food supplies. Additionally, there is a lack of models that can effectively simulate the necessary biophysical, technological, and market responses to develop realistic adaptation strategies in response to these events.

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