The Threat of Climate Change on Agriculture and Food Security

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ABSTRACT

OSLEY, SAMANTHA ANTONIA. The Threat of Climate Change on Agriculture and Food Security. (Under the direction of Dr. Stephen Graham).

As the effects of climate change continue to be studied, its impact on agriculture cannot be ignored. Climate change has led to an increased frequency and severity of extreme weather events, making the cultivation of crops humans rely on for a food source more difficult. More instances of droughts and flooding events lead to plants that experience greater stress, higher susceptibility to disease and pests, and can ultimately result in reduced yields. As the demand for food increases as populations rise, maintaining food production as well as providing food security is a critical priority to maintaining the health of humans globally. With lower crop yields, demand increases, often leading to increased prices of nutritionally dense foods. The following literature review sheds light on the abiotic and biotic factors from climate change that influence farming practices and crop yields globally. The effect of droughts and floods on crop growth will be considered, along with factors such as disease, pests, erosion, and stress combination. The cascading effects of climate change on the supply chain and access to food will be reviewed, along with potential adaptation strategies such as the integration of Climate-Smart Agriculture, the use of plant breeding, and finally an examination on the incorporation of plant growth-promoting rhizobacteria for mitigating drought stress.

DEDICATION

I would like to dedicate this literature review to my great uncle, Joseph J. Tumilowicz who passed earlier this year on March 2, 2025 at the age of 94. Uncle Joe dedicated his life to the pursuit of knowledge in the field of virology, publishing numerous papers on the Cytomegalovirus and cancer research.

He was a member of the United States Marine Corps and served with D Company, 2nd Battalion, 7th Regiment, 1st Marine Division during the Korean War. Following his service, he attended Rutgers University and earned a Bachelor of Science in Biology before pursuing his Ph.D. in virology at the University of Pennsylvania. After the completion of his Ph.D, he went to the Baylor College of Medicine, where he was a member of the Division of Experimental Biology and of the graduate school faculty. Once he retired, he sought out his family lineage and published a book entitled “Tumilowicz, Tumilovich, Tumilovics, Tumilovicius: A History/Genealogy”, which details his family’s ancestral roots.

He was an eager and dedicated student of life and science and took every opportunity to discuss with you the fragility, and conversely the stubbornness of humans. While pouring into this literature review, I was always aware of the enduring stamina he maintained while conducting his own research and remained inspired in my own pursuit of knowledge. Thank you, Uncle Joe.

BIOGRAPHY

Born in Raleigh, North Carolina, from an early age, I knew I had an affinity for plants and the natural world. This translated into plentiful time spent outside; a devotion to hiking, camping, and gardening, as well as a study on the local flora and fauna through a collection of written poems produced by me for my senior Independent Study in high school. I went on to earn my bachelor's degree in plant science at the University of Florida, with a focus on ornamental crop production through the university’s Environmental Horticulture Club where I was responsible for the cultivation of 4,500 poinsettias via rooted stem cuttings. Following my bachelor’s degree, I worked at North Carolina State University’s Mountain Horticultural Crops Research and Extension Center as a Field Technician under Dr. Dilip Panthee, the department head of the Tomato Breeding Program. After this experience, my passion for how climate and agriculture are intertwined developed and brought me to apply for entry to NC State’s Master of Environmental Assessment program. As a part-time student, in February of 2024, I accepted a full-time position with the Environmental Protection Agency located in the Research-Triangle Park for what was then known as the Center for Computational Toxicology and Exposure in the Chemical Characterization and Exposure Division as a Research Program Assistant. As I finish this program, I hope to continue to move forward in my pursuit of bridging the gap between agriculture and the environment with the goal of communicating science to the public in my next professional endeavor.

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CHAPTER 1: Attributing Increased Extreme Weather Events as a Result of Climate Change

I. Robust Event Attribution

Although it has been argued that the increased occurrence of climate events cannot be ascribed to climate change induced by human behavior, more studies have been conducted that provide evidence that climate change has largely escalated due to human activities that result from the increase of greenhouse gas emissions (Easterling et al., 2016). A developed method known as Robust Event Attribution has allowed scientists to determine the correlation between extreme weather events and anthropogenic-related climate change. This is a critical development in climate research, as it allows for a greater understanding of how to potentially reduce these extreme weather events and to further understand how humans affect climate change. This section reviews the attribution of increased extreme weather events as a result of climate change dictated by anthropogenic action, as well as the methods utilized to come to these determinations.

The two primary methods for establishing this correlation between human activities and climate include Observed and Modeled Temperature Changes and Observed and Modeled Rainfall Distributions (Stott, 2016). Data, such as temperature variation and rainfall distribution, are collected over long periods of time, and used to reflect a climate pattern rather than simply representing weather events (Easterling et al., 2016). Researchers will then perform a simulation of how the climate would be affected in the absence of human influence next to a simulation that accounts for human influence and attribution. Researchers choose an abiotic factor; either temperature or rainfall in this case, and "calculate the likelihood of exceeding this index with and without climate change" (Stott, 2016).

For example, using the Observed and Modeled Temperature Changes method, Stott (2016) references an example where the hottest summer on record in 2013 in eastern China was observed and estimated the likelihood of these high temperatures "increased by a factor of >60 as a result of human-induced climate change." Eastern China's June through August temperatures had increased by 0.82°C since data collection was initiated in the 1950s. Recorded daily heatwaves, i.e., days with a maximum temperature above 35°C (or 95°F) occurred for 31 days that summer; more than double the average from 1955-1984 (Sun et al., 2014). In order to come to these conclusions, Sun et al. (2014) compared the observed temperatures against the simulated 5-year mean regional average summer temperatures generated from climate models. Using regression analysis, a statistical tool for comparing observed changes versus predicted changes, researchers considered both anthropogenic and natural forces combined, then compared these results with those generated for natural forces only. Comparing the observed temperatures with one of these is known as a one-signal analysis, versus a two-signal analysis where both the anthropogenic and natural forces are considered in the comparison. This approach is helpful in identifying which forces can be attributed for these increases in temperature and the number of heatwave days recorded. In conclusion, the results attribute the rise in temperature is due to anthropogenic forces, such as greenhouse gas emissions, and that natural forces alone cannot account for this magnitude of warming.

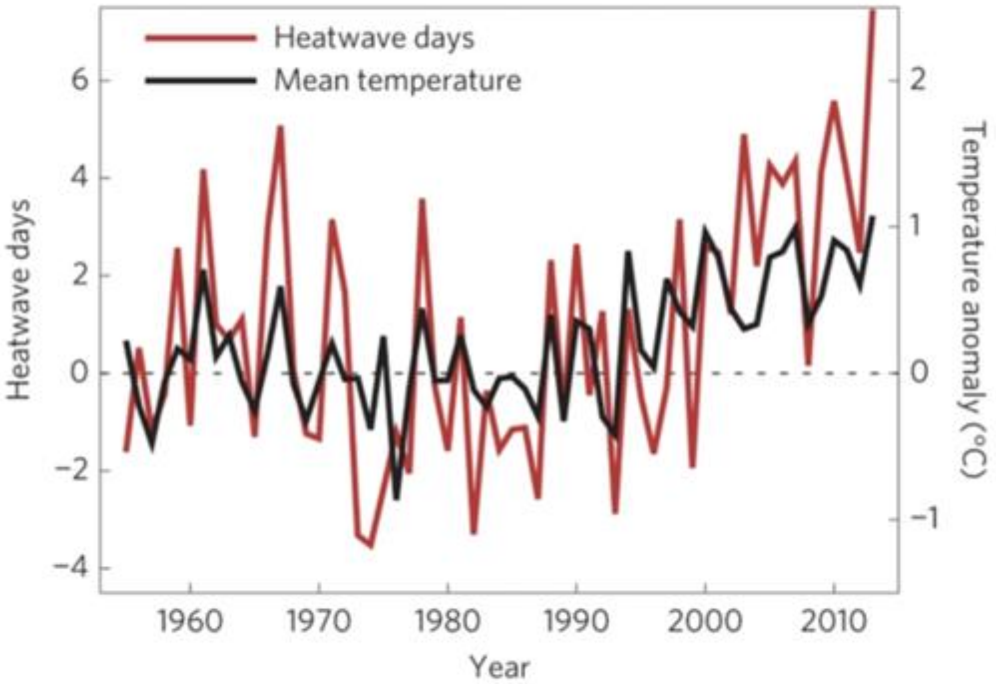
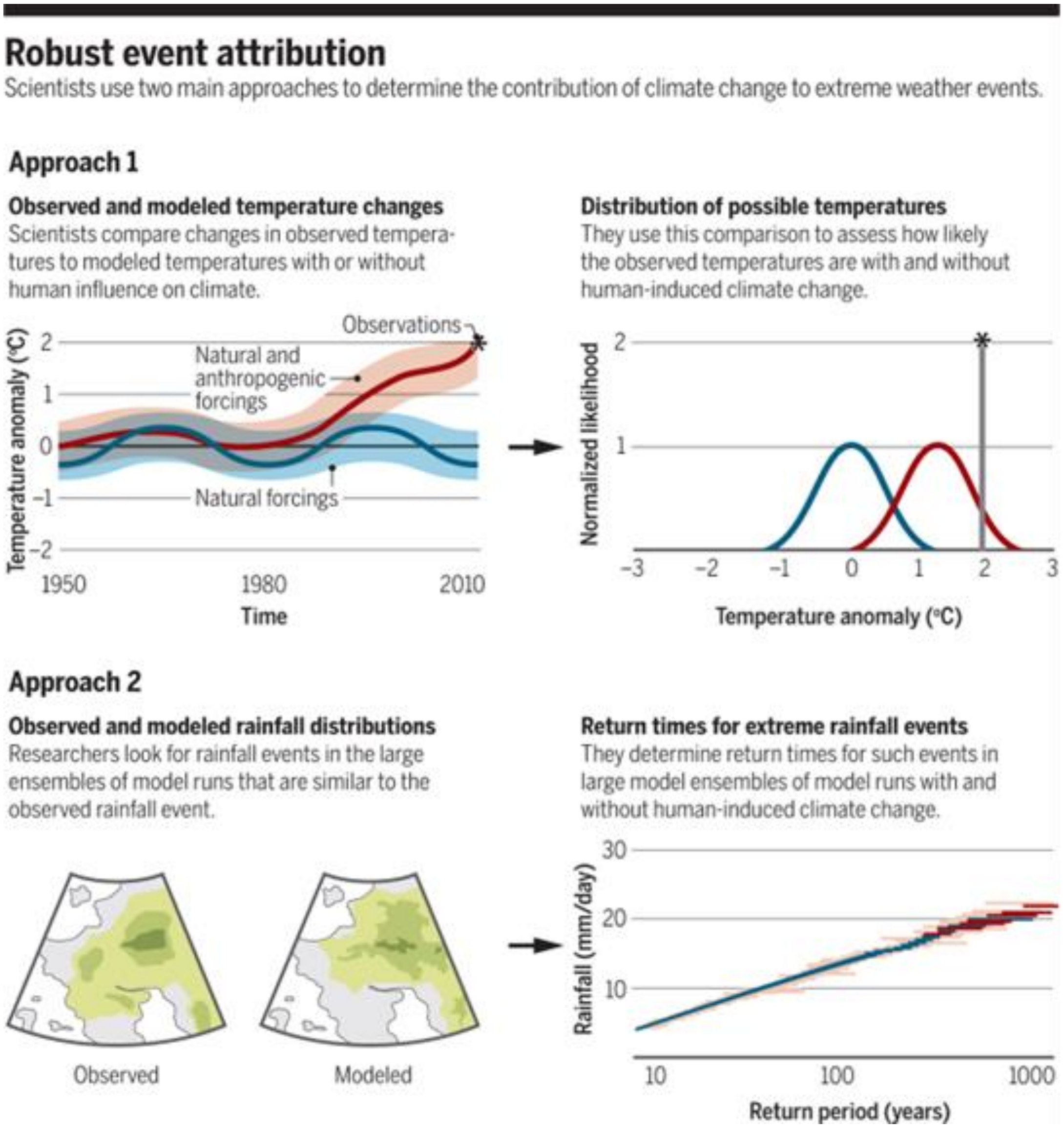


Figure 1. Number of heatwave days and the summer mean temperature in Eastern China (from Sun et al., 2014).

The second method for determining these correlations are valid uses Observed and Modeled Rainfall Distributions, which evaluates instances where unprecedented rain events occurred and their likelihood of recurrence. Simulations are performed for where anthropogenic influenced climate effects are included and compares it to a simulation of without anthropogenic influence. In this approach, researchers consider observed rainfall distributions over a selected period of time and geographic radius and compare these distributions to simulated rainfall distributions that would account for anthropogenic induced changes. Simulated anthropogenic induced changes could include an increase in greenhouse gas emissions, an increase in aerosols or particulate pollution, land use, such as instances of deforestation, or industrial waste heat, which can be described as the release of heat via fossil fuel-based power utilities or motor vehicles.



Robust event attribution

Scientists use two main approaches to determine the contribution of climate change to extreme weather events.

Approach 1

Observed and modeled temperature changes

Scientists compare changes in observed temperatures to modeled temperatures with or without human influence on climate.

Distribution of possible temperatures

They use this comparison to assess how likely the observed temperatures are with and without human-induced climate change.

Approach 2

Observed and modeled rainfall distributions

Researchers look for rainfall events in the large ensembles of model runs that are similar to the observed rainfall event.

Return times for extreme rainfall events

They determine return times for such events in large model ensembles of model runs with and without human-induced climate change.

Figure 2. Robust event attribution (from Stott et al., 2016).

Figure 2 above illustrates the two methods and provides an overview of how temperature and rainfall anomalies respectively are compared to simulations of anticipated weather based on anthropogenic influence. In Approach 1 (Figure 2, top panel), scientists compare observed temperatures to modeled temperatures (i.e., modeled for both with and without human influence on the climate) to gain an understanding of how likely the observed temperatures are a result of anthropogenic influence. In Approach 2 (Figure 2, bottom panel), the same method is used, except, instead of using observed temperatures, observed rainfall events are evaluated. Again, the impact of climate influencers are considered in the modeling of rainfall distributions over long periods of time. The frequency of modeled extreme events are identified and compared with the observed extreme events. Then, return times are used to characterize the observations as the average likely recurrence of these events and are simulated based on impact with and without anthropogenic influence.

II. Evidence of Increased Occurrences

When considering individual extreme weather events, it is difficult to point climate change as the sole factor of why they occurred, however, it is when you consider the broader scope and frequency of these events, as well as their severity that climate change can be pinpointed as a culprit. An important distinction when analyzing these instances is differentiating between weather and climate; weather is indicative of short-term stretches of time, whereas climate is indicative of longer-term, larger scale patterns. In a way, weather exists inside the scope of climate, and it is the inconsistencies or consistencies in weather that make up our overall climate. When seeking to evaluate whether or not climate change is to blame for these increased occurrences of extreme weather, essentially what information is being sought out or simulated is what would the climate look like "without human influence," and how does that simulation compare to the current or projected climate (Swain et al., 2020).

As discussed in the previous section, Robust Event Attribution is becoming an increasingly helpful tool for attributing climate change, specifically due to anthropogenic actions, as the reason for increases in temperature and changes in precipitation. The most recent Intergovernmental Panel on Climate Change Report (IPCC, 2022) states the "evidence of human influence on the climate system has strengthened progressively over the course of the previous five IPCC assessments, from the Second Assessment Report that concluded 'the balance of evidence suggests a discernible human influence on climate through to the Fifth Assessment Report which concluded that 'it is extremely likely that human influence caused more than half of the observed increase in global mean surface temperature from 1951 to 2010" (IPCC, 2022). This finding was largely based on new coordinated model results sourced from the World Climate Research Programme Coupled Model Intercomparison Project Phase 6 (CMIP6) (Eyring et al., 2021).

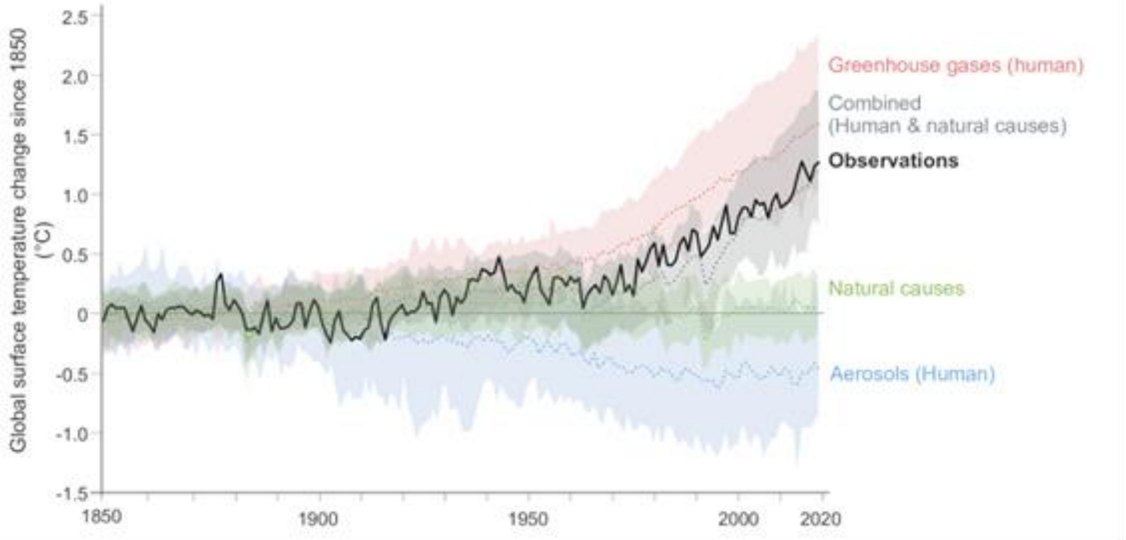


Figure 3. Observed warming (1850-2019) is reproduced in model simulations when including human influence (from IPCC, 2022).

Figure 3 above displays global surface temperature changes since 1850 in degrees Celsius, accounting for the influence from greenhouse gases and aerosols as a result of human activity, affects from combined human and natural causes, and natural causes. The black solid line represents the multi-model mean of temperature increase as a result of these different factors. The primary increasing factor represented here by the red shade, the greenhouse gases, has a significant influence on the increasing observed mean temperature; however, the magnitude of the increase is slightly counterbalanced by increases in atmospheric aerosols, represented by the blue band, which have a cooling effect. IPCC (2022) indicated the level of global warming, both observed and that generated using climate models, is only possible with the included anthropogenic effects, meaning the combined effect from both greenhouse gases and aerosols. The simulations produced when only including the natural processes, such as emissions from volcanoes or variations in the El Nino (i.e., events when the central and eastern Pacific ocean becomes warmer than usual by pushing heat from the ocean into the atmosphere) could not solely be responsible for the observed level of warming (IPCC, 2022). Additionally, data reporting on "warming in the lower atmosphere and cooling in the stratosphere, warming of the ocean, and melting of sea ice" also point to the result of anthropogenic activity (Eyring et al., 2021; IPCC, 2022).

III. Anthropogenic Role

The goal of these tools is to gain a greater understanding of what forces are driving climate change. When scientists refer to the anthropogenic forces contributing to climate change, this means the changes to Earth's natural systems caused by humans. When utilizing these approaches for event attribution, it is important to consider what sort of human activities contribute to these anthropogenic changes. Some of these anthropogenic factors include, but are not limited to: greenhouse gas emissions, aerosols and particulate pollution, land use, and industrial waste heat.

Greenhouse gas emissions refer to activities that emit gases that become trapped in the atmosphere and absorb infrared radiation, which is re-emitted, causing warming of the lower atmosphere. Some of these gases include carbon dioxide, methane, or nitrous oxide. Carbon dioxide can be released via burning fossil fuels, such as oil, coal or natural gas, through activities such as driving cars, the use of power plants for generating electricity, or manufacturing plants that burn fossil fuels in order to produce commonly used materials such as steel, cement, or plastic. The United States Environmental Protection Agency (EPA) reported on a breakdown of Total U.S. Greenhouse Gas Emissions by the four economic sectors: Agriculture, Industry, Residential/Commercial, and Transportation. The EPA tracks these emissions through the Inventory of U.S. Greenhouse Gas Emissions and Sinks.

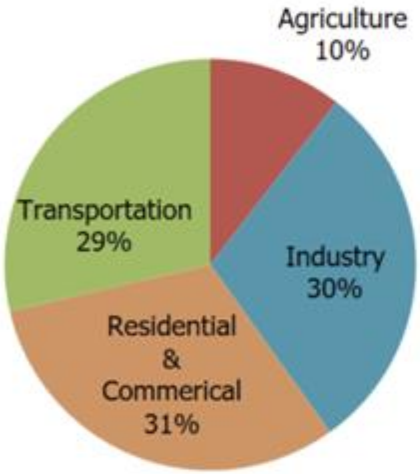


Figure 4. Total U.S. greenhouse gas emissions by economic sector including electricity end-use indirect emissions (from US EPA, 2025a).

Figure 4 illustrates that Residential/Commercial, Transportation, and Industry contributed approximately 30% each to the total greenhouse gas emissions, while the Agriculture sector contributed to about 10% of the total emissions. End-use indirect emissions refer to the greenhouse gases released by power plants that are responsible for creating the electricity in the Transportation sector. Residential and Commercial emissions contributed to 31% of the total emissions and results from energy use in the form of fossil fuels used for heating, ventilation, air conditioning, lighting, appliances, plug loads, and activities involved in handling waste, which is compounded by the fact that buildings use 75 percent of the electricity generated in the United States (US EPA, 2025a). Industry, responsible for 30 percent of the total emissions of greenhouse gases, includes the burning of fossil fuels for the production of raw materials. Transportation, responsible for 29 percent of total emissions, includes all the energy use associated with vehicles such as cars, planes, large shipping trucks, ships, often used for transporting goods, as well as human travel. The EPA reported that “over 94% of the fuel used for transportation is petroleum based,” meaning that these vehicles require gasoline or diesel fuel for power, which create these massive direct emissions (US EPA, 2025a). Coming in at 10 percent, the Agriculture sector is responsible for the least amount of total emissions. These include greenhouse gas emissions from livestock via flatulence (e.g., methane), soil degradation (e.g., carbon dioxide), and rice production (e.g., methane), with roughly 5 percent of direct emissions attributed to the use of agricultural facilities and equipment, such as large tractors and plows that require power from fossil fuels or electricity. Lastly, land use and forestry is worth considering as climate influencers, as these are responsible for absorbing carbon dioxide from the atmosphere, essentially acting as a sink for CO_2 emissions; with the EPA noting that since 1990, forest and land in the United States “has absorbed more CO_2 from the atmosphere than they emit, offsetting 13 percent of total gross greenhouse gas emissions” (US EPA, 2025a).

CHAPTER 2: The Impact of Frequent Extreme Weather Events on Agriculture

I. Stressors

With the increased occurrence of extreme weather events, stressors are more frequently introduced into a crop's lifespan. Examples of important stressors to crops include drought and flooding, disease (such as Phytophthora or water molds), introduction or adaptability of pests, and chemical and physical erosion of soil composition. These stressors often result in reduced crop yields and/or shorter plant lives contributing to lesser available market value crops. This chapter reviews these different stressors for how they influence a plant's vigor and longevity. In addition, a consideration of how a combination of these stressors takes a toll on plant growth is discussed with potential approaches to offset these combined effects.

a. Drought and Flooding

As the global CO_2 air concentration rises, the average global temperature also increases. Several studies have indicated that short-term exposure to elevated CO_2 levels resulted in elevated photosynthetic rates and increased leaf carbon gain (Tomimatsu and Tang, 2016). Although this increased concentration has the potential to accelerate photosynthesis in crops, resulting in greater productivity, this benefit is offset by the corresponding negative impact from higher temperatures and longer drought seasons (Malhi et al., 2021). When considering the effects of increased temperatures overall on the yield of agricultural crops, although there are short-term and smaller scale benefits, crop yields are ultimately at a detriment with increased temperatures that result in more frequent drought, thus increased plant stress.

Drought has now become considered as a primary cause of stress to crops globally (Buragohain et al., 2024). When considering the role of water in crop production, precipitation and groundwater availability is critical to the success of a crop. The amount of available water or lack thereof influences the rate of seed germination, instances of stress, and photosynthetic rates as it relates to the surface area of leaves (Rezaei et al., 2023). When a plant's relative water content is disturbed due to drought; leaf temperature, rate of transpiration (i.e., how quickly a plant can absorb water through its roots), and its release as water vapor, are negatively impacted. Canopy temperature will increase and stomatal conductance, or the diffusion of CO_2 through a plant's leaves, will decrease (Buragohain et al., 2024). When the pores on leaves close to reduce water loss via transpiration (i.e., stomatal closure), and when this also occurs on limited leaf surface area due to reduced overall growth from climate influencers, it negatively impacts the plant's RuBisCo activity. RuBisCo (ribulose-1,5-bisphosphate) is a critical enzyme that catalyzes the carboxylation, or addition of CO_2 to a plant's RuBisCO enzyme during the first step in the process of photosynthesis. However, when having a reduced surface area, a plant may limit its stress response by requiring less water uptake due to the reduced-sized leaves. While this response may help the plant in the short-term, this response is not sustainable for long-term crop production (Rezaei et al., 2023). As a response to these instances of drought increase, it is estimated that the frequency of irrigation events will increase by 10% with every 1°C increase in global temperature (Buragohain et al., 2024). The manifestation of this impact in terms of agricultural yield and resource costs will be discussed in detail in Chapter 4.

Increased instances of flooding due to climate change also can negatively affect crop growth. Excessive water can damage roots and reduce availability of oxygen to the root system (Rezaei et al., 2023). This impact due to flooding is possibly the greatest detriment to plant success. When this occurs, the root's ability to take up nutrients is measurably stalled and the distribution of minerals to different parts of the plant come from more mature and abundant plant tissues rather than the external environment. This means the plant will use its own stored resources previously used for growth to survive and is ultimately an unsustainable, short-term solution. More consistent flooding leads to free water remaining in the soil's composition, drastically reducing available oxygen as well as increasing the leaching of the soil nutrients. If the soil is subject to frequent agitation or standing water, a homeostasis cannot be achieved, rendering the soil unsuitable for productive crop development. Once oxygen is exhausted from the root system, new plant shoots become inactive due to lack of O_2 and roots begin to necrotize, or die off. Once this process begins, it is difficult for the plant's root system to recover, as the plant can no longer aid in draining excess water from the soil by uptaking water needed for survival (Stolzy and Sojka, 1984). The degree of damage from flooding depends on soil type, the slope of the land, and frequency of precipitation or flooding events (Stolzy and Sojka, 1984). Soil composition can be drastically altered when exposed to flooding, with excess water leaching vital nutrients from the ground, such as nitrogen and potassium. With less sun penetration, light and photon exposure to plants is also at a deficit, resulting in reduced rates of photosynthesis. In addition, flooded croplands have a greater susceptibility to plant diseases, which will be discussed in greater detail in the next section.

b. Plant Pathogens and Disease

Another plant stressor influenced by climate change is the rate of plant disease and plant pathogen presence. Through observational studies conducted on the rate of plant pathogens, it is suggested that the increase in global temperatures has the greatest influence on global pathogen distribution (Raza and Bebber, 2022).

Two key factors that influence plant disease are temperature and moisture, which are largely impacted by weather events such as flooding and when plants are grown in high humidity climates. With climate change, added variation of weather patterns encourages these factors, leading to greater instances of diseases and plant pathogens (Garrett et al., 2022). In order to understand the role climate change has in increasing disease frequency, the disease triangle, which measures the interactions between the plant, the pathogen, and the given environment, is utilized (Garrett et al., 2022). The relationship between these three factors will vary from plant to plant and can be considered more aggressive in some instances than others, due to the nature of the pathogen, or its virulence, and its mechanism of infiltrating a plant. For example, pathogens tend to thrive in warmer temperatures on plants that are grown more closely together, as they have an overall larger breeding ground, versus that existing with more dispersed plants. A warm, moist setting is more favorable for disease progression, compared to cooler, winter climates, where many pests are less active. In these instances, environmental factors such as temperature are a greater threat to a plant's success, rather than instances of pathogen infiltration. As the climate evolves, so does the distribution of pathogens globally.

Garrett et al. (2022) considered this phenomenon of the disease triangle under the biotic-abiotic-migration model (BAM) to gain a better understanding of how species scatter globally based on resources and climate. For example, Basidiomycota, a rust fungus, was observed in a lab model for inducing leaf stem rust on plants (*Puccinia graminis*) by monitoring the rate of infection based on temperature, humidity, precipitation, wind, and sunlight (Garrett et al., 2022). Infection was determined by the presence of germinating urediniospores (i.e., the spores of rust fungus started to grow) and found to occur with wet leaves and high light, and at varying rates based on temperature. This circumstance presents itself in humid conditions where sunlight is plentiful, as well as high rates of precipitation; creating an exceptionally humid environment. A second model which factored in "UV rays and the effect of frost on spore survival, temperature-dependent spore production, wind- and turbulence-driven spore release and dispersal, and wet and dry deposition of spores onto crops" also revealed that leaf surface wetness and temperature were the primary driving factors of disease progression (Garrett et al., 2022). These results indicate persistent moisture can have negative impacts on crop systems and as agriculture faces more frequent storms and flooding events, combined with high humidity climates, many crop systems are at risk. A computer crop model comparison conducted by Chaloner et al. (2021) was used to evaluate the infection rate and disease development of different crops such as maize, wheat, and soybean by estimating total projected crop production based on changing temperatures and how yields were affected. Current yield projection means from the year 2011-2030 were compared with future projections between the years 2061-2080 using three crop models and four global climate models that provide data on future temperature and rainfall predictions. The models accounted for CO_2 fertilization effects, since higher CO_2 levels can positively influence plant growth. In addition, they compared crops with irrigation versus those reliant only on rainfall events. The results of the experiment indicated that, specifically as global temperatures increase, so will disease pressure among these three crops; and that those plant species who may benefit from increased temperatures, the pathogens at risk for infecting them will also thrive (Chaloner et al., 2021).

c. Pests

Related to the degradation of agricultural yield outputs is the relationship between crop pests and climate change. Particularly in relation to an increase in global temperatures, pests have the potential to expand in populations, as warmer temperatures allow for greater endurance, specifically in terms of overwintering survival, or the ability for their population to persist through the colder months (Skendžić et al., 2021). Overall, consistently high temperatures can encourage the adaptation of many insect species, rendering traditional pest management tactics ineffective, requiring new method of development to combat increasing rates of pests. This section reviews how insects respond to changing climatic conditions as well as how this influences their toll on agriculture productivity. Reduced yields, with greater amounts of imperfect foods, or crops that are not up to market value, whether in size or due to insect damage, are just some examples of how agricultural output is implicated. Aphids (*Aphidoidea*) and how climate change influences pest pressure will be reviewed.

Temperature poses many impacts on insect pests and their survivability rates. These impacts include increased geographic range, more instances of plant disease outbreak on varying plant species, an increase in their overwintering survival, and therefore, overextend the pests' relationship with their natural enemies or predators (Skendžić et al., 2021). Meaning, with increased populations of pests, their predators are unable to maintain a regulated defense against them and keep pest populations at a lower and more manageable size. Physiologically, insect development, metabolism, reproductive rates, and even movement increase with temperature.

This is critical when considering changing pest populations with climate change, as increased movement has led to some pest populations migrating to unanticipated geographic regions, affecting crops that otherwise would evade these insects. As these pests evolve with increased temperature, combatting them with the use of natural enemies and traditional pesticides becomes a greater challenge.

In regard to the increase of CO_2 levels, the response of pests is more varied, and rather dependent on the pest's host plants. One way to evaluate this, for example, is by reviewing the difference between pest responses to varied CO_2 levels on C3 and C4 crops. C4 crops, such as maize, sorghum, and sugarcane utilize a granal and agranal chloroplast, meaning these plants are able to photosynthesize at a higher efficiency, undergoing two separate methods of photosynthesis. C3 plants, such as potatoes, rice, or wheat, can only utilize a granal chloroplast, making their capacity to photosynthesis lesser in comparison. The result is that increased CO_2 more so negatively affects C3 crops, such as the ones listed, making them more vulnerable to increased pest populations (Skendžić et al., 2021).

A common pest that affects many vegetables and fruits, such as tomatoes, peppers, and citrus plants, is the aphid. Aphids have what are known as piercing sucking mouthparts that they use to feed on the sap of plants, and when there is evidence of one aphid on a plant, there are many (Townsend, University of Kentucky). As aphids permeate a plant, they generally dominate the underside of terminal growth plant parts, or the tips of stems, where vertical growth occurs. This makes them especially problematic for developing crops. As aphids infest a plant, the plants can become yellowed and discolored due to the diminishing sap. In addition, as they feed on the plants, they release waste known as "honeydew", which can result in the production of sooty mold on plants, further limiting the crop's productivity. The saliva of aphids released into the plant can also lead to leaf puckering as well as distorted flowering, resulting in malformed fruits (Townsend, University of Kentucky). Aphids also act as major disease vectors towards crops, introducing disease, which cannot be eliminated simply by ridding the plant of infestation. This in particular poses the greatest threat to crop species. When considering the effects of climate change, specifically with drought, it was discovered that drought conditions can actually increase an aphid's ability to feed on plant sap, therefore increasing damage to the plant (van Munster, 2020). This is due to the alteration of water potential in a plant system when exposed to drought conditions. In the past 40 years, aphid migration has begun a month earlier in the year, due to increasing global temperatures (Luquet, 2018).

d. Erosion: Physical and Chemical

Soil erosion for decades has been an increasing issue with maintaining sufficient crop yields to feed the global population. Soil is a critical component of successful crop development, as it aids in nutrient delivery, sufficient water uptake, and influences the labor intensity of farmers, as it pertains to irrigation frequency and the turnover of land between growing seasons. With climate change, soil health is at risk, due to extreme weather events such as flooding and drought that can dramatically upset the landscape for growing crops. Erosion of soil due to water will be the focus of this section, with discussion surrounding the influence of human involvement and climate related activity and its detrimental effects. Projections developed by

Borrelli et al. (2020) indicate the potential for a more aggressive hydrological cycle that could increase global soil erosion due to water between approximately 30 and 66 percent.

Borrelli et al. (2020) modeled these potential changes in global soil erosion due to water by utilizing three Shared Socioeconomic Pathway and Representative Concentration Pathway Scenarios (SSP-RCP) scenarios (Borrelli et al., 2020). The Shared Socioeconomic Pathways refer to scenarios that involve population growth, economic development, environmental policy or technology use, whereas Representative Concentration Pathways refer to the level of greenhouse gases in the atmosphere in the future. Using a computer model, known as GloSEM, the three SSP-RCP scenarios represented possible future outcomes that consider climate change and human land use decision making: the first combined sustainable development and low-level climate warming, the second, included moderate development and moderate warming, and the third, incorporated high fossil fuel use and high warming. The first scenario resulted in erosion decreasing by roughly 10 percent, the second, erosion increasing by roughly 2 percent, and the third, resulted in an increase of erosion by roughly 10 percent. Referencing a report published in 2015 by the Food and Agriculture Organization of the United Nations, it was said that '...the majority of the world's soil resources are in only fair, poor, or very poor condition and stressed that soil erosion is still a major environmental and agricultural threat worldwide (FAO, 2015). This finding is due to a combination of many things, such as deforestation, overgrazing, ploughing, and unsustainable agricultural practices, leading to "nutrient loss, reduced carbon storage, declining biodiversity, and soil and ecosystem stability" (Borrelli et al., 2020). Soil erosion is manifested through loss of soil nutrients, or reduced soil fertility, leading to increased fertilizer applications, affecting crop outputs, and perpetuating greater financial burdens on farmers. Degraded soils have been shown to reduce crop yields and productivity, due to the plant's lack of available nutrients. In essence, healthy soil is necessary for the cultivation of healthy and hearty crops.

When flooding occurs, due to an extreme weather event or excessive precipitation, the properties of the soil and their capacity to stabilize a plant's root system weaken. Soil slaking, when the larger, dry pieces of soil break down into smaller pieces occurs when rapid inundations of water, due to a rain event or flooding can cause increased rates of erosion (Rupngam and Messiga, 2024). This negatively impacts the organic matter and nutrient distribution in soils, disturbing plant growth. Soil pH is impacted, as when flooding occurs, there is reduced available oxygen in the soil as the oxygen is pushed up and out of the soil and replaced with water. Soils tend to run more acidic, due to fertilizer applications and nutrient leaching, however, this varies on the growing region. Depending on the makeup of the soil, the result can be a more neutral or alkaline chemical composition. This is a critical component, as pH influences a plant's capacity for nutrient uptake with minerals such as magnesium and phosphorus in more acidic soils and iron and zinc in more alkaline soils. Air, water, and nutrient flow can all be affected by frequent flooding events (Rupngam and Messiga, 2024). The Food and Agriculture Organization reported that "between 2008 and 2018, approximately 21 billion dollars were lost in agricultural production worldwide as a result of floods (Rupngam and Messiga, 2024). With increased instances of flooding due to climate change, it is likely this number will grow, negatively impacting crop yields and food distribution.

II. Outcomes

a. Stress Combination

As these different stressors have been considered individually, it is important to address their connection to one another and how these overlapping factors make it more difficult to combat their undesired effects. This phenomenon is known as stress combination, where plants are exposed to multiple stressors at once or sequentially, ultimately resulting in reduced crop yields (Rivero et al., 2021). Some of the abiotic factors that can contribute to stress combinations are discussed above, including droughts, flooding, cold snaps, and heatwaves, along with biotic stressors such as pests and pathogens. In addition, anthropogenic stressors, such as pollution levels, play a role as stressors in agriculture, influencing soil microbiomes for the worse, through exposure to microplastics, metals, and antibiotics (Rivero et al., 2021). It is clear that individually these varied stressors pose risks to agriculture and overall food security; however, when combined, plants become more vulnerable and less productive. Potential combinations of these factors include drought and heat waves, flooding and pest infestation, or exposure to heavy metals combined with drought, to name a few.

When considering various combinations, it can be difficult to anticipate their effect, as each crop, depending on location, soil type, water needs, and climatic preference can respond differently when exposed to varied stressors. However, this is an important concept to further explore, because with greater understanding of a plant's response to these stressors, more actions can be taken in order to prevent these negative effects, as well as develop crop resistance to specific stressors through plant breeding and genetics. When stress occurs on a plant via one of these named factors, the plant is forced to evolve their homeostasis, or their regulated internal environment that manages the flow of water and nutrients through the body of the plant that works to maintain the plant's temperature and mineral content. During a drought, plants will close their stomata to prevent water loss; however, with exposure to heat, they will open them to increase transpiration and leaf cooling (Rivero et al., 2021). The greatest concern when considering stress combination is that one stressor may elicit a response from a plant that opposes another stressor's, leaving the plant more vulnerable and unable to adapt.

Two important processes that are affected by stress combination are photosynthesis and water- and nutrient-use efficiency. When under abiotic stress combination, "photosynthetic efficiency and transpiration rates decrease under conditions of water-deficit, salt, and/or heat stresses occurring together (Perdomo et al., 2017). Drought and heat lend itself to a significant reduction in photosynthetic activity, evident in experiments conducted for soybeans, lentils, chickpea, tomato, maize, and wheat (Rivero et al., 2021). Interestingly, in the case of tomatoes, when exposed to a "combination of salt and heat stress, tomatoes prioritize heat stress responses over salinity responses, essentially making the effect similar to just that of heat, and the opening of stomata during this stress combination allowed plants to increase CO_2 assimilation rates and improved the overall stress response (Colmenero-Flores and Rosales, 2014; Rivero et al., 2021). This is encouraging when considering how other plants may respond to combination stress and the potential adaptations possible in a changing climate.

b. Impacts to Growth: Reduced Yields and Shorter Plant Life

When plants experience stress whether from drought, flooding, nutrient deficiencies, or increased exposure to pests, they are less productive as they are forced to allocate their resources towards adapting to the given environment rather than producing fruits, resulting in reduced yields and crop quality, shorter plant life, and are overall more difficult to manage. This section reviews how different climatic conditions can influence the crop cultivation process and ultimately how the increased frequency of these events influences crop production over an extended period of time.

The “driving mechanisms of crop yield change” include elevated carbon dioxide levels, water availability, high temperatures, and heat and frost stress (Rezaei et al., 2023). Increases in carbon dioxide influence photosynthesis by actually increasing photosynthetic productivity while reducing photorespiration, as described in Section I of Chapter 2. Again, variation in CO_2 levels has a greater effect on C3 crops like wheat and rice than C4, like millet and sorghum, due to C3 crops having a singular utilization of granal chloroplasts for photosynthesis. “Stomatal conductance decreases under elevated CO_2, thus enhancing transpiration efficiency and minimizing water loss through the stomata for both photosynthesis types” (Rezaei et al., 2023). Although considered a positive phenomenon, in the long term, this is not a sustainable mechanism of action.

In terms of the impact of water availability, outcomes can vary depending on the crop’s water requirements as well as if the crop is undergoing irrigation events or is simply reliant on precipitation. Temperature plays an important role in water availability, as it influences evaporation and transpiration rates, or how much water is readily available to be taken up by the plant. Water availability or lack thereof can have many repercussions on a crop system, beginning with the delay of seed germination, perpetuating lower crop yields before fruit development even begins (Rezaei et al., 2023). Additionally, when experiencing drought-related stress, plants are subject to lesser leaves and reduced photosynthesis due to stomatal closure (Rezaei et al., 2023). This means that one of the key enzymes that collects CO_2 during photosynthesis can become damaged under drought conditions, as well as the thylakoid membranes, or the structures within chloroplasts that are the site of light energy being transformed into chemical energy. This damage can greatly reduce photosynthetic rates, perpetuating lower yields and smaller fruit size.

More frequent high temperature events can affect the productivity and lifespan of crops due to several different factors. In many cases, high temperatures can result in shorter active growing periods of plants, thus shortening their life span. Development rates of fruits can be accelerated, triggered by warmer than average temperatures, signaling the plant to expedite growth. On the other hand, longer warm seasons can also extend plant life through delayed frost conditions, which are also unfavorable to many spring and summer annual crops, or crops with one growing season. However, extended periods of high temperatures require a greater amount of water and if this demand is not met, drought stress will persist, leading to yield loss due to “reduced pollen grain number due to pollen sterility, grain abortion, reduced assimilate transport to grains and accelerated leaf senescence,” or leaf death (Rezaei et al., 2023). In high temperature settings, photorespiration increases and photosynthesis decreases, and roots are vulnerable to heat, as it can interrupt water and nutrient uptake to the plant, resulting in more yield losses (Rezaei et al., 2023).

To summarize, the yield response to these individual drivers will vary for some C3 and C4 crops and is dependent on the duration and intensity of elevated carbon dioxide levels, water availability, high temperatures, and heat and frost stress. For example, a literature review conducted by Rezaei et al. (2023) demonstrated that "wheat yield is least affected by drought when stress intensity is comparable, with maize having a much greater sensitivity to drought stress." Rezaei's synthesis of the findings are depicted below in Figure 5. In terms of excess water, a combination of multiple field experiments revealed that millet had the greatest sensitivity to waterlogging conditions, followed by sorghum, maize, and wheat. Again, this can be influenced by the duration of unfavorable conditions, along with the maturity of the crop. Figure 6 below pictures the Waterlogging-driven yield changes compiled from multiple datasets (Rezaei et al., 2023). Lastly, the yield versus seasonal mean temperature pictured in Figure 7 exhibited a clear negative correlation between increasing temperatures and measured yields. Again, this is crop specific, and particularly important during the developmental phase known as anthesis, when the flower bud on a plant begins to open and when it is fully functional for pollination (Rezaei et al., 2023).

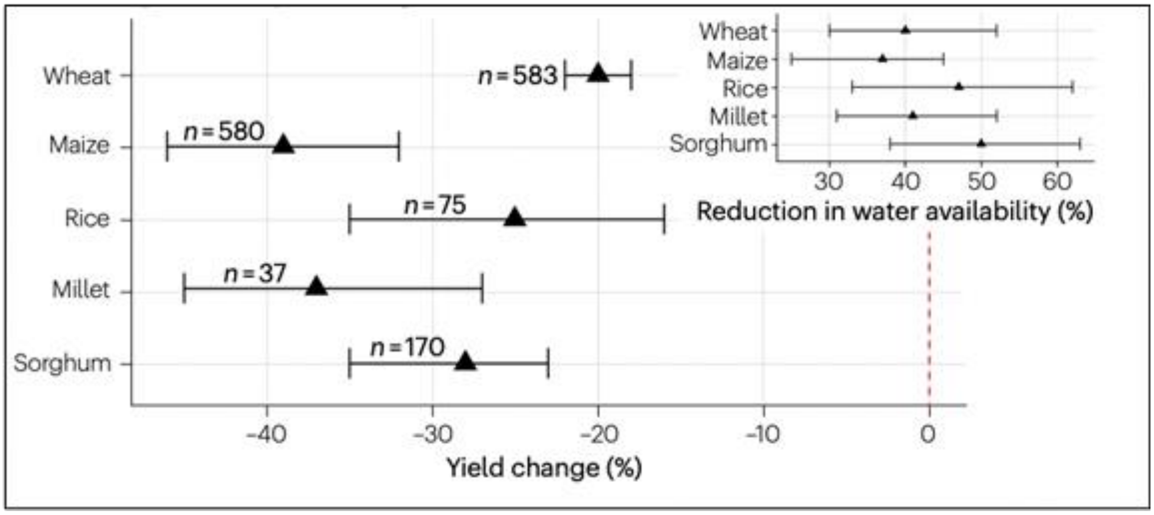


Figure 5. Drought-driven yield changes in wheat, maize, rice, millet, and sorghum (from Rezaei et al., 2023).

Figure 5 illustrates "n=" for each of the crops, meaning the number of drought experimental studies that were included for each crop, with the triangle representing the average yield change because of drought. The horizontal line for each crop shows the range of results from the included experiments. Maize experienced on average roughly a -40% yield change, with wheat experiencing the least at roughly -20% yield change. The top right graphic illustrates the reduction in water availability for each of the crops, with sorghum experiencing the greatest reduction, on average at roughly 50% and maize experiencing the least, at roughly 36%.

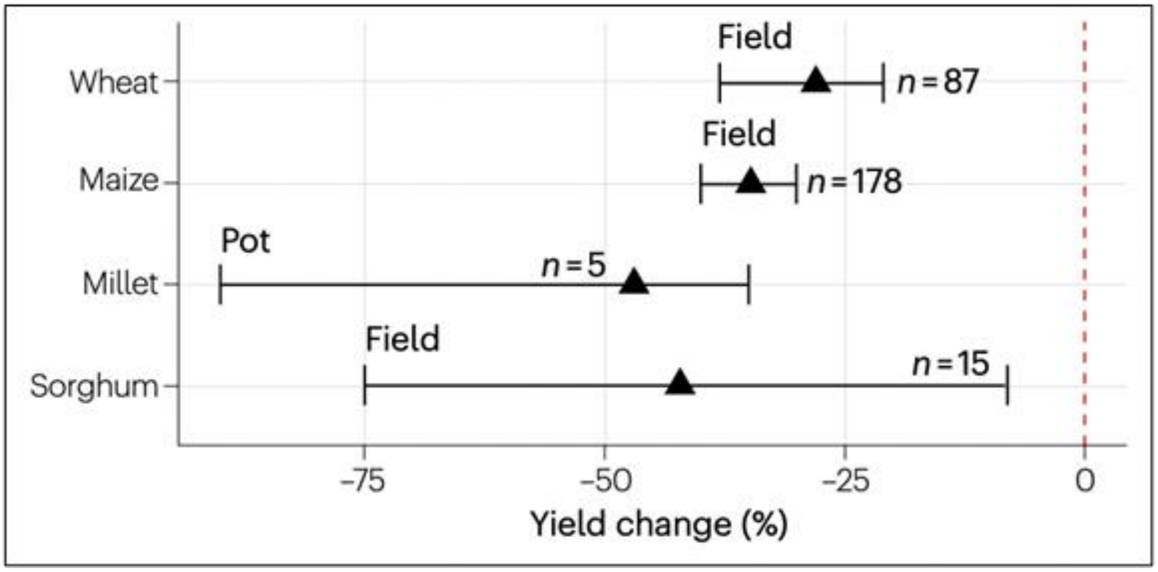


Figure 6. Waterlogging-driven yield changes in wheat, maize, millet, and sorghum (from Rezaei et al., 2023).

Figure 6 illustrates "n=" for each of the crops, meaning the number of waterlogging experimental studies that were included for each crop, with the triangle representing the average yield change due to the effects of waterlogging. Also indicated above is whether the crop was grown in the field or a pot in the included experiments. In this case, millet experienced the greatest negative percent yield change, at on average roughly -50% and wheat experienced the least negative percent yield change at roughly -25%.

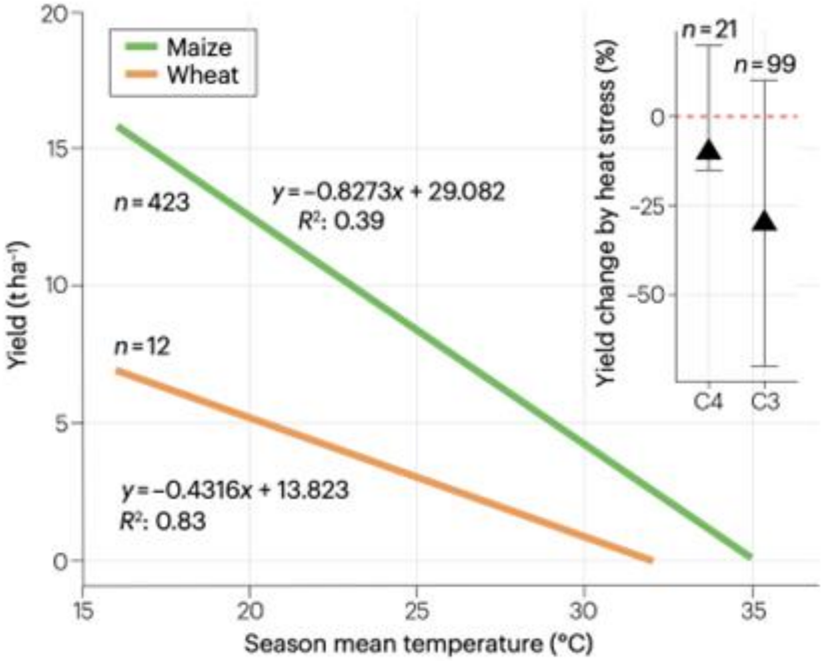


Figure 7. Yield versus seasonal mean temperature of maize and wheat (from Rezaei et al., 2023).

Figure 7 illustrates the crop yield versus seasonal mean temperatures of maize and wheat, the green line representing maize, and the orange line representing wheat. "N=" represents the amount of sample experiments used for each crop represented in the figure. In the case of maize and wheat, both experienced significant decline in yields with increases in the season mean temperature, with maize experiencing its greatest decline at 35°C and wheat's at roughly 32°C Celsius. For every 1°C increase, maize experienced a decrease in yield of roughly 0.83 tons per hectare, and wheat experienced a decrease in yield by roughly 0.43 t/ha. The top right corner illustrates the yield changes by percent of heat stress of C4 plants, such as maize and C3 plants, such as wheat. C4 crops experienced a smaller yield decline on average than C3 crops, indicating C4 plant's higher tolerance to heat stress.

CHAPTER 3: Climate Change's Influence on the Cost and Accessibility to Food

I. Economic and Social Repercussions to Agriculture

In discussion of how climate change has influenced crop yields and the cultivation process, it is important to consider how this affects the cost of food and access to it for the public. Because climate change reduces crop yields, and requires in some cases, supplemental watering events due to drought and additional disease prevention methods due to increased susceptibility, increased labor is needed as a response in many instances. Ultimately, the effect of reduced yields and increased labor use trickles down to the distribution of crops from farms to grocery stores. Chapter 3 will provide an overview of how climate change can influence the cost of food and accessibility to food by consumers. When crops become more difficult to cultivate due to environmental conditions, more money is required to pour into resources to mitigate these challenges. As the cost of agriculture increases, along with the labor necessary to put it into practice, this influences the costs associated with harvesting, cleaning, transporting, and ultimately selling the crops as marketable commodities.

A study conducted by Bandara and Cai (2014) estimated food production by 2030 "will experience declines of 4%, 11%, and 7% for rice, wheat, and cereal grains from climate-change induced land productivity change compared with the baseline of food production (Sahoo et al., 2024). The factors, or stressors that can ultimately influence the cost of groceries include temperature, droughts, floods, pests and disease, erosion, as well as extreme weather events which were discussed in greater detail in Chapter 2. Unanticipated changes in temperature can lead to reduced yield outputs and unexpected extreme weather events, such as hurricanes, can have massive repercussions on a growing season and can devastate a farmer's livelihood instantaneously. Droughts are a major source of increased costs for farmers and require advanced irrigation systems as a supplement to the lack of regular precipitation. Increased flooding events can lead to loss of the topsoil layer, a feature critical for delivering important nutrients to crops. Flooding can also excessively saturate the entire soil composition, leading to root suffocation and erosion of land. This cascade of events can quickly become an issue of longevity for a field's capacity to adequately grow crops in successive seasons due to soil fertility deterioration. Pests and disease create another financial stressor, as increased frequency of pesticide prevention treatments are needed to avoid infestation of crops (Sahoo et al., 2024).

Another consideration when looking at climate change's toll on agriculture is the impact on agricultural workers. Agricultural workers already face potentially harmful exposure to the elements and workplace conditions and, when coupled with the impacts from climate change, they experience greater possibility of harm on the job. Increased temperatures put workers at risk for afflictions such as heat stroke or heat exhaustion (US EPA, 2025b). With an increase in disease and pest control, exposure to pesticides also poses a greater risk. Injuries of this nature can be as minor as a skin irritant or as drastic as chemical burns, or long-term illness due to chronic inhalation of potentially harmful chemicals. Increased exposure to pests such as mosquitoes and ticks can also lead to potential injury and illness (US EPA, 2025b). Rosenbloom (2022) reported that 86 percent of agricultural workers in the United States are foreign born and that 45 percent of all US agricultural workers are undocumented. This lends itself to greater risk of injury due to a potential language incompatibility that could lead to miscommunication of safety concerns. Table 1 represents the distribution of English language proficiency for undocumented agricultural workers and highlights the increased risk of harm due to potential miscommunication in the workplace. Forty-two percent of recorded workers do not speak English while 34 percent do, but not well. Nine percent are reported as speaking English very well and an even smaller percentage of 4 percent only speak English. With the increased risk of injury on the job due to the impacts of climate change, worker safety and protection could not be more critical.

Table 1. English language proficiency distribution of undocumented agricultural workers (2021) (reproduced from Table 2 of Rosenbloom, 2022).

English Proficiency	Total	Percent
Doesn't speak English	117,800	42%
Yes, but not well	95,900	34%
Yes, speaks well	34,600	12%
Yes, speaks very well	24,200	9%
Yest, speaks only English	10,500	4%

I. Notes: Numbers are rounded to the nearest hundreds.
II. Percentages may not add up to 100 due to rounding.

In addition to the risks associated with foreign-born farm workers, marginalized communities and black, indigenous, people of color also face the risk of food insecurity due to the effects of climate change. In 2023, 13.5 percent or 18 million households in the United States were estimated to be food insecure (US EPA, 2025b). Meaning, these households did not have the resources available to provide enough food in their home to adequately feed all their family members. The EPA (2025b) wrote that "U.S. households with above-average food insecurity include those with an income below the poverty threshold, those headed by a single woman, and those with Black or Hispanic owners and lessees." In African countries such as Ethiopia, people are at risk of food insecurity and increased poverty due to their reliance on rainfall and temperatures amenable to growing adequate food supply (Mekonnen et al., 2021). Warming in Africa is predicted to exceed the global annual mean, with an increase of 3 to 4 degrees Celsius over the next century" and with that crop yields will reduce, and the cost of food will increase significantly (Mekonnen et al., 2021). Developing countries will face the brunt of food insecurity due to their heavy reliance on agriculture for their economy and sufficiency. More specifically, the study performed by Mekonnen et al. (2021) surveyed households in Ethiopia on their "calculated household available energy," or essentially the number of calories consumed per adult per day and compared it with the minimum required kcals of 2200. Of the 185 surveyed households, 112 (61%) were consuming less than the recommended number of kcals per day. As the effects of climate change persist and possibly worsen, there will be increases in global food insecurity.

II. Agricultural Supply Chain Effects

The agricultural supply chain, meaning the network that is required to take harvested crops and process, pack, transport, and deliver them to consumers, can be influenced by many environmental factors that would upset the overall process flow. This sub-section details how climate change can impair these processes and negatively impact food security, and more specifically, affect nutrition. It has been estimated with every 1°C increase in temperature, and in the absence of having genetic improvements to crops and CO_2 fertilization, yields of wheat, rice, maize, and soybean are at risk of declining by 6 percent, 3.2 percent, 7.4 percent, and 3.1 percent respectively (Ahmed et al., 2023). It is important to note that agriculture itself contributes in a large way to climate change because it requires an ever-increasing amount of land and resources due to soil depletion. Starting from the farm, methane, the greenhouse gas emitted from degradation of cattle manure, contributes to a significant release of methane (i.e., a greenhouse gas) into the atmosphere. Agricultural systems as a whole are responsible for roughly 30% of global anthropogenic greenhouse gas emissions when considering emissions from livestock, land use, and water usage (Bačėninaitė et al., 2022). Needing to grow more crops requires more land, which leads to increased clear-cutting forests to be repurposed as agricultural land. Water use would also coincidently increase, in addition to increases expected with climate change alone, as more irrigation events are required due to drought and increased global temperatures. The water footprint of agriculture, or the "volume of water needed for the production of goods and services consumed by the inhabitants of a country," is using roughly 70% of available freshwater towards irrigation events (Ahmed et al., 2023).

With an increasing global population, the pressure to feed the world is greater than ever, and in order to do so sustainably, management of earth's natural resources is critical. This includes the implementation of sustainable growing practices and water usage that mitigate the impacts of climate change.

Figure 9 displays the "cascading effects of climate change on food security and nutrition" (Ahmed et al., 2023). When considering the multi-faceted impact climate change has on agriculture and food security, the results can be manifested in many other agricultural sectors, such as food harvest, distribution, prices, quality, and accessibility. The process flow begins with examining different environmental factors that are influenced by climate change, such as land degradation, temperature, and precipitation. These factors, when disturbed, can affect important agricultural necessities, such as water availability, pesticide use, plant disease, and livestock cultivation. The adjustments needed to correct for climate change, such as increased pesticide applications or irrigation events to offset the effect from increases in temperature, require additional financial resources and ultimately would have repercussions to local economies. As yielding the same quality and quantity of food becomes a challenge, costs will increase as food availability decreases. Effectively, this is how climate influencers sequentially trickle down into the food system. More specifically, access to high quality and nutritious foods has become an inaccessible commodity for many. Without having the financial resources to keep up with increased costs for food items, consumers will turn to cheaper, less nutritionally dense options.

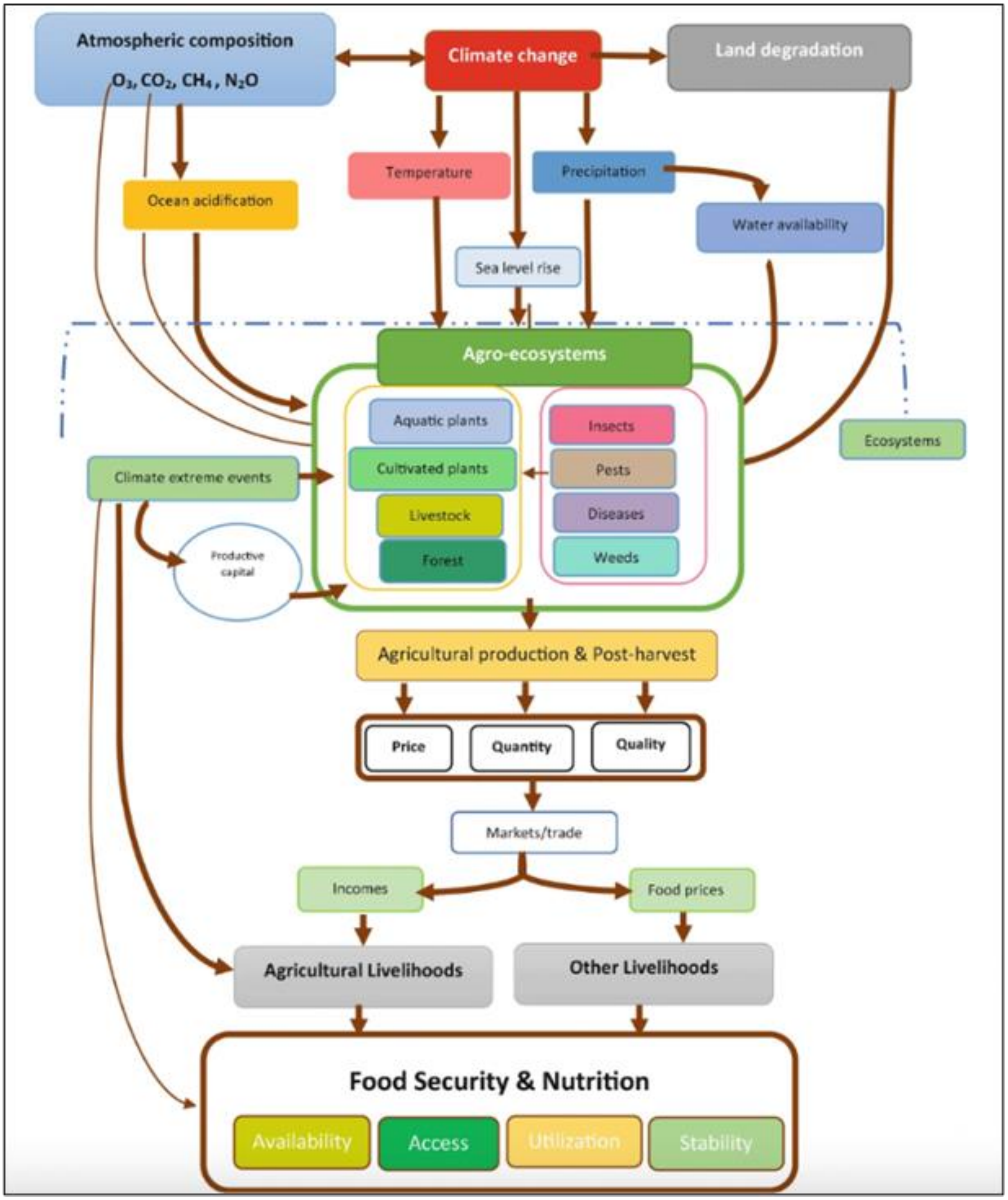


Figure 9. **The cascading effects of climate change on food security and nutrition (from Ahmed et al., 2023).**

III. Transportation and Storage of Foodstuffs

When considering the actual transportation of foodstuffs, climate change can affect the delivery of them in a multitude of ways due to complications during travel. In many instances, foodstuffs can be transported hundreds or thousands of miles from farms to grocery aisles. As a result of these long distances and extreme weather conditions, timely deliveries of foodstuffs can be affected. For example, the United States Department of Agriculture (USDA) reported that "approximately 30% of food in the U.S. is wasted each year, with significant losses occurring during transportation due to spoilage, damage, or inefficiencies in the supply chain (USDA, 2020). Further, if there are extreme weather events such as a hurricane or snowstorm, transportation systems (i.e., roads and railways) can be blocked or damaged, necessitating alternate routes be taken in order to reach the desired destination (Sahoo et al., 2024). These alternate routes often impose further delays beyond original transportation distances, which can result in spoiled goods, leading to excess food waste and an increase in resources spent on transportation. This would lead to an increase of prices at the point of sale due to the additional costs associated with extra delivery expenses.

In addition to the transportation of foodstuffs, their preservation is a critical component to ensure goods are fresh and retain an adequate expiration date from the time they are harvested to the time they are shelved. Climate change can affect this component of food availability, particularly when it comes to cool storage. With increasing temperatures, more energy is needed to keep foods chilled and to preserve food quality and safety, leading to greater refrigeration costs (Sahoo et al., 2024). This is especially critical for fruits, vegetables, dairy, and meat which all run the risk of spoiling more rapidly when compared to dry goods such as wheat or coffee. As global temperatures continue to increase, more energy and possibly equipment maintenance are required to maintain food freshness during transportation.

IV. Strategies for Mitigating Negative Impacts

There are many options for minimizing the impact climate change has on agriculture as well as the cascading effects it can have on humans. Many of these tactics have been explored and implemented around the world, many of which have had positive results, however, global participation to incorporate climate change mitigation strategies into policy actions is necessary to achieve effective and long-lasting change.

Climate–Smart Agriculture

Climate-Smart Agriculture (CSA) is defined as "an integrated approach to managing landscapes - croplands, livestock, forests and fisheries - that address the interlinked challenges of food security and climate change" (World Bank Group, 2024). The global production of food via agriculture is responsible for emitting one-third of methane emissions and will only increase with demand as the population grows. With increased agriculture, there is decreased biodiversity through actions such as clear-cutting forests and repurposed land for crop cultivation. In addition to utilization of land for agriculture, an increase in consumption of fresh water or irrigation to support crop growth is a concern. With global agriculture consuming roughly 70% of fresh water, strategic irrigation, timed with predicted droughts or flooding events, is necessary to minimize water waste (World Bank Group, 2024).

CSA prioritizes both increased agricultural productivity and the reduction of greenhouse gas emissions. By focusing on how climate change adaptation and mitigation measures can be integrated into the agricultural system, three goals are yielded: increased productivity, enhanced resilience, and reduced emissions (World Bank Group, 2024).

The World Bank Group, an international institution that extends grants and loans to developing countries, with the goal of enhancing economic development, has supported many countries, such as Kenya, Malawi, China, and Somalia in implementing CSA actions. The World Bank developed a Climate Change Action Plan (2021-2025), where they highlighted agriculture, food, water, and land as key resources to address to achieve the goals of the Paris Agreement, which aims to limit global temperature increase to below 2 degrees Celsius. CSA Country Profiles have been developed to gain a better understanding of what needs the country has in order to progress in a sustainable and positive way. In addition, the organization has extended multiple millions of dollar loans and established several programs, such as the China Green Agricultural and Rural Revitalization Program for Results, which operates to promote economic and agricultural development in rural areas. If these priorities were implemented into agricultural policy, a much greater and unified global effort towards practicing sustainable agriculture in order to minimize the environmental impact of greenhouse gas emissions could take place.

Agro-Climatic Advisory Services (AAS)

The Agro-Climate Advisory Platform (ACAP) is a center in the Bicol Region in the Philippines that is devoted to developing Climate Information Services, such as weather and climate data sourced from the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) that can be disseminated for use across the area (Alliance Bioversity and International Center for Tropical Agriculture). The goal of this organization is to improve farmers' access to climate services, or climate data, such as information on precipitation and temperature that can be used to their advantage in order to plant at the most strategic time.

ACAP is an agriculture platform that uses bulletins and text message alerts to reach farmers with current, and up-to-date information with combined "climate and agricultural insights with timely, weather-adjusted recommendations" for farming (Alliance Bioversity and International Center for Tropical Agriculture). Currently, the program supports two areas in the Philippines, aiding these areas to more effectively produce rice, corn, and cassava (i.e., all major food crops in these two areas) with the help of this information. The platform plans to expand to more provinces, with the goal of supporting roughly 320,000 farmers and fisherfolk as a whole.

The goals of ACAP represent an excellent example of putting agriculture practices that prioritize reducing resource waste that can result from the unanticipated effects of climate change. A customizable program established in different countries and cities globally, catering to different climate-related geographical concerns could have a major impact on minimizing wasted resources, developing intentional planning and harvest schedule, and maximizing yields in a way that avoids climate-related pest issues. With this goal, the priority is financing the development and implementation of these programs. As discussed previously, organizations like the World Bank provide the means to countries to put these plans into action. An emphasis on developing and low-income countries must be maintained, as these countries will require financial support from that of developed countries in order to gain the greatest investment from adopting the CSA platform.

In addition to these broader, collective strategies, action can also be taken on a more local level to help reduce harm to the environment created by humans. This includes being intentional about when fertilizer applications take place, in order to reduce runoff of harmful chemicals into the water supply that can negatively impact water quality as well as surrounding ecosystems. When fertilizer applications take place, nitrogen and phosphorus can run off due to rain or snow fall and these chemicals can build up in the soil and leach into groundwater, leading to potential algal blooms. In addition, this can lead to the exposure of harmful chemicals to humans and wildlife by consuming water that has been infiltrated by pesticide runoff. Monitoring weather and integrating this information into pesticide application scheduling can assist in reducing the risk of runoff and supporting the health of the environment as well as minimizing financial resources spent on environmental cleanup efforts.

Plant breeding is another ongoing effort that helps different crops evolve with climate change. Different cultivars of plant species, such as different types of tomatoes, can be cross-pollinated and bred together to generate cultivars that share favorable traits from each parent plant. This can include traits such as disease resistance, high fruit yield, favorable fruit size, and heat resistance; all ideal traits for crops exposed to the effects of climate change. For example, this work is performed at North Carolina State University’s Mountain Horticultural Crop Research and Extension Center (MHCREC). Their fresh market tomato breeding program emphasizes “combining early and late blight resistance, Fusarium wilt race 3, a virulent plant pathogen, and tomato spotted wilt virus resistance into superior tomato breeding lines and hybrids” (Konsler, 2025).

Lastly, on an individual level, with the cost of food increasing and crop yields declining, reducing food waste is critical to minimize financial strain to the public on food expenses as well as preserving and utilizing the crops that were successfully cultivated and distributed to the public. With that being said, an important distinction in terminology is the difference between “food loss” and “food waste,” the former which refers to “losses occurring upstream in the food supply chain, mainly during planting, cultivation, harvesting, processing, storage and first agricultural processing, losses usually caused by the inefficiencies of the supply chain” (Pilone et al., 2023). The latter refers to instances where “any wholesome, edible substance that is wasted, lost, degraded, or consumed by pests at any stage of the agrifood supply chain, instead of being intended for human consumption” (Pilone et al., 2023).

Food waste is an ongoing issue, particularly at a household level. It was reported that in 2021, “1.3 billion tonnes of food were lost or wasted with one third of food produced for consumption lost, 42 percent of which households were responsible for” (Pilone et al., 2023). As the global population continues to increase with an estimated world population of 9.6 billion people by 2050, mindful consumption and conservation of purchased foods is critical to minimize food waste (Pilone et al., 2023). Household members going to the grocery store must shop thoughtfully in order to contribute to the preservation of food. The strategies reviewed in this section all perpetuate a system of lesser waste.

CHAPTER 4: Methods and Conclusions

I. Methods and Limitations

The goal of this literature review was to seek out publications and studies that provided background information and evidence of climate change's implication on agriculture and food security. Once the topic was developed and the subject of each chapter of this review was determined, the next steps were to identify resources that could support the specific discussion.

The methods for developing the execution of the search began with generating a list of terms for use on finding data relevant to climate change, climate change's association with extreme weather events, how weather affects agriculture, and how reduced crop yields influence the cost of food production and distribution. Once a list of search terms were compiled, the author used PubMed as the primary search engine for seeking relevant peer-reviewed sources. Identified sources were then screened by reviewing their abstracts to ascertain their relevancy to the particular topic. To conclude whether a source was useful or not for inclusion in the review, key items such as publication date within a recent time, roughly the past five years, were considered. If the source provided relevant data from a model or field study, the use of their results to further correlate climate impacts to agriculture and food security was also considered. Additional sources were sought when gaps in information were identified. Resources such as the IPCC Sixth Assessment Report (2022) and reports from the EPA were referenced for their up-to-date data reports and relevancy to the topic area of interest.

Table 2. Literature review search terms and number of papers generated.

Search Term	**Number of Paper Selected**
Climate change and agriculture	20
Soil erosion	3
Plant disease	4
Pests	4
Flooding and drought	8
Climate robust event attribution	3
Global food security	5
Climate-Smart Agriculture	2
Household food waste	2
Plant Growth Promoting Rhizobacteria	5

The limitations of this assessment included the inability of some historical models to accurately predict future weather patterns, as more advanced technology is being developed to aid in the understanding of the anthropogenic role in climate change as well as predicting extreme weather events. Additionally, there are a multitude of financial limitations that counter the goals of achieving global food security and maintaining sufficient crop yields to feed the growing population. The mitigation and adaptation methods reviewed in this assessment are ideal for achieving these goals; however, their implementation is expected to be timely and costly, nonetheless.

II. Future Considerations using Plant Growth Promoting Rhizobacteria (PGPR)

Many environmental factors that contribute to the overall well-being of a plant and its capacity to maintain homeostasis were discussed in this review. The two primary abiotic factors that influence a crop's success are temperature and rainfall, as examined through the use of Robust Event Attribution in Chapter 1. With an increase in global temperatures and less reliable precipitation patterns, crops are now more than ever susceptible to drought and drought stress. When plants experience drought stress, there is stomatal closure, reduced water uptake, and plant hormone disruption, all of which contribute to reduced growth rates (Buragohain et al., 2024).

When considering future methods in order to mitigate impacts from drought, the use of plant growth-promoting rhizobacteria (PGPR) during crop production provides hopeful results. As plants experience drought stress, this impacts different genes inside the plant that influence the plant's response by either evading, enduring, or preventing the unwanted effects of drought (Buragohain et al., 2024). PGPR has the ability to aid plants with "osmotic adjustments, antioxidant activity, and phytohormone production, not only ensuring the plant's survival during drought conditions but also enhancing its overall growth" (Buragohain et al., 2024). As discussed in Chapter 2's subsection of Erosion: Physical and Chemical, soil composition is critical to the plant's success. The composition refers to the size of the particles of soil that keep a plant rooted, the moisture content, along with the mineral and microorganism components of the soil. Soil microbes, such as different types of bacteria, protozoa, and fungi exist in the soil rhizosphere; the small layer of soil surrounding a plant's roots. Rhizobacteria, a commonly present microbe, is largely dependent on that of root exudates, or the sugars and amino acids released from plant roots (Buragohain et al., 2024). One of the species of this bacteria includes PGPR, which plant roots can be colonized by and has shown to "improve soil fertility, encourage plant growth and development, and increase the production of crops" (Buragohain et al., 2024).

Buragohain et al. (2024) discuss several strategies for employing PGPR into crop production and the benefits of doing so. Although extremely impactful on plant growth, microbes can also undergo the effects of drought, osmotic stress, or the loss of water from their cells and damage to their DNA. The shape of their proteins can change, their enzymes become less effective, and their energy sources are depleted. This can result in the generation of free radicals, a type of molecule that has the capacity to destroy proteins and fats, as well as induce cell lysis or cell bursting. However, PGPRs have the ability to aid plant growth through these challenges by producing essential tools, such as osmolytes which prevent cells from drying out, antioxidants, plant hormones that assist with root growth, extracellular polymeric substances that coats the roots of the plant and bacteria to hold water, and can even have the ability to modify a plant's roots to increase water uptake (Buragohain et al., 2024). Due to these capabilities, PGPRs are able to better fortify themselves against drought through these measures.

Buragohain et al. (2024) generated a table that reported the effects of different strains of PGPR with several different host plants. Table 3 shows a sample of the table along with some of the observed effects of the PGPR application. Firstly, the PGPR *Paenibacillus polymyxa* was applied to the soil of an *Arabidopsis thaliania*, or a Thale cress plant and resulted in "resistance and tolerance to drought stress by increasing gene expression associated with abiotic stress" (Ngumbi and Kloepper, 2016). *Phyllobacterium brassicacearum* was applied to the Thale cress plant as well and Bresson et al. (2013) found that there were symbiotic changes in transpiration, photosynthesis, and abscisic acid (ABA); a plant hormone that regulates growth and stress response, and that this led to a greater water-use efficiency. When *Asospirillum brasilense* sp. was applied to the Thale cress plant, Cohen et al. (2014) noted that there was an increase in photosynthetic pigments, ABA, proline, an amino acid useful in building proteins, and lipid peroxidation, which is the occurrence of oxidative damage to lipids. However, the greater concentration of proline available can help offset this effect. Lastly, *Bacillus cereus, Bacillus subtilis*, *Serratia* sp. was applied to the *Cucumis sativa*, more commonly known as the cucumber and resulted in an "increase in chlorophyll content which lessened wilting brought on by the production of scavenging enzymes, and improved root morphology" (Wang et al., 2012).

Table 3. Examples of plant growth-promoting rhizobacteria (PGPR) used to reduce the effects of drought stress (modified from Table 1 of Buragohain et al., 2024).

Sl no.	**PGPR**	**Host Plant**	**Effects of PGPR**
1	*Paenibacillus polymyxa*	*Arabidopsis thaliana*	Resistance and tolerance to drought stress by increasing gene expression associated with abiotic stress
2	*Phyllobacterium brassicacearum*	*Arabidopsis thaliana*	The coordinated changes in transpiration, photosynthesis, and ABA content result in higher water-use efficiency
3	*Azospirillum brasilense* sp.	*Arabidopsis thaliana*	Increase in photosynthetic pigments, ABA, proline, and lipid peroxidation
4	*Bacillus cereus, Bacillus subtilis, Serratia* sp.	*Cucumis sativa*	Increase in chlorophyll content lessened wilting brought on by the production of scavenging enzymes, and improved root morphology

In conclusion, the use of PGPRs have proven to be an effective and useful method for reducing the effects of drought stress on plants and should be further considered and explored as a mitigation strategy for navigating increases in global temperatures and decreases in consistent precipitation that have led to greater instances of drought. This is both an environmentally safe and sustainable mechanism of action.

III. Summary of Key Findings and Conclusions

The goal of this literature review was to assess and discuss the effects climate change has on agriculture, food production, and food security. This discussion begins with explaining how climate change influences the frequency of extreme weather events, that in turn take a toll on agricultural production. Through the development of Event Attribution as a technique for associating the likelihood of extreme weather via precipitation or temperature as a result of anthropogenic forces, scientists have been able to gain a greater understanding on the influence humans have on climate change, and in turn this data can be used to generate alternative adaptation and mitigation strategies for navigating a changing climate. Both Observed and Modeled Temperature Changes and Observed and Modeled Rainfall Distribution models allow for the exploration and understanding of how anthropogenic influences can potentially impact long-term frequencies of precipitation patterns and temperature changes. Through the use of these models and others, it was found that "human influence caused more than half of the observed increase in global mean surface temperature from 1951 to 2010" (IPCC, 2022). Greenhouse gases and aerosols as a result of human activity, as well as combined human and natural causes, and natural causes were assessed when evaluating temperature changes from 1850 to 2020 and revealed that the increases in temperature that have occurred would not be possible without the contribution of human activities. The United States Environmental Protection Agency (EPA) also reported on a breakdown of Total U.S. Greenhouse Gas Emissions by the four economic sectors: agriculture, industry, residential/commercial, and transportation in 2022, with residential and commercial emissions in the lead, responsible for 31 percent of emissions in the country.

Chapter 2 served as an opportunity to explore the impact of frequent extreme weather events on agriculture by discussing the many stressors that influence the success of crop production. These included drought and flooding, plant pathogens and disease, pests, and both physical and chemical erosion. In addition, stress combination, or the effect of multiple stressors on the success of crop growth was reviewed, along with their repercussions which primarily consist of shorter plant life and reduced crop yields. Instances of drought have been on the rise, in conjunction with increases in global temperatures, resulting in longer warm seasons in many cases. Drought, related to a plant's deprivation of water, can be a major stressor on all developmental stages of plant growth, particularly seed germination. Lack of water can delay or halt germination, causing reduced yields on the front end of crop production. Flooding's greatest threat is to the crop's soil composition, as it can lead to degradation and dissemination of nutrients and soil texture. In addition, when plant's root systems are inundated with water, roots lack access to oxygen, ultimately resulting in plant senescence. Regarding plant pathogens and disease, increases in global temperature have led to an increase in the presence of both. The impact of increases in temperature on pathogens and pests include increased geographic range, more instances of plant disease outbreak on varying plant species, an increase in their overwintering survival, and therefore, implicate these pests' relationship with their natural enemies or predators (Skendžić et al., 2021). Pests and pathogens can cause damage to a plant's anatomy, particularly their terminal growth plant parts; or the tips of the plant's leaves where new growth occurs, in the case of aphids. This causes stunted growth, imperfect fruits, or unmarketable fruits, drastically reducing yields and crop quality. As pest and pathogen occurrence increases, so does crop susceptibility to disease and various deformities. Increased frequency of pesticide applications will be necessary to combat these undesirable effects, as well as the modification of pesticide applications and active ingredients in order to effectively combat evolving pest and disease populations. Erosion, both physical and chemical via wind or, specifically water, can have lasting ramifications on soil composition and can harm future growing seasons due to degradation of soil properties, such as nutrients like magnesium, phosphorus, iron, and zinc. Soil slaking, when the larger, dry pieces of soil break down into smaller pieces, due to flooding or intense rain events can also increase erosion, creating unstable and loose soil, unsuitable for plant roots to develop in. The combination of multiple stressors existing at once was also considered. Photosynthesis and water- and nutrient-use efficiency are at the greatest deficit when undergoing stress combination. When under abiotic stress combination, “photosynthetic efficiency and transpiration rates decrease under conditions of water-deficit, salt, and/or heat stresses occurring together (Rivero et al., 2021) It is vital to begin further exploring the combination of multiple stressors on crop systems, as the progression of climate change will certainly result in greater instances of stress combination. With all of these factors being considered, the result is reduced crop yields and shorter plant life.

The focus of Chapter 3 was to consider how climate change influences the cost and accessibility of food for the public. As discussed in previous chapters, climate change has taken a large toll on the production of food, as well as the distribution. With unfavorable growing conditions leading to reduced yields and necessitating more advanced growing methods and increases in labor, it has become more expensive to cultivate an adequate number of crops. Particularly in the case of droughts, more irrigation measures have been put in place to adequately water crops. These increases in costs from a growing standpoint then trickle down to the prices of groceries in the store. Growers are expected to experience a decline in several major crops, including rice, wheat, and cereal grains by 2030. Additionally, the changes in the growing process also lend themselves to greater risks for agricultural workers. Increased labor means greater instances of injury to workers in the form of heat exhaustion, exposure to harmful chemicals from pesticide applications, and exposure to harmful pests such as mosquitoes and ticks throughout the workday. A language deficit is also apparent in the agricultural field with a recorded 42 percent of workers not speaking English well in the United States (Rosenbloom, 2022). This deficit can greatly contribute to miscommunications in the workplace, resulting in more injury.

Food insecurity is a growing problem within the United States and globally as the effects of climate change persist. Figure 9 details the cascading effects of climate change on food security and nutrition courtesy of Ahmed et al. (2023). Beginning with the effects of climate change via temperature, sea level rise, precipitation and how this influences water availability for crops and in turn impacts agro-ecosystems, such as livestock and cultivated plants; agricultural production and post-harvest practices are further implicated. Not only is the grow process affected, but the transportation of goods is also at risk due to extreme weather events that require alternate routes to be taken, more gas used, extended refrigeration of perishable goods and more frequently leading to spoiled goods.

Some strategies were examined for mitigating these effects, which include the integration of Climate-Smart Agriculture (CSA), an approach that incorporates climate data into the grow process to help anticipate unfavorable weather conditions, such as anticipated droughts, floods, and storms that might otherwise devastate a growing season. CSA aims to increase agricultural productivity while also reducing the CO_2 emissions generated by agriculture. This methodology has been utilized in many countries at this point, but its benefits would be exponential if it were to be included in global legislation. The Agro-Climate Advisory Platform (ACAP) is a climate-smart initiative that provides increased access to weather data to farmers to aid in their planning for the growing season. On an individual level, conscious application of fertilizer is encouraged to reduce potential runoff of harmful chemicals, as well as conservation of water, and lastly mindful consumption of goods to reduce food waste at a household level.

Overall, this literature review aimed to synthesize the implications that climate change has on agriculture and food security by examining the relationship between both abiotic and biotic factors and plant growth. Additionally, understanding how the overall climate and a decline in crop yields impacts access to food from farms to grocery stores, and how specifically, marginalized and low-income communities experience this deficit to a greater degree. Finally, mitigation and adaptation strategies, such as Climate-Smart Agriculture, plant breeding, minimizing food waste, and the use of plant growth-promoting rhizobacteria were emphasized as ways of sustainably reshaping the way farmers and researchers approach climate change and agriculture simultaneously. Climate change is progressing, and action must be taken to support the longevity of the food supply and access to nutritious foods by the public.

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