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The Future of Agriculture in Georgia Under Climate Change: *A Comprehensive Analysis Using Temperature and Precipitation Data*

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An abstract of

a thesis submitted to the Faculty of Emory College of Arts and Sciences

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Abstract

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Climate change is a complex and interdisciplinary challenge that impacts agricultural systems worldwide, with implications for both cropping patterns and farm labor conditions. This thesis examines how climate change, particularly extreme temperatures (including heat and cold), and variable precipitation affect agricultural systems and farmers in Georgia, United States. Georgia is a unique agricultural state due to its crop diversity as well as its dependence on migrant farm labor through the United States Department of Agriculture (USDA) H-2A program. This research integrates farmer interviews, future climate projections, and a review of existing literature to assess the impact of extreme temperatures and changing precipitation levels on agricultural systems in Georgia. This study finds that extreme temperatures are going to become more unpredictable and intense as climate change worsens, and precipitation levels in the state will become more variable. Both changes will produce challenges and opportunities for Georgia's agricultural industry. This study concludes with potential solutions to inform future farm policy in the state, specifically around climate-smart agricultural practices to move towards an equitable and climate-resilient food system in Georgia.

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1 Introduction

Climate change is having a profound impact on agricultural systems worldwide and will continue to do so in the future. Climate change is formally defined by the United Nations (UN) as "long-term shifts in temperatures and weather patterns" (UN, n.d.). These changes are caused by increased greenhouse gases in the atmosphere, primarily from the burning of fossil fuels like coal, oil, and gas (UN, n.d.). Today, people worldwide are experiencing the impacts of climate change from increases in extreme weather events like flooding and droughts, to reduced agricultural yields, to financial losses from climate disasters. Historically, average temperature has risen worldwide due to climate change caused by increased greenhouse gas (GHG) emissions such as carbon dioxide since the industrial revolution. According to existing literature, average temperatures in the Southeast are also likely to rise in the future which has both negative and positive implications for the agricultural industry. Rising temperatures can have implications for changing the growing season of key crops, causing milder winters and late freezes which in turn affect crop yield and other variables which will be discussed in this paper.

Along with a long-term rise in average temperatures, climate change has caused an increase in the unpredictability and frequency of extreme temperatures (both cold and heat). These changes can manifest as extreme weather events such as freezes, droughts, or tropical storms as well as others. Extreme temperatures will cause irreversible damage to our agricultural systems which are heavily dependent on the climate. Sun, water, air, and soil are the natural factors that affect where and how we grow food. However, several human factors such as farm labor, access to land, and financial barriers have deeper implications on where and how we grow food. Natural factors are being severely impacted by climate change and human factors will also suffer from climate change in different forms which will be discussed in this paper.

Currently, one major concern for agricultural systems is extreme heat which the Federal Emergency Management Agency (FEMA) defines as "a period of high heat and humidity with temperatures above 90 degrees for at least two to three days" (FEMA, n.d.). Extreme heat can also be based on how unusually hot and humid it is for a certain area, meaning that the definition of it varies by place. Therefore, extreme heat can be subjective depending on the location in question. In the Southeastern United States (US), climate change is increasing the frequency and intensity of extreme heat events which have negative implications for Southeastern agricultural systems. Extreme heat is worsening crop productivity, disrupting crop viability, changing pest and pathogen populations, and affecting farm labor health and wellbeing. Similarly, extreme cold is also rising in the Southeastern US with rising unpredictability around winter freezes that can cause agricultural fields to freeze over and kill crops.

Climate change is also causing precipitation to become more unpredictable. There have been changes in average precipitation levels, namely an overall decrease in average precipitation levels in the Southeastern US. Georgia, nonetheless, is an exception to this trend because is said to see an increase in average precipitation in the future (Walthall et al., 2012). An increase in average precipitation levels is likely to affect water and soil quality, cause an increase in flooding, and affect pest and pathogen populations due to increased moisture levels. Furthermore, climate change is causing an increase in extreme precipitation, ranging from extremely dry conditions (where there is a lack of regular rainfall) to extremely wet conditions (where heavy rainfall is abundant). Changing temperatures are linked to changing precipitation levels, specifically concerning extreme heat which can cause a drought by drying up the soil and decreasing the moisture in the air. Agricultural drought occurs when the moisture in the soil reaches a point that is too low for crops to thrive, which has negative impacts on cropping systems. However, during more humid seasons such as the spring and summer, warmer air can mean wetter conditions which can cause flooding and extreme precipitation. These conditions can significantly impact crops by causing an oversaturation of soil and increases in crop disease outbreaks.

1.1 Study Area

The Southeastern US is a highly productive agricultural region that is facing severe impacts due to climate change. Climate change in the Southeast has led to a significant increase in the frequency and intensity of extreme weather events such as floods, droughts, heat waves, cold outbreaks, winter storms, and severe thunderstorms (Ingram et al., 2013). This paper focuses on the state of Georgia, one of the top agricultural producers in the nation. According to Georgia Farm Bureau, the agricultural sector is Georgia's oldest and largest industry. It was valued at $83.6. billion in 2024 (Kane, 2024). The diverse food and fiber crops grown in the state range from row crops like cotton, peanuts, and corn, to fruits and vegetables such as peaches and cucumbers. Nationwide, Georgia procures the most blueberries, peanuts, pecans, spring onions, and (broiler) chickens (Georgia Farm Bureau, n.d.).

Agricultural production within Georgia varies across six different eco-regions, which each have specific bioclimatic characteristics and topographies (see Figure 1). For example, the Southwestern Appalachians are a mountainous region that is well suited for cattle and poultry operations as well as small grains. The Ridge and Valley area is made up of valleys and ridges which makes it less suitable for growing row crops but better for producing food for cattle such as hay (Marable et al., 2023). The Southeastern Plains and Southern Coastal Plains are where most of the state's agricultural production happens and both regions are well diversified. These eco-regions are mainly flat and are comprised of well-draining, sandy soil. This makes the Southeastern part of Georgia suitable for row and forage crop production including cotton, peanuts, blueberries, and Vidalia onions (Marable et al., 2023).

Figure 1

Eco-Regions of Georgia

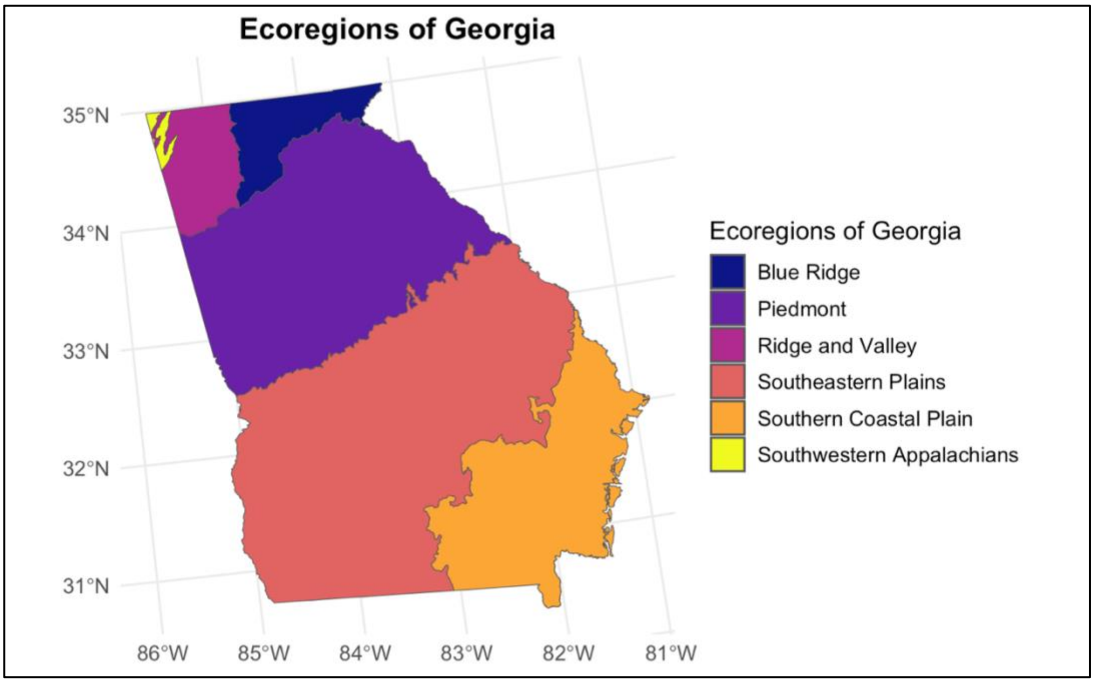
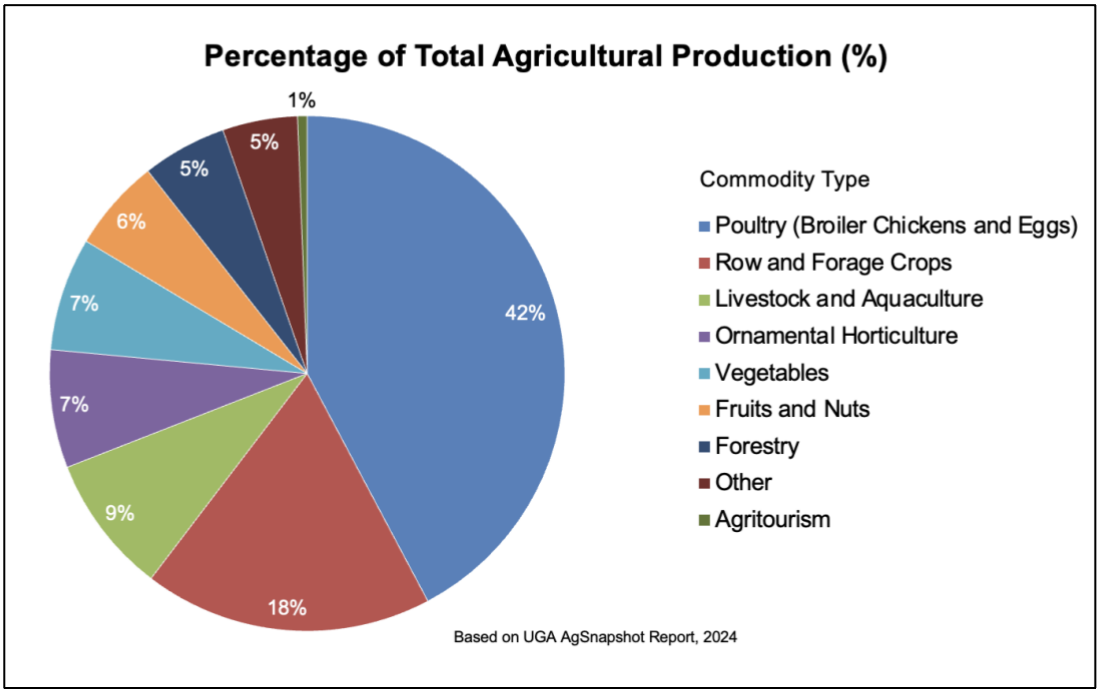


Figure 2

Agricultural Commodities Produced in Georgia



Georgia is an extremely agriculturally diverse state, producing several kinds of agricultural commodities that can be seen in Figure 2. For this paper, the crop focus will be on edible crops such as row crops, fruits and vegetables, and animals used for meat, eggs, and dairy. Ornamental horticulture, forestry, and agritourism will be ignored. The most abundant agricultural commodity produced in the state is poultry (which consists of broiler chickens raised for meat and eggs). Poultry makes up nearly 50% of agricultural production in Georgia, making the state a national leader in poultry production (Kane, 2024). The second most widely produced commodity is row and forage crops which make up 18% of production. Row and forage crops consist of cotton, peanuts, and corn among others. Georgia is the number one producer of peanuts in the country, mainly growing them in the Southeastern part of the state due to sandy, well-draining soil (Kane, 2024). Livestock and aquaculture comprise 9% of production and consist of cattle, lamb, goat, and fish production. Vegetables make up 7% of agricultural production and include sweet corn, onions, peppers, and tomatoes, which grow across Georgia (Kane, 2024). Finally, fruits and nuts add up to 6% of production. Georgia produces blueberries, peaches, and pecans as its main crops in this category (Kane, 2024).

Because of the tremendous agricultural diversity for specialty crops, Georgia needs a large farm labor pool. The state depends heavily on migrant farmworkers, many of whom are part of the USDA's H-2A program. The USDA H-2A program is a temporary agricultural program implemented by Congress in 1986 as part of the Immigration Reform and Control Act. This program allows employers to hire foreign workers for a limited period if they have been unsuccessful in hiring American workers (U.S. Department of Labor, n.d.). Nowadays, migrant farmworkers make up a major branch of the US agricultural workforce. In Georgia, around 60% of agricultural jobs are fulfilled by H-2A workers and has one of the highest H-2A worker populations in the country, closely following California, Washington, and Florida

(Cabrera, n.d.). As a result, it is important to discuss how climate change will affect the farmworkers who grow and harvest our food in Georgia. On top of climate change, farmworkers face many socioeconomic issues due to their constrained mobility and lack of social protection as part of the H-2A program. They also tend to be more vulnerable to health issues like heat stress and heat exhaustion as temperatures become hotter.

The high population of migrant farmers, however, makes Georgia a diverse state from a demographic perspective and a cropping perspective. Although the majority of Georgia's farmers are white (94%), there is still some diversity with the remaining 6%: 4% are black farmers, 1.5% are Hispanic farmers and the remaining 0.5% are Asian, American Indian, or Alaskan Native or Native Hawaiian or Other Pacific Islander (Daniel & Shonkwiler, 2022). All these farmers bring knowledge from their cultural backgrounds and grow crops known to them, making some of Georgia's fields very diverse. The eco-regions in Southern Georgia grow many kinds of fruits and vegetables and are unlikely to run out of water as the Central Valley in California would.

In Georgia, climate change is severely affecting agricultural systems. While all the issues discussed in the introduction are affecting Georgia, extreme heat stands out as a major stressor for agricultural systems. Certain parts of Georgia can experience up to 30 extreme heat days per year (Rollins School of Public Health, 2022), which can manifest as heat waves or drought and result in negative impacts on agricultural systems and farmworker health. To date, there has been relatively little research on the impacts of changing climate on the diverse agricultural systems in Georgia—from the implications for on-farm production to the impacts on farmers and farmworkers. This thesis integrates farmer interviews, an analysis of climate data, and a literature review to assess how future changes in temperature and precipitation might affect Georgia's cropping systems—including impacts on pests and pathogens, farmer and farmworker health, water and soil quality, and livestock and poultry production. It seeks to bridge an existing gap in the literature to provide a systems-thinking, holistic overview of what the future of agriculture in Georgia looks like considering climate change.

2 Methods

2.1 Data Visualizations

Climate data presented in this project comes from the WorldClim, "a database of high spatial resolution global weather and climate data" (Fick & Hijmans, 2024). The data is formatted into climate layers (climate grids) with a spatial resolution of 1 kilometer. To inspect the WorldClim data, users must select one of 19 bioclimatic variables. These variables have been derived from monthly temperature and rainfall values and formatted as points and grid lines. Each variable is further categorized into historical or future projections (which show how the climate in Georgia is changing over the next 80 years). This paper focuses on future projections of a subset of variables over the following periods: 2021-2040, 241-2060, 2061-2080, and 2081-2100. 2100 is commonly used as a time benchmark for scientists and policymakers to project the long-term impacts of climate change, so it is a useful measure for understanding how climate change will affect agricultural systems in the future. The chosen variables are split into temperature and precipitation categories.

The temperature variables are:

- **Annual Mean Temperature**
    - Annual mean temperature is the mean of all the monthly mean temperatures. Each monthly mean temperature is the mean of that month's maximum and minimum temperature.
- **Maximum Temperature in the Warmest Month**

  - This variable represents future projections of the maximum recorded temperature during the warmest month of the year. The warmest month is not clarified by WorldClim but is interpreted as a month during the summer (July or August).
- **Minimum Temperature in the Coldest Month**
  - This variable represents future projections of the minimum recorded temperature during the coldest month of the year. The coldest month is not clarified by WorldClim but is interpreted as a month during the winter (January).

The precipitation variables are:

- **Annual Precipitation**
  - Annual precipitation is the sum of all the monthly precipitation estimates across one year.
- **Precipitation in the Wettest Month**
  - This represents the precipitation levels during the wettest month across Georgia. According to the National Weather Service (NWS), the wettest month in Georgia tends to be March (NWS, n.d.).
- **Precipitation in the Driest Month**
  - This represents the precipitation levels during the driest month across Georgia. According to NOAA, the driest months in Georgia vary between September and October (NWS, n.d.).

All the temperature variables were recorded in degrees Celsuis and recoded in R-studio into Fahrenheit. All the precipitation variables were recorded in millimeters and recoded in R-studio into inches.

The future projections of bioclimatic variables are presented using a framework called the Top of FormShared Socio-economic Pathways (SSPs). According to the Intergovernmental Panel on Climate Change (IPCC), SSPs are “climate change scenarios of projected socioeconomic global changes up to 2100” (IPCC, 2021). Specifically, this paper visualizes the six key temperature and precipitation variables using three out of the five key SSPs: SSP245, SSP370, and SSP585. In the lowest emissions SSP scenario (SSP245), humans are taking stronger action to mitigate climate change by reducing emissions from pollution industries and moving towards net-zero emissions by 2100. The likely temperature range increase for this scenario is between 2.1 and 3.5 degrees Celsius (°C). In the middle SSP (SSP370), the temperature change threshold increases to 2.8-4.6 °C. This is the most likely scenario considering the way the world is currently operating; hence in this paper, SSP370 is the baseline SSP. In the highest SSP scenario (SSP 585), humans take little action and proceed with business as usual. If this occurs, CO2 emissions are likely to triple by 2075 (IPCC, 2021). The temperature threshold for this SSP is significantly high at between 3.3 and 5.7 °C.

2.2 Annotated Bibliography

The second piece of quantitative data in this paper is a literature review on the impacts of climate change on agriculture in Georgia and on the wider Southeast. Using the guidance of Emory Environmental Science Librarian, Kristan Majors, I collected peer-reviewed articles using Google Scholar, and the Web of Science through the Emory Libraries website. When finding articles, I inputted a variety of search terms to ensure I found articles that were relevant to my research. I used different combinations of search terms such as ‘climate change’ and ‘the Southeast’ as well as ‘climate variability’ and ‘agriculture’ along with ‘Georgia.’ Generally, it was difficult to find articles specifically on climate impacts on Georgia’s agricultural system, as opposed to the wider Southeast, which further highlights an existing gap in research. The chosen articles were focused on the bounds, direction, and magnitude of climatic changes in the Southeastern US and the impacts on agricultural systems. The key points I focused on were the spatio-temporal scale of the study and specific crops studied (e.g. specialty or commodity crops) as well as the major results. In addition to peer-reviewed literature, this thesis cites many reports from organizations such as the USDA and the University of Georgia's Agricultural Department. Overall, there are a variety of sources used in the annotated bibliography of this paper which can be found in the references section.

2.3 Semi-structured Interviews

This paper utilizes interview data from Dr. Emily Burchfield's FACES lab research. Post-doctorate researcher Dr. Scott Schnur conducted around 30 semi-structured interviews with food systems experts (n = 9) and farmers using conventional and alternative practices (n = 21) in Georgia. Interviewees were chosen and contacted via referrals from previous research collaborators and outreach to local farm operators through farmer advocacy organizations or local extension agents (Schnur et al., 2024). Interviews were conducted in three different ways: in-person conversations, video calls, or phone calls. Everyone's identity has been protected and coded with a special speaker number. I would like to formally acknowledge Dr. Scott Schnur's work and thank him for allowing me to use his research in this paper. I confirm that I have been through the Institutional Review Board (IRB) training and have been legally approved by Dr. Schnur and the IRB to use this interview data.

The interviews were conducted to understand "differences in the perspectives on climate and food system futures articulated by stakeholders with varying approaches to agriculture" (Schnur et al., 2024, p.1). The interviewees were intentionally spread across the state to receive a diverse set of responses. Conventional and alternative farmers cultivate different crops at different farm scales; both large and small-scale. Each interviewee has a connection with the land in Georgia through directly growing fresh produce, herding cattle, running community gardens, or researching specific crops. The farmers doing alternative practices are growing organically, certified naturally grown, low-till/no-till or have missions related to sustainability. On the other hand, conventional farmers do not explicitly focus on alternative farming methods.

I read the cleaned transcripts (which were generated using Otter.ai) in detail and synthesized notes from these interviews related to personal experiences with extreme temperatures and variable precipitation in Georgia. Climate change has impacted these individuals and their operations at varying degrees via temperature or precipitation variability and extreme weather events. Throughout the paper, I include anonymized quotes from the interviews to highlight and emphasize personal experiences about climate change. Although there are some quotes from professors and farm consultants, I felt their thoughts best represented how farmers are feeling about climate change in Georgia, so chose to include them. The intention behind using interview data in this paper was to incorporate a qualitative aspect to this scientific paper that helped understand firsthand perspectives on how stakeholders are reacting and responding to climate change in Georgia. I incorporate a mixture of quotes in this paper. Some quotes directly support my argument about the implications of climate change for agriculture in Georgia, and others contradict or challenge my arguments.

3 Results

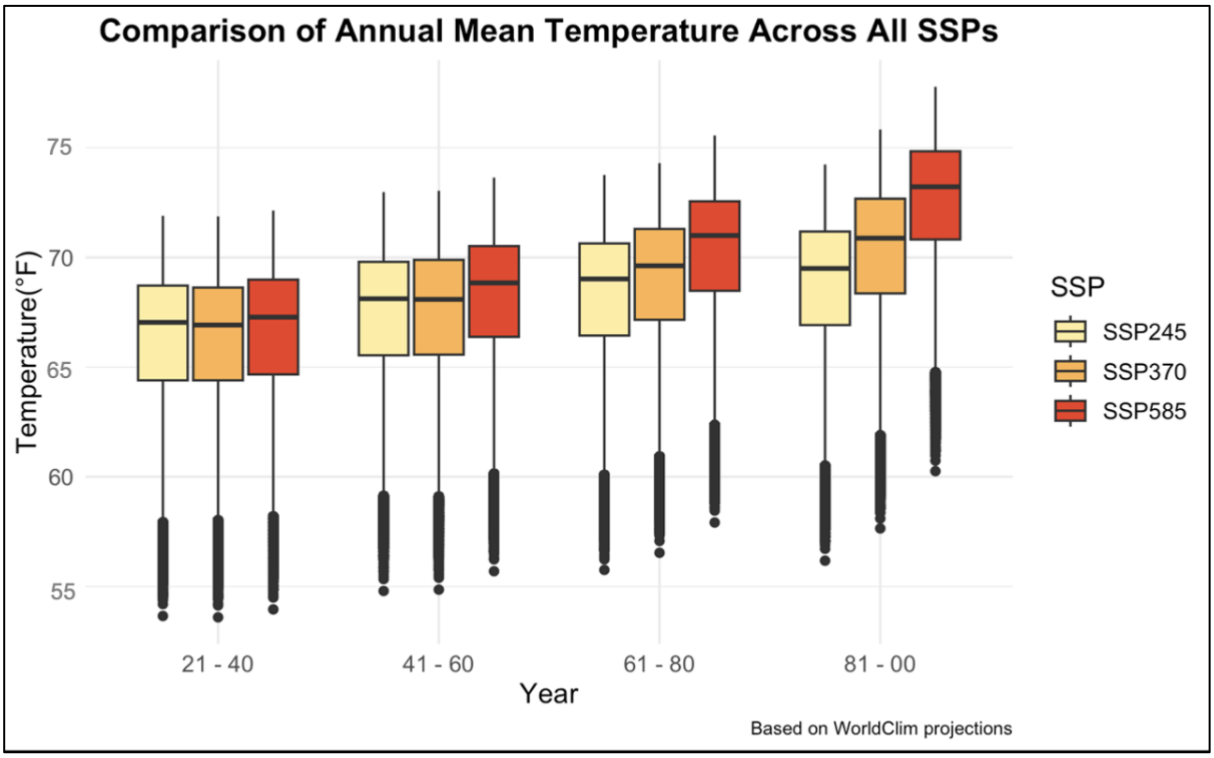
3.1 Temperature

Climate change in Georgia is causing extreme temperatures to become more unpredictable and frequently occurring. Temperature affects many variables that are crucial for the reliable functioning of agricultural systems such as agricultural productivity, crop yields, pest and pathogen populations, and livestock health. Those at the center of the changes in extreme temperatures are farmworkers – who must bear extreme temperatures and extreme weather events to harvest crops. The following section will cover an overview of how each of the three temperature variables from the WorldClim database (Annual Mean Temperature, Maximum Temperature in the Warmest Month, and Minimum Temperature in the Coldest Month) are changing in 3 SSPs (245, 370, and 585). After discussing the variables, each section will cover the implications of the changes in temperature for Georgia's agricultural systems by pulling together the literature review and what farmers and researchers say these temperature changes mean for farming operations in Georgia. Finally, this section concludes with a focus on farmworkers and the implications for farmworker health in Georgia as a result of climate change, specifically extreme heat.

3.1.1 Annual Mean Temperature

Figure 3

Comparison of Annual Mean Temperature Across SSPs

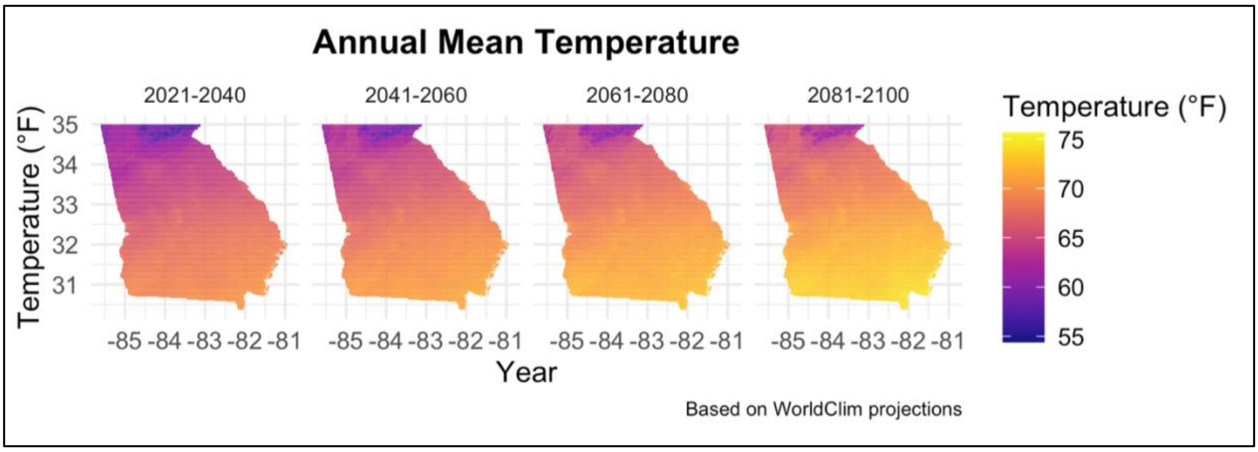


The figure above (Figure 3) represents a box and whisker plot that visualizes how the annual mean temperature in Georgia will change over the next 80 years in each SSP. Each SSP is visualized by a different color, shown in the legend on the right side of Figure 3. The box and whisker plot (boxplot) shows the median annual mean temperature projection for each SSP, represented by a thick black line. The box around the median value represents the lower quartile (Q1), where only 25% of the values fall under, and the upper quartile (Q3), where 75% of the values fall under. Therefore, the length of the box represents the interquartile range (IQR) which is calculated by subtracting Q1 from Q3. The black lines above and below the box represent the 'whiskers' which extend to the length of 1.5 x the IQR. The black dots at the bottom of Figure 3, which are also occasionally found at the top of a figure, represent outliers. Outliers are values that fall more than 1.5x the IQR from Q1 or Q3, making them significantly different from the majority of the data values.

Figure 3 shows a clear overall upward trend in projected annual mean temperature across all three scenarios. This means that annual mean temperature is likely to rise in Georgia over the next 80 years. There is more pronounced warming over time, especially towards the years of 2061-2080 and 2081-2100. In the early decades (2021–2040), temperatures across the scenarios are relatively close, with SSP585 showing slightly higher values. As the century progresses, the difference among the pathways becomes more evident, particularly in the 2081–2100 period, where SSP585 exhibits the highest median temperatures (73°F), followed by SSP370 (71°F) and SSP245 (69°F). The IQR appears to remain relatively consistent across all scenarios, suggesting that while median temperatures rise, the variability in annual mean temperature does not expand significantly. However, the whiskers and outliers indicate that extreme temperatures (both high and low) persist. The whiskers and outliers could be attributed to differences in temperatures among Georgia's six eco-regions as regions like the Blue Ridge and Ridge and Valley are significantly cooler than the Southeastern and Southern Coastal Plains. This can be seen in Figure 4 below, which shows how the annual mean temperature will change over the next 80 years across the state. Between 2081 and 2100, the Southeastern and Southern Coastal Plains will face significantly higher annual temperatures of up to 75°F compared to other eco-regions. The Blue Ridge, Ridge and Valley, and Southwestern Appalachian regions stay relatively within the 60-65°F range across the 80-year projection. Therefore, while there is overall warming across the state, the warming is more evident in the more agriculturally productive eco-regions. Overall, the findings show that certain situations such as higher emission pathways (SSP 585 in particular) will lead to the most severe warming which has critical implications for agricultural systems and cropping yields, as well as farmer and farmworker health.

Figure 4

Annual Mean Temperature from 2021-2100 (SSP370)



The positive trend for annual mean temperature in Georgia will affect its cropping systems. Cropping systems determine how crops grow, cover sequences such as harvesting and tilling, and understand the kinds of management techniques being used due to climate change. Any kind of temperature change will cause changes to crop harvests, especially for crops that are extremely sensitive to temperature change such as maize and wheat. Therefore, the rise in temperature (such as a rise from 67-73 °F in SSP585) can affect common crops grown in Georgia. According to a study by Cammarano et al. (2016), which simulated air temperature changes on crop yield in the Southeast, warmer temperatures cause a change in the yields of maize (corn) and wheat. For every unit increase in temperature (in °C), corn faced a 13% reduction in yield, and wheat suffered a 6.5% reduction in yield. Due to rising annual mean temperatures in Georgia, the yield of corn and wheat in Georgia could be lowered during warmer periods of the year. This could result in farmers being negatively affected as their revenue from corn and wheat will be lowered due to lower yields and poorer harvests. Considering that row crops make up 18% of agricultural production in Georgia, the implications on farmers will be significant.

While the yield of certain crops may decrease due to rising temperatures, there could be positive implications elsewhere. The growing season of several crops is being impacted due to warming temperatures. According to speaker 2317, the director of an agricultural network in Georgia and a translator of research to non-scientists, “About a one-degree Fahrenheit change in temperature results in about a one-week increase in the length of the growing season.” Longer growing seasons could therefore be beneficial for farmers who cultivate specific crops and do not have a large window of time to harvest them. For example, a cattle farmer from Woodbury, Georgia (speaker 2312) has experienced longer growing seasons and milder winters which have helped with growing grass and hay on their farm. They mentioned “I feel like we're getting a longer growing season. I felt like since we're having milder winters, I feel like we're able to start growing grass again in our area.” The longer growing is “good because you can produce more.” This allows farmers to benefit from longer growing seasons and capitalize on growing crops earlier in the season. Additionally, speaker 2917, an agricultural extension specialist, was further supportive of longer growing seasons. They said “If you have a bit longer growing season, you might be able to double crop. You can put in something early, harvest it, and put in a second crop." This could potentially help farmers reduce the risks associated with climate change because "now they're having income from two crops instead of one."

Warmer annual mean temperatures could also bring new crops into the state. For example, there has recently been a trend towards citrus and olives in Georgia as the climate becomes warmer. One citrus farmer in Georgia (speaker 1830) mentions citrus is the "one thing that you can do with small acreage, [and] low capital input, because you don't have to have a lot of machinery." Therefore, if citrus trees can be maintained and cared for until they fruit, citrus could be an opportunity for farmers in Georgia. Rising temperatures could especially be an opportunity for new farmers in the state who are looking to grow crops that require a low initial investment and capital input.

On the other hand, a report on regional climate impacts states that "longer growing seasons and increased CO2 have positive effects on some crop yields, but this could be partially counterbalanced by the negative effects of additional disease-causing pathogens, insect pests, and weeds" (Karl et al., 2009, p.121). Therefore, extreme temperatures could have a counter effect on pathogens and pests in Georgia as they are highly influenced by the surrounding air temperature. The warmer the air temperature, the more likely it is to see increased pest and pathogen presence (Subedi et al., 2023). So, a rising mean annual temperature is likely to worsen pest and pathogen populations in the agricultural industry, which has implications for growing and harvesting crops. Pests could carry and spread disease to the farmworkers harvesting crops, especially if there is long-term exposure. Due to the poor healthcare protections given to the majority of the migrant farmworkers in the H-2A program, a disease contracted on the field could be deadly to some workers. This is because many of them lack health insurance and cannot afford to pay out of pocket to be treated for their illnesses. Pests may also spread disease to the crops in the field itself, resulting in lower yields and vulnerable farmworkers. Moreover, since temperatures are increasing overall, particularly with warmer winters, this means farmworkers will have to spray more pesticides and fungicides to get rid of the pests and pathogens.

According to speaker 5521, a grower of peaches and pecans in mid-Georgia, there is an “earlier arrival of beetles and other bugs coming out of hibernation” in Georgia. If the farm operator cannot afford to spray pesticides during high pest presence, their entire fields may be at risk of being infected with contagious diseases which will lower crop yields. As a result, this could have a domino impact as lower sales will result in lower revenues and might jeopardize their livelihoods. Other farmers do not see such a large pest issue during the milder winters. One fresh-cut flower farmer in Atlanta (speaker 1509) mentioned that “Mild winters here are the perfect growing season and there's almost no pests.” Perhaps, because this farmer is an urban grower in Atlanta, they see fewer pests than the peach and pecan grower in mid-Georgia. Interestingly, there is a contrast in how farmers are viewing changes in pest populations in Georgia as a result of the changing climate.

3.1.2 Maximum Temperature in the Warmest Month

Overall, Figure 5 shows an overall positive trend in projected maximum temperature in the warmest month across all three SSPs. In the earlier decades (2021-2040 and 2041-2060), the median temperatures are not noticeably different from each other; however, the difference becomes more pronounced as the figure moves into the later decades. This could be because of humans not taking enough action against climate change, thus causing the temperatures to rise. In 2081-2100, each of the three SSPs all have very high maximum temperatures during the warmest month, especially SSP585 with a median temperature of approximately 100°F. The IQR appears to remain relatively consistent in the earlier time periods; however, it does increase especially in 2081-2100 particularly with SSP245. This suggests that while the mean maximum temperatures are rising, variability is also rising. The whiskers and outliers indicate that the maximum temperatures can also be milder in certain areas, going as low as 78-80°F

Figure 5

Comparison of Maximum Temperature in the Warmest Month Across SSPs

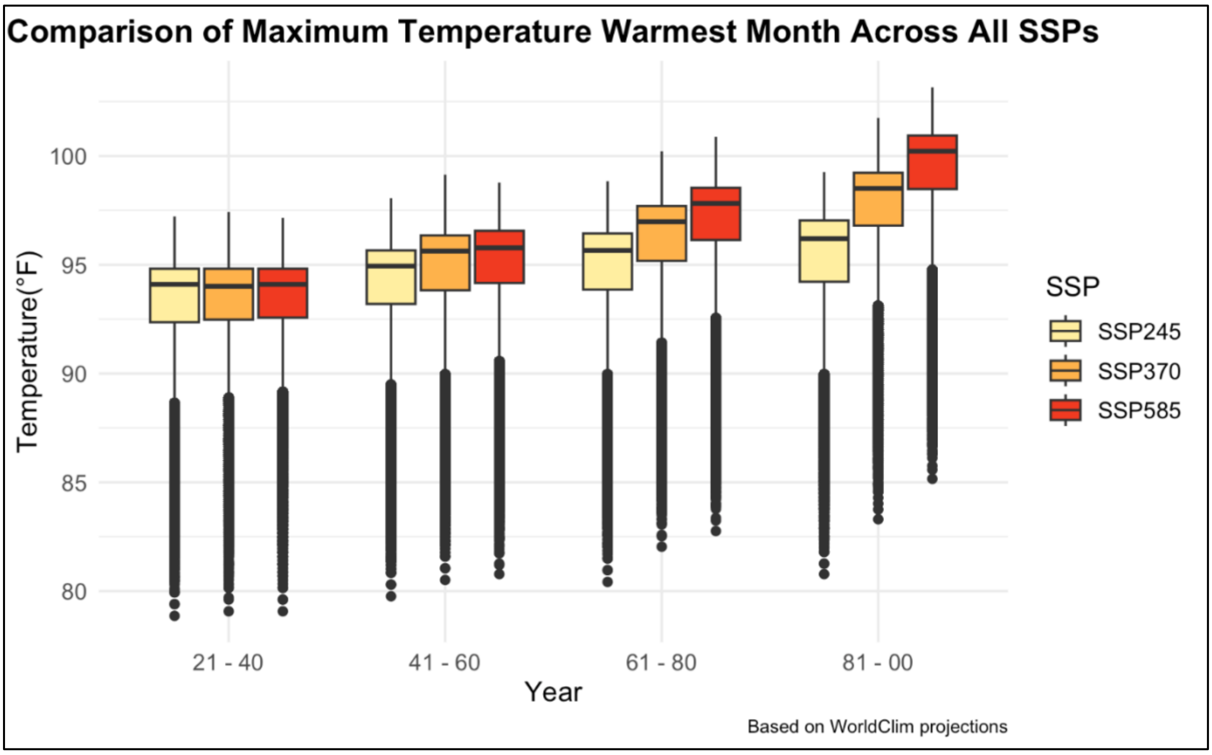
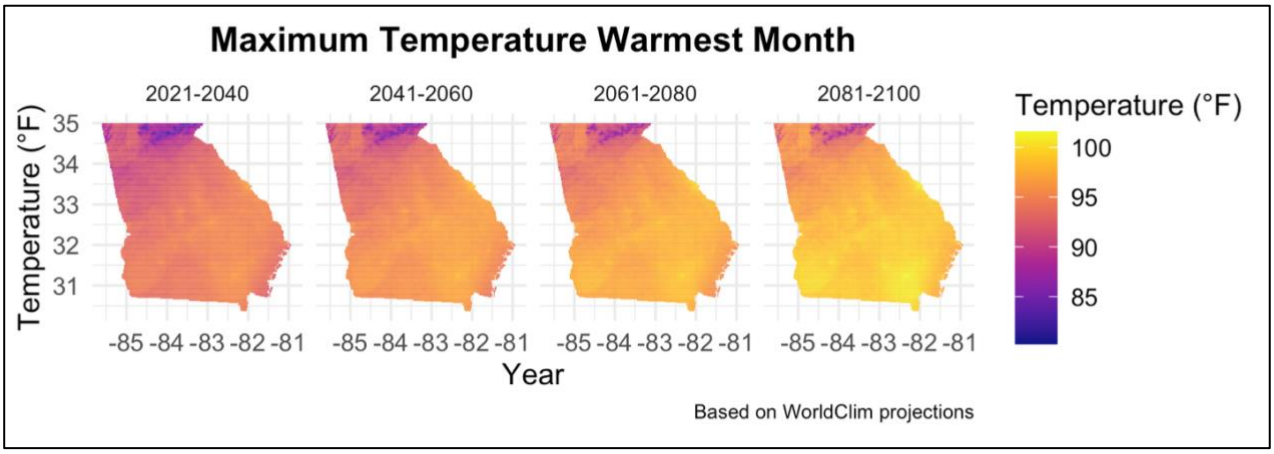


Figure 6

Maximum Temperature in the Warmest Month 2021-2100 (SSP370)



Once again, the whiskers and outliers could be due to temperature differences among Georgia’s six eco-regions. Figure 6 demonstrates a noticeable temperature change across all the eco-regions in Georgia. The Southeastern and Southern Coastal Plains regions are warming significantly more than other regions like the Piedmont and Blue Ridge areas. The Southeastern and Southern Coastal Plains are highly productive agricultural lands, so the temperature changes showing temperatures reaching 100°F in many cases is worrisome. The warmest month of the year in Georgia is likely to fall in the summer months, which means the summers will get warmer and extreme heat will become more common; thus causing a domino effect on our food system. It may be hazardous to work or even be outside, resulting in a major loss of revenue for farmers trying to harvest summer crops in Georgia.

The increase in maximum temperatures in Georgia can negatively impact crop yields in Georgia, especially due to the prime increases being in agriculturally productive areas (see Figure 6). A study by Eck et al., (2020), examines how surface crops (such as corn, soybean, peanut, and sweet potatoes) are experiencing declines in yield due to higher maximum temperatures during the growing season. This will have domino effects on crop yields and harvests for farmers will be lower than usual resulting in lost revenue. Overall, the study emphasizes the importance for farmers to understand how surface crops respond to short-term climate variability (through temperature changes) so farmers can adapt accordingly and prevent such issues from happening in the future. Another study by Sharma et al., (2023), focuses on oats and sorghum crops in the Southeast, analyzing factors like temperature and precipitation. In the study, oat yields decreased with higher temperatures, while sorghum yields increased. Overall, a 1°C temperature increase reduced oat yield but increased sorghum yield, suggesting some crops might benefit from higher-than-normal maximum temperatures (Sharma et al., 2023).

According to the USDA, livestock and poultry production systems are also vulnerable to temperature stresses which can lead to reduced productivity and loss of revenue (Walthall et al., 2012). Georgia produces the most broiler chickens in the nation, meaning that poultry production is a significant contributor to the economy and a big employer of farmers (Kane, 2024). Higher temperatures could result in heat stress for poultry and lower their immunity levels, making them more vulnerable to diseases. Additionally, there will be a similar impact on livestock. Higher temperatures are likely to reduce livestock productivity because heat stress disrupts the animals' metabolism leading to decreased feeding rates and lower dairy production for cows (EPA, 2017). One livestock farmer from Bowden, Georgia (speaker 1954) mentioned how chickens and turkeys are more vulnerable to extreme temperatures and events than cows, pigs, and sheep. The cows, pigs, and sheep are hardier than chickens and turkeys. Therefore, there are now concerns about chickens and turkeys responding to a rapidly changing climate (particularly extreme heat) which could impact poultry farmers' revenue streams and livelihoods down the line, affecting a large portion of Georgia's agricultural output.

Another livestock farmer who tends to many different kinds of animals including cows, hogs, and pigs, believes that animals will naturally adapt to the changing temperatures. Speaker 4701, a livestock farmer from Southwest Georgia believes that "a good healthy animal … will naturally adapt if you got everything they need." While they have noticed that extreme heat is affecting their hog and cow populations, they have not made drastic changes to their operations. Instead, speaker 4701 has strategically placed their hogs where "[their] hogs can stay in the natural spring so they can cool themselves whenever they want to" and provided "small watering holes for the cows so they can go in and cool their hooves and cool themselves." Therefore some farmers are less concerned about their animals reacting to climate change, but instead are focusing on providing them with the resources they need to adapt to warmer and drier conditions. This suggests that farmers are continuing to produce and farm crops or animals as normal, regardless of changing climates. Instead of changing what they are growing, some farmers, such as speaker 4701, are simply moving their animals around to ensure protection against unpredictable future weather.

3.1.3 Minimum Temperature in the Coldest Month

Figure 7

Comparison of Minimum Temperature in the Coldest Month Across SSPs

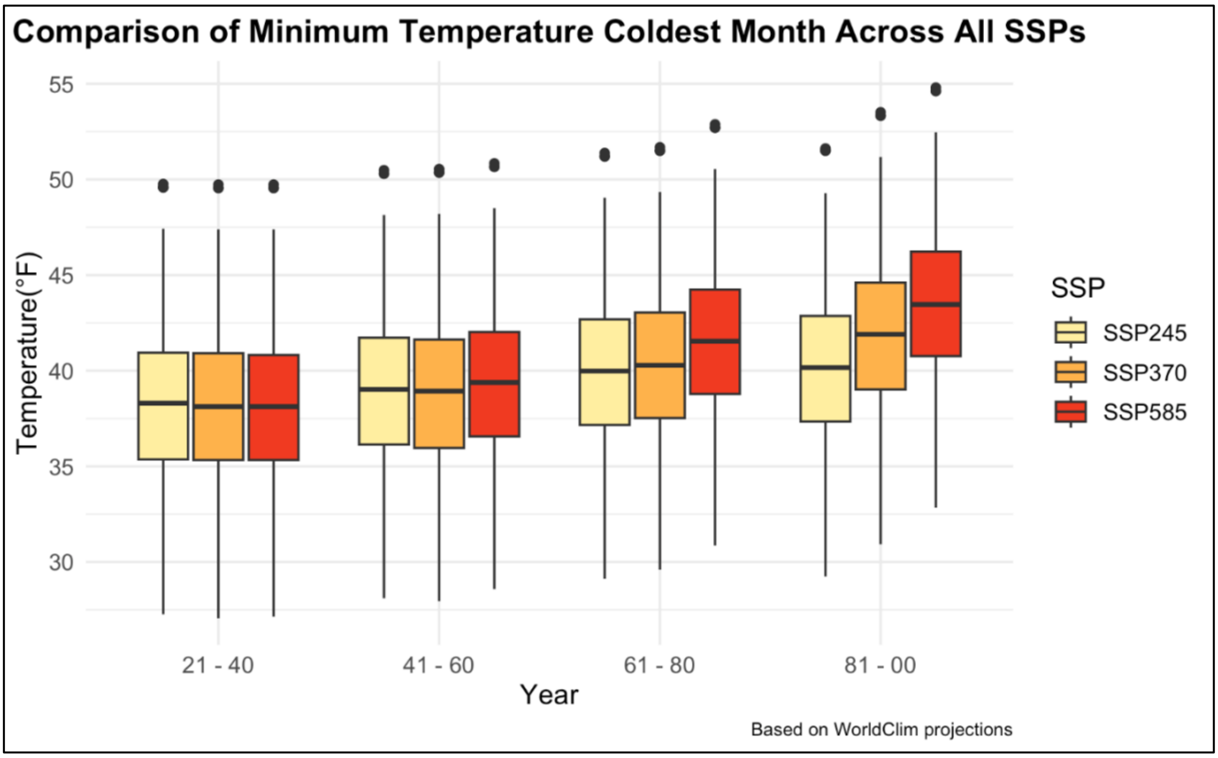


Figure 7 shows an upward trend in projected minimum temperature in the coldest month across all three scenarios. While early projections (2021–2040) show similar temperatures across all scenarios by 2081–2100, SSP585 exhibits the highest increases, reaching a median of approximately 43°F. SSP245 and SSP370 show more moderate warming, with minimum temperatures rising from around 38°F to just above 40°F and 42°F, respectively. The IQR appears to remain relatively consistent across periods, suggesting similar variability in each 20-year period. The whiskers and outliers indicate that the minimum temperatures can also be warmer in certain areas, going as low as 55°F for SSP 585 in 2081-2100. Once again, this could be due to differences in temperatures among Georgia's six eco-regions, although the visualization (Figure A2) does not show as intense of an eco-region variation as the annual mean temperature or maximum temperature in the warmest month. The coldest month in Georgia tends to be January, and temperatures can go extremely low (NWS, n.d.). Lately, there have been freezes during the colder months of January which can negatively impact crops and jeopardize revenue streams for farmers. Certain fruits such as berries and peaches are especially vulnerable to freezes and must be well protected to make it through the colder months. As the colder temperatures increase over the years, this could cause the growing seasons to shift – creating unpredictability along the way.

The positive trend in minimum temperatures during the coldest month suggests winters in Georgia are likely to get warmer over the next 80 years. For farmers growing fruit, rising temperatures can significantly impact the chill time/hours. Chill time is the number of days below 45 degrees Fahrenheit that a fruit tree needs to feel refreshed and ready to work. For peaches (one of the state's most commonly grown fruits), around 800-1000 chill hours are required for the trees (Tiernan, 2022). Due to climate change, winter temperatures are rising, as seen in Figure 7, meaning the chill hours for fruits in Georgia will be affected. Peach farmers especially struggle with chill hours and have been doing substantial adaptability and suitability work to trial new varieties of peaches to see whether they can withstand the changing climate. For example, a peach and pecan farmer in Georgia (speaker 4003) mentioned that usually there were "1100-1200 hours of chill every decade from the 60s 70s, 80s, 90s, 2000s, even the 2015 and then in 2016 through today we have not gotten more than [500]". This is a significantly low number compared to the recommended 800-1000 hours and could result in fruit trees not reaching the desired ripeness to be sold. This means that farmers need to watch how the minimum temperatures during the coldest month are changing in Georgia as they are important in influencing chill time for fruits.

Similarly, milder winters were noticed by a fruit and vegetable farmer on the Oxford College farm (speaker 2739). They commented that “During the wintertime when it used to reliably get down to the forties, fifties, a lot of times it's still up in the sixties and the temperature doesn't drop like it used to.” While this speaker hinted at overall milder winters, the WorldClim future projections reflect different numbers from what was mentioned. According to Figure 7, the projected minimum temperature during the coolest month can drop to as low as 35 degrees Fahrenheit between 2021-20140, which is significantly lower than the “sixties” figure speaker 2739 is referring to. This suggests there may be a disparity in what the quantitative data is showing about temperatures and what farmers are noticing and feeling on their farms. Moreover, it is important to acknowledge that the “swings and dynamic nature of weather has really increased” and that the “frost may come as early in the fall as it ever did, or as late in the spring as it ever did.” This further suggests the unpredictability of frosts which severely impacts fruit growers like speaker 2739 who rely on colder temperatures for their fruit to ripen.

On the same trajectory, a sustainable farming expert in South Georgia (speaker 3819) is noticing eco-region variability across Georgia which the WorldClim data fails to capture. Speaker 3819 mentioned that “One of the things that climate change models have said about Georgia is we're not going to get on average that much hotter, that much warmer.” However, the climate data from WorldClim, suggests otherwise. Figure 3 projects that annual mean temperatures will rise by almost 5 degrees Fahrenheit in SSP585. While the term “much” is subjective and could be interpreted differently, it seems this agricultural expert was less concerned about rising temperatures in Georgia. Instead, they showed more concern over temperatures getting cooler in the Northern parts of the state. While the eco-region map does not represent this variability (see Figure A1), the speaker mentioned that "There are going to be places in North Georgia that actually get cooler, longer periods, between frosts which isn't great for growing certain crops." This suggests that certain agricultural experts are predicting the Northern eco-regions of Georgia including the Blue Ridge and Southwestern Appalachians may see cooler weather. Particularly with freezes, speaker 3819 noticed that "There was one year when it was six months between hard freezes and that did a lot of damage to strawberry and blueberry growers." Overall, this suggests a nuanced perspective from an agricultural expert which is not well-reflected in the quantitative data and suggests there is richness in talking to agricultural stakeholders to understand what they predict will happen to future temperatures based on lived experiences.

Despite challenges associated with the possibility of milder winters in Georgia, there are opportunities arising. One cattle farmer in Woodbury, Georgia (speaker 2312) mentioned that since the winters in Georgia have gotten milder, this has resulted in a longer growing season for farmers cultivating hay and pasture. They said "I feel like the winters have gotten more mild. We usually have once or twice where it's brutally cold but that's a short span, just a couple of days or a week here or there. I think it's gotten somewhat warmer." As a result of milder winters, livestock farmers do not have to go through as much hay to feed their animals. In colder temperatures, livestock must eat more hay to maintain their body temperature and keep warm, meaning farmers have to go through more hay feed. The cattle farmer further said "The night[s], sometimes I feel like they've gotten warmer. There's not such a drop in the temperatures at night." Although milder winters are better for hay and pasture growth as well as conserving it for feed, the winters should not become too warm as this could be harmful to livestock health if temperatures grow very warm during the usual winter months.

3.2 Impacts of Temperature Changes on Farmworkers

Increasing temperatures in Georgia will also have significant implications for farmworkers, in particular migrant farmworkers. Migrant farmworkers are mainly people of color from Mexico and South America and have historically faced racial exclusion in the US (Minkoff-Zern & Sloat, 2017). Racial exclusion entails language barriers among other psychosocial stressors, such as inadequate documentation which have made migrant farmworkers extremely vulnerable from a socioeconomic standpoint (Castillo et al., 2021). Migrant farmworkers also face stressors such as poor health outcomes, invisibility to the community, and social exclusion. For example, many of them are isolated from their families which can affect their health and well-being due to a lack of communication with loved ones. Most farmworkers are also paid using the piece system which pays wages depending on the quantity of crops harvested. These wages are extremely low and often do not cover basic living costs such as food and water which has led to issues like food insecurity. In fact, according to a study on the predictors of food in migrant farmworkers in Georgia, "around 62% of [migrant farmworkers] did not have enough food" (Hill et al., 2011). This is surprising considering farmworkers pick fresh produce for a living but are rarely given any to take home for themselves or their families. The factors that contribute to lack of access to food include lack of cooking facilities (including a fridge and oven), transportation problems, and having children, which adds more mouths to feed. On top of this, the H-2A program provides poor living conditions for migrant farmworkers. Their living quarters are poorly maintained, dirty, and very cramped, often resulting in the spread of disease due to the lack of cleaning and care taken (Grinspan & Thompson, 2020). Migrant farmers therefore face poor wages, unsafe and unhygienic living conditions and are further suffering from climate change causing increased variability and extremes.

Climate change is exacerbating many of the vulnerabilities they already face such as worsening heat stress due to the rising intensity and frequency of extreme heat events as seen in Figures 5 and 6. Therefore, farming during the summer months, particularly in the peak afternoons can be very difficult for Georgia's farmworkers. An Oxford College Farmer of fruits and vegetables (speaker 2739) commented that "a big issue is the heat in the summers", and they are concerned about temperatures "reach[ing] a certain point where [in] the afternoons, [they] almost can't work outside if it's too hot and humid." The migrant farmworkers employed through the H-2A program tend to work on large commercial farms which often violate the health and safety protocols of the employment contracts. Protections such as frequent water breaks and rest breaks are neglected by employers which can lead to migrant farmworkers facing dehydration, heat exhaustion, and heat stroke (Bail et al., 2012). On top of the poor farmworker protections, there is a lack of robust health insurance plans which further inhibits farmworkers from having a good quality of life. Due to most migrant farmworkers being dependent on their employers for health insurance and healthcare, they often do not get medical assistance when they are ill or at risk of heat stroke, which increases their social vulnerability.

Moreover, as section 3.1.1 discusses, rising temperatures will lead to increased pest populations and increased pesticide spraying. As a result, there will be increased health issues for farmworkers. Due to higher pest populations as a result of milder winters, farms are likely to increase pesticide usage. Pesticides are more commonly sprayed on commercial and row crop farms, as opposed to certified organic farms which puts farmworkers on the fields at risk. Exposure to harmful pesticides is scientifically proven to cause severe health impacts such as neurological damage, memory loss, cancer, and reproductive effects (Castillo et al., 2021). In addition, pesticide exposure can also cause more short-term effects such as nausea, vomiting, and itching/ burning eyes. In 2016, estimates showed that "between 10,000 and 35,000 farmworkers suffer acute pesticide poisonings every year in the United States" (Castillo et al., 2021 p.260). In reality, the accurate number is likely much higher due to poor reporting protocols. Pesticide poisoning can take place in a variety of ways including "via pesticide drift from treated fields to nearby homes…, through the take-home exposure pathway (i.e., when workers who have applied or come into contact with pesticides carry pesticides into the home on their clothing or shoes, potentially exposing other household members), and by consumption of contaminated food and water" (Castillo et al., 2021 p.260). Furthermore, due to a lack of safety training provided to migrant farmworkers about pesticide usage and a lack of sticking to the right hygiene practices, there could be further exposure to diseases. If a farmworker is exposed to a disease and on top of that faces a lack of health insurance, they may be unable to receive treatment and therefore will have to take a break from work. Due to the piece wage system, farmworkers could suffer from no pay which will worsen food insecurity issues. It could also potentially impact farmworkers' families in their home countries if they are remitting money back home.

3.3 Overall Impacts of Temperature on Agriculture in Georgia

Overall, there is a lot of variability between temperatures in Georgia as shown by the data visualizations, literature, and lived experiences of farmers. It is important to consider where the farmland is and how temperature is influencing farms in specific eco-regions in Georgia. Within the state, there are approximately 42,000 farms (Kane, 2024), but not many of those are in urban areas. Most lie in rural areas, especially in the Southeastern plains eco-region. In spite of that, urban farms see more extreme fluctuations in temperature. An urban Atlanta vegetable farmer specializing in turmeric production (speaker 2850) commented there is a "sharp contrast between day and night temperatures and having … really cold nights followed by … seventy, eighty-degree days." They further mention that this is due to the "urban island effect, just the city heating up a lot because of lack of tree cover and concrete." This is a vital point to consider as several factors can affect the temperature in an area such as elevation, tree cover, population density, and others.

In the context of stakeholders, farmworkers remain the most vulnerable to climate change, particularly due to rising temperatures, in Georgia. Due to their poor socioeconomic status and a lack of care taken for their well-being by employers, they suffer from many issues. Certain policies can help farmworkers become more resilient to climate change and reduce their socioeconomic vulnerability, which will be discussed in the solutions section (four).

3.4 Precipitation

Climate change in Georgia is causing precipitation to become more unpredictable. Reliable precipitation is crucial for the functioning of agricultural systems. It affects components like crop yields, pests and pathogens, and especially water and soil quality. Although the majority of the Southeast is supposed to see reduced precipitation levels due to climate change and warming temperatures, Georgia is predicted to see increased precipitation and irregular rainfall patterns as climate change becomes more intense (Walthall et al., 2012). A rise in extreme heat could, however, push precipitation levels in the other direction and create drought-like conditions, which would dry up water sources and reduce overall rainfall. Therefore, while Georgia is likely to see more rainfall, there is still a significant amount of unpredictability with precipitation in this state. The following section will cover an overview of how three precipitation variables from the WorldClim database (Annual Precipitation, Precipitation in the Driest Month, and Precipitation in the Wettest Month in Georgia) are changing in 3 SSPs (245, 370, and 585) as well as the implications of the changes for Georgia's agriculture.

3.4.1 Annual Precipitation

Figure 8

Comparison of Annual Precipitation Across SSP

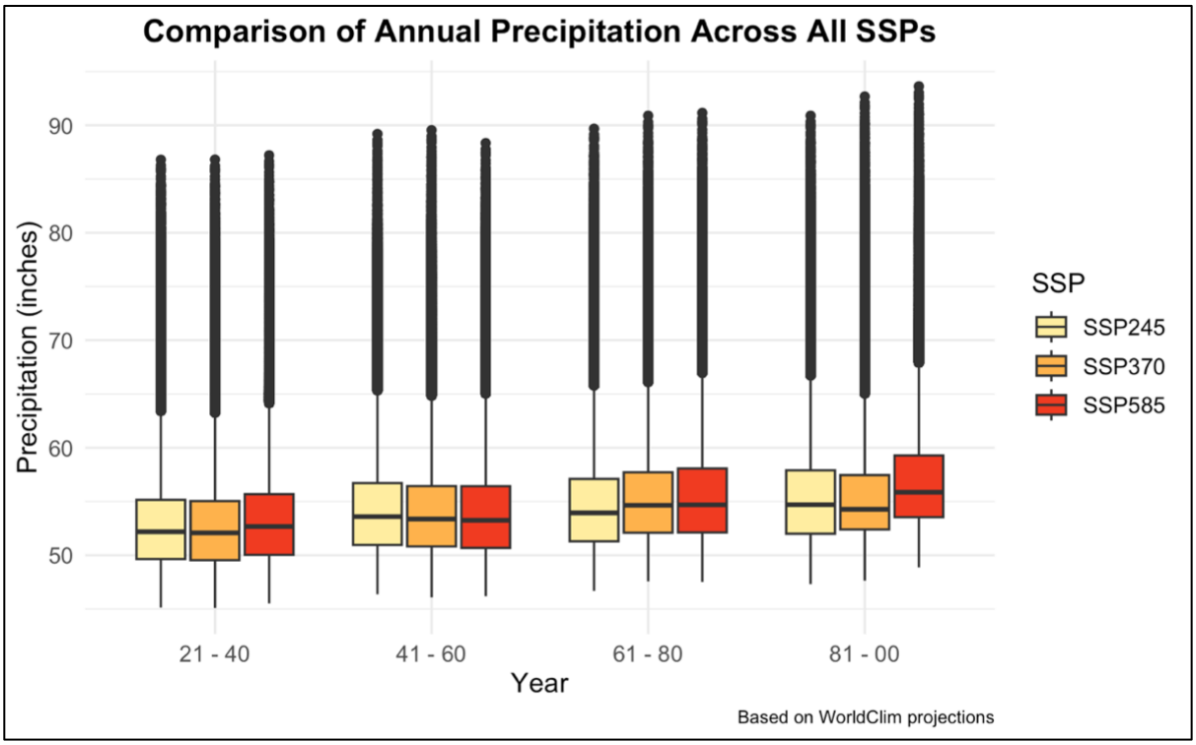


Figure 8 shows some changes in annual precipitation across SSPs; however, they are not as noticeable as the differences in annual mean temperature. The median and Q1 and Q3 levels of precipitation for each SSP remain between 50 and 60 inches. Also, the outliers for annual precipitation for each of the SSPs stay reasonably consistent in each of the 20-year periods. In SSP245, there is approximately a 1-inch increase in projected annual rainfall in Georgia between 2021 and 2100, showing small differences over the years. Interestingly, in SSP370, the annual precipitation level in 2081-2100 is slightly lower than in SSP245. Perhaps this follows the annual mean temperature graph (Figure 3) and suggests that since SSP370 will be warmer than SSP245, warmer conditions could result in drier conditions in the future. There may also be certain climatic conditions associated with drier conditions such as drought or extreme heat. In the final time block, SSP585 shows an overall greater change in annual precipitation than the other two SSPs. Between 2081 and 2100, the median rainfall value for SSP585 is approximately 56 inches of rainfall, which shows a decrease from Georgia's average levels last year (63 inches). This could suggest a dry spell in the future which could have detrimental impacts on Georgia's agricultural system. Also, like temperature, there is likely some variability amongst the different years due to variability amongst the eco-regions in Georgia as each of them has different terrains and elevations, causing different precipitation levels (see Figure A2).

Overall, the annual precipitation levels in Georgia are increasing which has implications for cropping patterns, pests, pathogens, and water and soil quality as well as livestock. The USDA predicts that changing precipitation levels will alter many variables including "cropwater requirements, crop-water availability, crop productivity, and costs of water access across the agricultural landscape" (Walthall et al., 2012, p.5). While Figure 8 shows increasing annual precipitation, there is also not a clear increase. In some years, rainfall increases in each SSP, while in others, it decreases. This follows the pattern from the semi-structured interview responses, as many farmers in Georgia have mentioned flash flooding, and tornadoes, hinting at irregularity. There is often a period of high amounts of rain, followed by periods of no rain. According to an urban flower and vegetable farmer based in Atlanta (speaker 3726), they mentioned Georgia is "experiencing more and more volatile weather and getting warmer and even with all the flooding, also experiencing greater droughts." This hints at the need for increased research efforts into climate modeling to predict future precipitation due to the negative implications associated with not being prepared.

One study by Anandhi & Bentley (2018), conducts an analysis of climate variability in the Southeast. It highlights how changing precipitation patterns in the Southeast impact irrigation scheduling, and when combined with temperature changes, affect water management. This means that Figure 8, which shows changing precipitation patterns in Georgia, could lead to issues around irrigation scheduling and water management for Georgia's farmers. The study emphasizes how farmers must adapt their water management strategies to account for unpredictable rainfall, prolonged dry spells, and intense precipitation events. Due to an irregular trend in precipitation, as seen in Figure 8, farmers need to ensure they have a water source during the drier spells which can include irrigation. This is even causing concern among urban farmers as one tomato and okra farmer (speaker 3726) said "[they] never thought that irrigation would be an issue in a low-lying section [in] Atlanta, Georgia." The farmer further asked questions like "Do we need a rain cap system or do we need an irrigation line or do we need pumps to get the water out?" This emphasizes that farmers are unsure about how to proceed with unpredictable precipitation patterns and are worried that relying on irrigation alone may not work with climate change on the rise. Irrigation is essential during dry spells as, without sufficient watering, crops can dry out and die, causing financial losses for farmers. Speaker 3276 also mentions they want to have "water management that doesn't just rely on earthworks and irrigation systems, but would actually look more at water capture systems that work alongside the roadways." Water capture is a solution that could help alongside reliable irrigation during drought-like conditions and will be discussed more in the potential solutions section (four) of this paper.

Regarding pest populations, under a changing climate, some of the environmental thresholds currently keeping pests in check could be exceeded due to increased precipitation variability. This is likely to make pest outbreaks more common because of increased climate variability (Walthall et al., 2012). Any kind of extreme, whether it is wet or dry conditions, is unfavorable for farmers and could result in high populations of pests. For example, in periods of excess rainfall, there tend to be pockets of stagnant water. If there are small dips in the soil, near an agricultural field, this could create a breeding ground for mosquitoes and other water-dependent pests. The pests that breed in the stagnant water pools could potentially impact nearby crops by eating them or stinging farmworkers. Therefore, in Figure 8 which shows how each SSP changes every 20 years, there could be pest outbreaks in wetter years like 2081-2100.

Furthermore, pasture (hay) is affected by variability in rainfall which affects livestock farmers in Georgia in particular. One cattle farmer from Woodbury, Georgia has a strong stance on rainfall. Speaker 2312 commented, "We are either getting way too much rain or not enough." In the previous year, their farm struggled with too much rain which resulted in not being able to harvest the hay (by cutting and baling it) due to a lack of drying time. There was too much rainfall and not enough dry days, which meant that the hay had to be fed to livestock earlier in the season. Although they "don't know if there's a certain pattern … it seems like you're either getting it or you're not." This is common among farmers' attitudes toward rainfall. Particularly for livestock farmers, not only do they have to think about their animals, but also the animal feed like hay and grass. Therefore, changes to annual mean levels of precipitation as shown in Figure 8 have impacts for all farmers in Georgia, and for livestock feed too. Since livestock makes up 9% of Georgia's agricultural sector, this could cause extreme financial losses for livestock farmers and Georgia's economy.

Another cattle farmer from Southwest Georgia (speaker 3819) strongly believes that flooding should be more of a concern than the unpredictability of precipitation. They stated "On the farm, we're going to see more flooding. We'll have a severe drought maybe once, maybe twice a decade, but the flooding is going to be pretty intense." This suggests a different perspective on future precipitation compared to speaker 2312 who believes that drought and flooding are both causing major challenges for cattle farmers in Georgia. The implications of flooding will be further discussed in section 3.4.3**.**

3.4.2 Precipitation Levels in the Driest Month

Figure 9

Comparison of Precipitation in the Driest Month Across SSPs

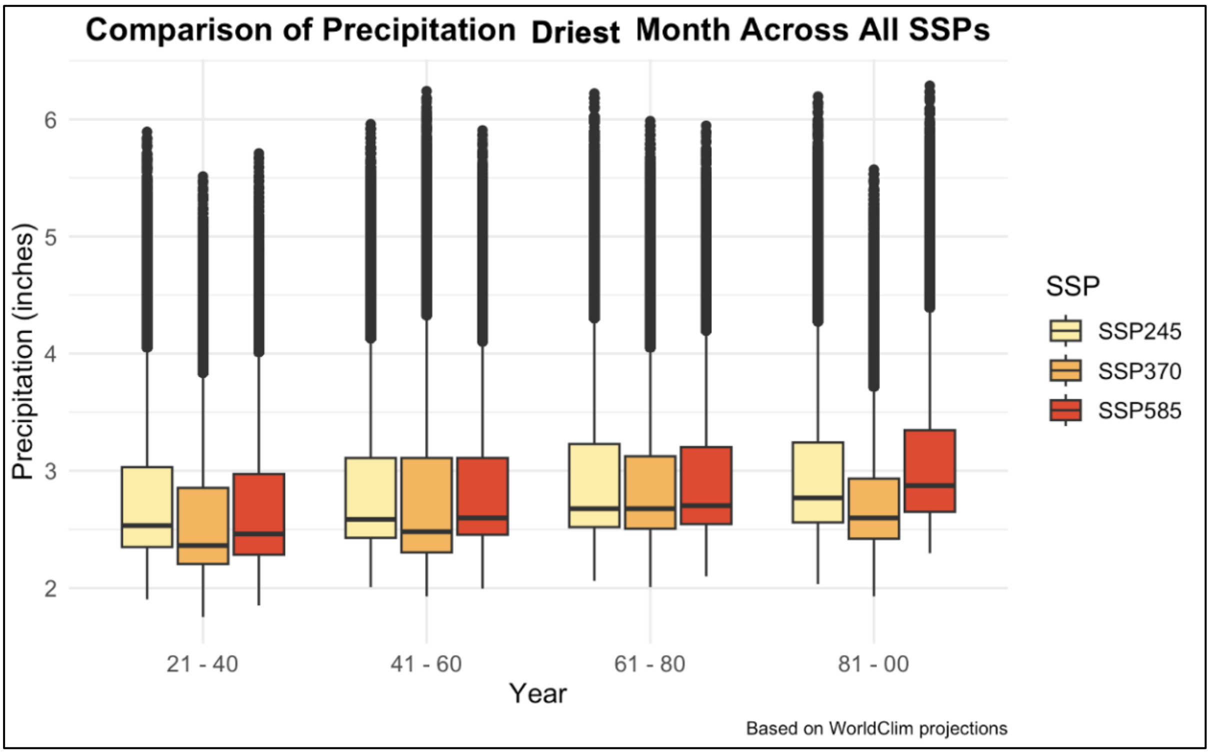


Figure 9 shows some fluctuations in the precipitation levels during the driest month across three SSPs. Overall, the precipitation numbers vary between 2 inches and 3.5 inches of rainfall, with a significant portion of outliers between the 3.5 and 6.5-inch mark. This is likely due to eco-region variability in Georgia which causes certain areas to have higher rainfall levels than others (see Figure A3). SSP245 shows a small increase spread out over relatively consistent figures ranging from 2.5 inches to 2.7 inches. SSP370, on the other hand, shows an overall bell-shaped curve, starting at 2.4 inches and increasing to 2.6 inches. For the final SSP (585), average precipitation levels increase more than they do in SSP245 and SSP370, reaching 2.8 inches. The low levels of rainfall could be associated with many different climate events and extreme weather events such as drought and extreme heat. This creates a positive feedback loop as when the weather is drier and hotter, there will be less rainfall, and the cycle will keep continuing in a vicious loop. Dry conditions could have many implications for agricultural systems, especially on yield and soil quality.

During the driest month in Georgia (which tends to be between September and October), there are approximately 3 inches of rainfall (NWS, n.d.). In every SSP in Figure 9, the median precipitation level is well below 3 inches, particularly for SSP245 and SSP370. Less rainfall means crops are not getting the water they need to thrive, which can result in poor harvests, certain crops not being able to grow, and farmers losing out financially. In some cases, a lack of rainfall can result in an extreme weather event called 'a drought.' This is likely to occur during the first 20 years of Figure 9 as the precipitation levels during the driest month are extremely low. A drought is "a period of unusually persistent dry weather that persists long enough to cause serious problems such as crop damage and/or water supply shortages" (USDA, n.d.). A drought tends to be paired with scorching temperatures which means farmworkers are especially at risk of being affected. Drought, combined with a lack of breaks, hot days, and poor working conditions can result in dehydration and heat exhaustion for migrant farmworkers, especially due to their lack of social protection.

Agricultural drought occurs when the "amount of moisture in the soil no longer meets the needs of a particular crop" (USDA, n.d.). They are hurting crop yields as explained by a study that states that "drought conditions result in negative departures from expected yield" (Eck et al., 2020, p.1). This means farmers have had to alter their growing seasons (similar to when there are periods of extreme heat) to have their crops planted before the drought takes place. For example, speaker 4701, a livestock and cotton and peanut in Southwest Georgia commented "we have our drought usually and July. So we had to get ahead of it and plant earlier so the crop can be mature by the time the drought and the heat gets here." This shows how farmers need to be adaptable to changes in precipitation levels and react accordingly depending on when the drought will arrive in their state.

Another farmer hints at the concerns over dry soil which is a byproduct of agricultural droughts. A sheep farmer from Carrol County, Georgia (speaker 5209) said "If it gets too dry that's a big problem, your soil life is going to degrade pretty rapidly.” Soil is generally affected by extremely dry or extremely heavy precipitation through a process called soil erosion. When there is excess rainfall during a storm or hurricane, the high intensity of rain combined with a high amount of rain can result in the top layer of the soil being washed away. The loss of topsoil can degrade land productivity, leading to reduced crop yields and long-term soil infertility. On the other hand, prolonged dry spells make the top layer of soil dry and sandy, which increases the risk of it being blown away during high-speed winds or storms.

Additionally, another study by Shin et al. (2020), uses climate models to understand future crop yield projections in the Southeast. Specifically, this study simulates the impact of higher temperatures and less rainfall in Georgia. Looking at the temperature variables, there is going to be an overall warming in Georgia and rainfall will also decrease before it increases. These findings show that with changes in temperature and rainfall, there could be lower crop yields, especially without irrigation being used to counteract the dry conditions. Even so, one solution mentioned in the study is adjusting the timing of planting crops without irrigation (Shin et al., 2020). This could potentially counteract the reductions in crop production in the future. This solution will be further discussed in the potential solutions (section four) of this paper.

There have also been concerns over lower precipitation levels affecting surface water supplies in Georgia. A fruit and vegetable farmer at the Oxford College Farm (speaker 2739) predicted “People relying on surface water are going to see problems like streams drying up and being intermittent.” This quote suggests that although warming temperatures and less precipitation are putting surface water supplies at risk, there are things that can be done to mitigate these risks such as using well water (further discussed in section four). In addition, during periods of dry spells and a lack of rainfall, water reservoirs are not being replaced as frequently as they used to, which causes water scarcity issues and raises costs for farmers. During these periods, less water is likely to flow into the Chattahoochee and other major rivers which will lower the water level in Lake Lanier and other reservoirs, limiting municipal water supplies for Atlanta and other cities (EPA, 2017). Moreover, as previously discussed, warmer temperatures are affecting the rates of evapotranspiration which means that lakes and streams are being evaporated much quicker than previously, resulting in reduced water availability in reservoirs. This could potentially lead to water scarcity issues for farmers.

3.4.3 Precipitation Levels in the Wettest Month

Figure 10

Comparison of Precipitation in the Wettest Month Across SSPs

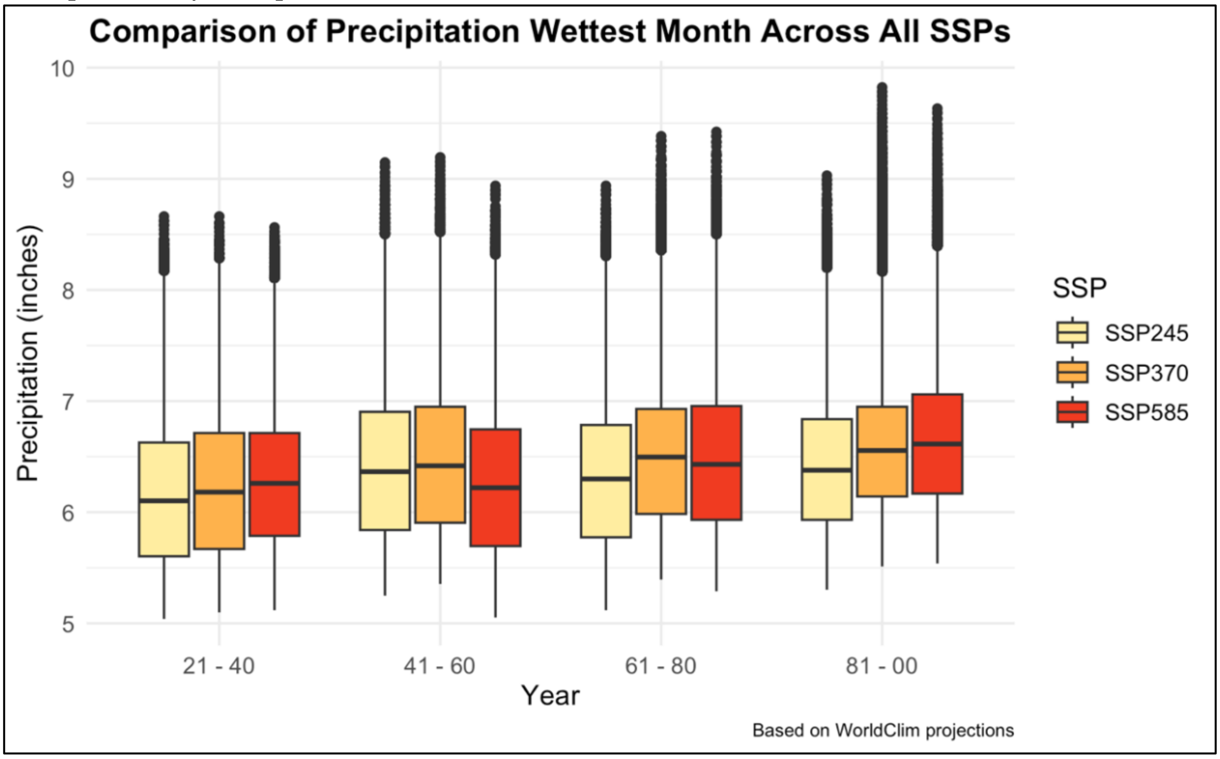


Figure 10 shows an interesting pattern for precipitation levels in the wettest month for SSP245, 370, and 585. Overall, the figures fluctuate between 5.6 inches and 7 inches of rainfall, with a significant portion of median precipitation levels between the 6.0 and 6.5-inch mark. In all three SSPs, there is a 0.3-inch increase in the median precipitation levels during the wettest month. For SSP245, precipitation increases from 6.1 to 6.4 inches. For SSP370, precipitation increases from 6.2 to 6.5 inches. For SSP585, precipitation increases from 6.3 to 6.6 inches. This is a unique pattern, as each SSP is projected to have very different future temperatures which will influence precipitation levels. Perhaps the warmer conditions in SSP585 (see Figure 3), cause more condensation for the clouds and hence produce an abundance of rain. In this situation, however, the precipitation pattern is similar for all three scenarios with SSP585 ending with the highest projected rainfall in inches. Many outliers in Figure 10 are much above the 5 and 7-inch range and stretch from between 8-10 inches. The outliers might be due to eco-region variability in Georgia which causes certain areas to have higher rainfall levels than others (see Figure A4). The outliers are also likely to cause extremely wet conditions which could lead to flooding on agricultural fields.

The extreme amounts of precipitation falling in Figure 10 can have negative implications for crop yields due to flooding. The USDA mentions that extremely heavy rainfall can cause physical injuries to plants/crops, excessive water being injected into the root zone of crops, and enhanced pressure by pests and pathogens (Walthall et al., 2012). In the Eck et al., (2020) study which talks about the negative implications of drought on crop yields, there is an equal or greater impact on crop yields during wet periods. The study finds that excess moisture in the latter part of the growing season (Sep-Oct) can be equally damaging for certain regional crops, including peanuts and sweet potatoes due to issues such as mold and fungi which are generally harbored during wetter periods of the growing season. Peanuts are commonly grown in Georgia because the moderate climate enables peanuts to thrive. While they do not require a lot of fertilizer and sequester nutrients easily, peanuts are very sensitive to excess moisture which can cause foliar disease and underground fungi to sprout. The fungal pathogens from these peanuts can rot peanut pods and kill the plants, causing farmers to lose out on their harvest and end up with a reduced yield. The risk of diseases and mold can also affect cotton crops as peanuts and cotton are used together in rotational cropping systems in Georgia. Therefore, excess precipitation levels can also cause a risk to cotton crops. With unpredictable precipitation, cotton and peanut farmers are struggling to decide when to plant their crops to avoid excess moisture conditions. This lack of certainty is causing risks to the harvests of cotton and peanuts, which contribute to the 18% row crop production of Georgia's agricultural sector.

Similarly, sweet potatoes and corn (both popular crops in Georgia) are also vulnerable to excess moisture. Corn is susceptible to excess water in the early growth stages, which can result in reduced growth or even plant death, while deficit soil water leads to less growth and yield if the stress occurs during the grain-filling period of growth (Hatfield et al., 2011). A rural land use expert from Tifton, Georgia (speaker 6101) mentioned that on their farm they "have a lot of issues with smut [soot] … a black fungus that gets into grain crops." This further proves that excess precipitation and humid, moist conditions can result in issues for farmers cultivating row crops like peanuts and corn.

On the other hand, there could be some opportunities arising from increased precipitation levels in Georgia. In a study conducted on cotton and soybean yield in the Southeast by Sharma and co-authors, there is a proven positive correlation between rainfall and cotton yield (Sharma et al., 2022). Using a panel data approach, the study assesses the impacts of climate variables such as daily maximum temperatures, and rainfall on cotton and soybean yields. The data is taken from all Southeastern states, including Georgia, and averaged per growing season. For cotton specifically, increased rainfall results in a positive effect on cotton yield. While this study is a rare piece of literature that proves there could be positive implications of increased precipitation, there is overall a need for the development of climate-resilience cotton varieties that can tolerate unpredictable climates. Specifically, the study ends by pushing for more research on drought and flood-resistant cotton and soybean varieties while simultaneously improving the current irrigation system.

In addition, water and soil availability and quality are heavily influenced by heavy precipitation levels which have a domino impact on cropping systems. The topmost layer of soil (topsoil) is especially vulnerable to high precipitation levels via soil erosion. The topsoil is the most fertile layer which contains essential nutrients and organic matter that support plant growth. During periods of rain, the topsoil is the first to be washed away. Due to its importance for the health of crops, increased precipitation and storms can degrade land productivity, leading to reduced crop yields and long-term soil infertility. One sheep farmer in Carrol County, Georgia (speaker 5209) has noticed that, like dry conditions, wet conditions also threaten the safety and sustainability of farms. Speaker 5209 is struggling to implement sustainable agricultural practices on their livestock farm, but there are concerns about heavy rainfall washing away the soil. They are worried about "the heavy rainfall. It can really degrade soil structure, particularly bare soil," which means that soil erosion is a likely issue on this farm and many other farms in Georgia.

However, prolonged dry spells that come immediately after heavy rainfall can lead to soil compaction and reduced infiltration, making it harder for water to be absorbed. This cycle of extreme wet and dry conditions exacerbates land degradation and makes water management more challenging for farmers. Additionally, when dry spells are followed by wet spells in areas of soil with limited water-holding capacity, flooding is likely to take place. This is because the soil has become dry over time and is unable to hold a lot of water at a time (Walthall et al., 2012). Flooding is not necessarily an issue in all the eco-regions of Georgia but instead in specific areas. According to speaker 3819, a sustainable farming expert in South Georgia, there is concern about flooding in the "Piedmont area where a lot of production is in the lowlands and along the mostly leveled river, [and] the floodplains, those farmers are facing a lot more risk." This quote shows that depending on where farmers are in Georgia, they face a higher or lower risk of flooding. Severe flooding will end up killing crops, while less severe flooding will weaken crops and result in lower yields for farmers (Walthall et al., 2012). Further consequences of flooding in such areas include a risk of water contamination as if there are chemical spills or interference with sewage streams, that could enter the water supply and affect irrigation sources or drinking water. On the positive side, the primary benefit of flooding could be the filling of reservoirs of irrigation water that will help hedge against drought in the future (Walthall et al., 2012), provided contamination does not occur.

Like temperature, precipitation also affects pest, pathogen, and disease populations but to a lesser extent. When there is a shock in the moisture of the ground, going from a wet to a dry and hot spell, this can have negative impacts on disease presence. In the case of tomatoes grown in Georgia, they are extremely sensitive to the wetness of the soil, and fluctuations in moisture can cause an increase in diseases. This is well described by a tomato farmer (speaker 8916). They mentioned a situation with tomatoes where there was heavy rain the day before and "the next day the sun came out, it [was] ninety-five degrees, you got soaking wet ground…and in the first forty eight hours, [they] identified about seven foliar diseases." This is one example of a situation where crops are unable to immediately adapt to changes in rainfall and when a very wet humid day is followed by a hot and dry day, the crop goes into shock and is unable to defend itself against diseases. Even spraying pesticides and fungicides in this situation cannot help, which shows how sensitive crops are to precipitation.

Alternatively, some agricultural experts see benefits to flooding in small doses for their operations. One refugee farm community worker (speaker 6553), stated that "There's positives with floods too when they're somewhat controlled." This is an unusual stance to have on flooding considering how most literature portrays flooding as an enemy for farmers. However, speaker 6553 could be hinting at benefits of flooding benefitting farmers during drier spells. This will be further discussed in solutions section (four).

3.5 Overall Impacts of Precipitation on Agriculture in Georgia

Overall, precipitation is likely to increase in the next 80 years for Georgia. These changes will have positive and negative implications for agricultural livelihoods, farmers and farmworkers, and cropping patterns. Farmers need to understand these implications and be as prepared as possible to ensure their crops are well protected in extreme conditions. Naturally, this is not an easy feat, but considering the literature and climate projections, there is enough evidence to suggest farmers must be ready for wetter conditions.

4 Potential Solutions

Although climate change will present significant challenges in the state, it may also push Georgia's agricultural system to become more sustainable and adaptable. This section will discuss some of the potential solutions regarding climate change and how our agricultural systems and Georgia's farmers can adapt to extreme temperatures and variable precipitation to best protect themselves against these shocks and hedge their farms for future years. Many solutions are directly from farmers who discuss how they have implemented their experiences with sustainable farming practices in their fields. Interestingly, these solutions are also discussed in articles from the annotated bibliography that investigate sustainable farming practices in the Southeast.

4.1 Sustainable Farming Practices

Within Georgia, agriculture accounts for 10% of GHG emissions (EPA, 2024). These emissions can be reduced using a variety of management shifts that reduce soil disturbance, increase biomass in soil/ and or support the efficient management of agricultural inputs like fertilizer, pesticides, and irrigation (Burchfield, 2024). The management shifts discussed in this section are sustainable farming practices which are designed to help promote sustainable farming and preserve the land for future generations. The practices that can help promote sustainable farming were first defined by the Food and Agriculture Organization of the United Nations (FAO) as "Climate-smart agricultural practices." Climate-smart agriculture "sustainably increases productivity, resilience (adaptation), reduces/removes GHGs (mitigation), and enhances achievement of national food security and development goals" (FAO, 2010). These practices help to reduce GHG emissions from agriculture and help food systems become more resistant to climate change. Therefore, climate-smart agriculture could be seen as a combination of adaptation and mitigation strategies towards climate change.

4.1.1 No-Till and Low-Till Agriculture

Tilling is a process that involves farmers turning the top layer of soil over before planting their crops (USDA, n.d.). Low-till agriculture means that farmers till their fields less before planting, and no-till means that farmers do not till their fields at all. Instead, they use specialized equipment to form channels that have enough room for seeds to be planted. This minimizes soil disturbance and prevents their soil from being vulnerable to wind and water erosion as well as moisture loss (USDA, n.d.). Low and no-till practices are grouped by the USDA as conservation tillage practices. These practices also help the soil sequester dioxide, as compared to tilling which causes the soil to release carbon dioxide, contributing to GHG emissions (Burchfield, 2024).

There are several recorded benefits of no-till agriculture in literature as well. In one study, Nouri and co-authors analyze 30 years of climate data and cotton yield. The findings show that long-term no-tillage situations enhance agroecosystem resilience and yield stability under climate extremes as well as maximize yield under favorable climates. The research further shows that no-tillage benefits are tied with enhanced soil structural stability and organic carbon and enhance the effectiveness of legume cover crops in stabilizing cotton yield (Nouri et al., 2021). A cotton farmer from Fort Valley, Georgia (speaker 7391) also said "no-till is just tremendously helpful because …[in] a big rain event, your level of soil infiltration is so much higher in a no-till environment, and you don't get the erosion". This quote reflects the farmer's experience with no-till agriculture, suggesting that no-till agriculture could be a beneficial solution in both a heavy precipitation situation and during a dry and warm spell because the soil can store water.

However, no-till agriculture is an expensive practice as unique equipment is required for preparing the soil. Instead of using a traditional drill, farmers need to use a no-till drill and other kinds of specialized equipment which can be costly for small-scale farms. These are upfront costs that are required and the return on investment for a no-till farm will not be immediate for farmers. Instead, they may have to wait for many years to see the long-term benefits of no-till practices which means farmers could be operating at a loss until then. There are options for farmers struggling with up-front equipment costs such as equipment sharing programs, but this is difficult if farmers need equipment at the same time. In addition, transitioning from conventional tillage to conservational tillage practices is a long-term process and involves a steep learning curve for farmers. No-till agriculture can change moisture levels in the soil which gives rise to new kinds of diseases such as soil-borne fungal diseases that conventional practices keep at bay (Huggins & Reganold, 2008). Therefore, farmers will have to learn to navigate new diseases and other nuances that come with conservation tillage practices that were not a concern when conventional practices were used.

4.1.2 Cover Cropping

According to the USDA, a cover crop is any crop grown to cover the soil and may be incorporated into the soil later for enrichment (USDA, n.d.). Cover cropping is a strategy used by many farmers which involved planting cover crops on the same field as crops that are growing to be harvested. Cover crops (including grasses, legumes, and forbs) have a wide variety of benefits including adding organic matter to the soil, protecting against pests and pathogens, reducing soil erosion, and suppressing weeds (Burchfield, 2024). The most beneficial impact for farmers is arguably improving yield production, which can improve output and increase crop revenue. In the Southeast, different cover crops are suitable for various seasons including warm and cool seasons throughout the year. During the winter, cereal rye and radish are commonly planted cover crops, in the cool season, crimson clover and annual ryegrass are planted and in the warm season, buckwheat and cowpea are regularly planted.

On the contrary, one barrier to implementing cover cropping, similar to no-till agriculture, is the extra cost of cover crop seeds which makes input costs higher for farmers. On average, the price of crimson clover is $24/acre, the price of radish is $16/acre, and cereal rye is $30/acre (USDA, n.d.). These costs add a financial barrier for farmers trying to switch to more sustainable farming practices. On top of this, cover cropping is highly dependent on growing seasons and the growing seasons of cover crops must match the cash crop being grown on a field. Often, the growing seasons of cover and cash crops may not align which means farmers will have to terminate the cover crop before harvesting the cash crop. Furthermore, there is a risk that a cover crop’s water usage may hurt cash crop yields (Hoorman, 2009). Given the potential risk of drought and extreme heat in the future in Georgia, this could steer farmers away from cover cropping as water shortages are likely to be an issue in the state in the future.

4.1.3 Rotational Cropping

Rotational cropping involves farmers varying the crops grown in each field from year to year (USDA, n.d.). This staggering of crops helps each crop to have optimal growing conditions. For example, in the discussion about cotton and peanuts in section 3.3.3, farmers use rotational cropping with peanuts being grown first, closely followed by cotton. This results in a symbiotic relationship between both crops as peanuts sequester the exact nutrients that cotton requires to grow. Peanuts are a legume that fixes nitrogen into the soil. The fixed nitrogen can later be used for cotton production which allows the cotton and peanuts to be mutualistically beneficial for each other.

Furthermore, combining rotational cropping with cover crops is helpful for farmers. An Oxford college farmer of fruits and vegetables (speaker 2739) supported the idea of rotational cropping and said, “One dream scenario is to have a farm where half of it is in cover crop and half of it is in crops for a three year period because that would eliminate a lot of those diseases that become problems for vegetables.” This is because a farm that follows a partially rotational cropped and cover cropped pattern, would have healthier soil that can mitigate many diseases. Healthier soil has organisms that attack fungi and bacteria in the soil which creates a healthier ecosystem, and as a result, more productive crops. Other benefits of rotational cropping include increasing yield, improving nutrients, and disrupting the lifecycle of pests to reduce chemical use. These are issues that were discussed in section three for both extreme temperatures and variable precipitation. Hence, rotational cropping can be a beneficial solution for agricultural systems and farmers facing climate change in Georgia.

Despite the benefits, the drawbacks of rotational cropping are an inhibitor of the widespread adoption of rotational cropping by farmers in Georgia. For example, similar to cover cropping, in a rotational cropping system, the two crops that are grown in conjunction with each other need to have similar growing patterns and seasons. Peanuts and cotton work well together because the peanuts sequester the nutrients that cotton crops need to grow. However, a mutualistic relationship is not a universal case for all crops. In the case of rotational crops, farmers would also have an added crop to manage which would need adequate sun, soil, water, and most of all, time spent understanding and learning a new practice. In one study by Burchfield et al., (2024), an investigation was conducted on rotational cropping benefits for a variety of crops in the US. The conclusion was that the benefit of rotational cropping was noticeable for cotton and winter wheat but had the opposite impact on corn yield and a neutral impact on soybean yield. Also, the effects of rotational cropping were apparent with high fertilizer rates for soybean and wheat, and with low fertilizer usage for cotton. Therefore, some studies that investigate the drawbacks of rotational cropping suggest that this practice may not be widely adopted by all farmers in Georgia depending on what crops they specialize in.

4.2 Heat and Cold Resistant Farming Practices

Farmers are attempting to mitigate the extreme heat in the summers by building hoop houses or high tunnels that can help control the climate. They can help control moisture, humidity, and temperature levels inside the tunnels which helps mitigate the risk of working outside in extreme temperatures. This way they are not only protecting their health but are still able to harvest crops and make a living from it. One fresh-cut flower farmer in Georgia (speaker 1509) felt positive about high tunnels and said the “tunnels, with good ventilation and shade cloth ... give you some cooler temperatures” which “helps cool the soil and help everything grow better through the warmer months.” Another effective strategy that helps crops during the summer months is “having irrigation on timers and having sprinklers on timers…Just having pulses through the day when it's really hot and then you get evaporative cooling on the leaves of your plants, that can help ease some stress through the summer heat.” Therefore, high tunnels seem to be a great source of temperature control for farmers and can help them combat the rising temperatures discussed in section 3.1 both from a health perspective and from a cropping systems perspective. Annual mean temperatures as well as the maximum temperatures during the warmest month will go up in Georgia according to WorldClim projections, so farmers in the field must take the precautions needed to protect themselves. Nonetheless, features like high tunnels come at a financial cost for farmers, and many small farmers cannot afford those costs. Recently there have been some federal funding programs to help small farmers afford infrastructure like high tunnels. These programs come in the form of grants sponsored by the USDA's National Resource Conservation Service which several small farms in Georgia have utilized successfully.

To save on the cost of high tunnels and other cooling features, farmers often choose to work during earlier hours of the day to escape the afternoon heat and finish their harvest before dangerous temperatures emerge. Still, there are existing organizations and programs trying to help farmworkers deal with extreme heat in Georgia. The Emory University Physicians' Assistant (PA) program started the Emory Farmworker Project in 1996 which provides necessary free health care to farmworkers across the state of Georgia (Emory University School of Medicine., n.d.). The program plays a small part in solving the healthcare justice issue for farmworkers. Heat-related illness is especially an issue for migrant farmworkers as their employee contracts rarely provide them with adequate access to healthcare and sufficient water and rest breaks throughout the day. Therefore, a solution like the Emory Farmworker Project has the potential to help many migrant farmworkers who are in tough situations. The program holds two outdoor clinics at farms around Valdosta and Bainbridge in South Georgia every June and October, providing care to around 2500 farm workers and their families each year. The clinics are run by Emory students, faculty, clinicians, interpreters, and volunteers and offer a wide range of medical services including pregnancy tests, antibiotics, and dental care along with free medications (Walljasper, 2024). Emory also partners with several other organizations around Atlanta including the PA Program at Mercer University, family therapy students from Valdosta State University, nursing students from Bainbridge College, and medical students and faculty from the University of Georgia and Morehouse University. Volunteers who are Spanish and Creolespeaking also help bridge the language barrier between medical professionals and farmworkers (Emory University, n.d.).

If this solution can be scaled up and taken on by other local Georgia Universities, particularly the larger agricultural schools, medical care can be substantially improved for migrant H-2A workers across the Southeast. Furthermore, while the H-2A program has been intended to be highly regulated to ensure farm workers are regularly monitored, get safe housing, and are provided food, water, and transport, this rarely happens in the workplace. Therefore, we require increased regulation for programs like the H-2A program which could make an immense difference to farmworkers' quality of life and well-being.

Livestock and poultry are also very vulnerable when it comes to extreme temperatures, particularly those being grazed outdoors. One agricultural expert in Georgia (speaker 2917) talked about breeding cattle that are resistant to heat. Traditionally, the main cattle that are herded in Georgia are Angus cattle which have black hides. However, Angus cattle are very sensitive to heat and in the hotter months as "they're not putting on weight, they produce less milk, and they're less fertile." This means that cattle farmers are losing out on yield because they are processing fewer cattle in the summer months and losing out on revenue as a result. To adapt to the hotter temperatures in Georgia, "they're starting to experiment with crosses with Brahmas which have a white coat and are from India so they're more heat sensitive or heat tolerant." The white coat is more reflective than black coats which absorb heat more, so by experimenting with cross breeds of cattle, farmers can ensure the health of their livestock and ensure their output is not suffering as much during the summer. Certain characteristics are considered by cattle farmers when choosing which breeds to herd on their farms including reproductive efficiency, maternal performance, growth and feed efficiency, and quality of meat (Madhuri et al., 2009). The Angus cattle, while they have darker coats and are less heat tolerant, have an increased capability to marble, bright red meat, early sexual maturity and fertility as well as higher ease of calving compared to the Brahma species (Thrift & Thrift, 2003). Therefore, from a productivity standpoint, Angus cattle outperform Brahma cattle, deciding to crossbreed or completely switch herds, is difficult for cattle farmers in Georgia.

While extreme heat is important to consider, from the WorldClim visualizations, there is also an increasing concern over extreme cold in Georgia (see Figure 7). Although Georgia is in the Southeast, winter freezes and frosts have been a common issue for farmers in the state and they must prepare adequately to deal with such extremes. For berry and peach farmers especially, their crops are vulnerable to freezes. High tunnels can help combat the extreme cold during the winter months, similar to how they combat the extreme heat in the summers. Fruit farmers can further combat the extreme cold using microjet freeze projection technology. A citrus farmer in Thomas County, Georgia (speaker 1830), mentioned that as the Georgia winter temperatures continue to drop, they use microjets (irrigation streaks that put out steady streams of water) on their citrus trees. This demonstrates how modern technologies allow crops that are sensitive to temperature extremes to grow in Georgia and how farmers are adopting them. Interestingly, some growers of blueberries and peaches see climate change as both a problem and an opportunity. While their crops are sensitive to freezes and variability in chill hours, climate change could allow farmers to discover something new. A blueberry farmer in Georgia (speaker 5468) said “You may have to change what you're growing, you may have to change the way you're growing. So you may discover something great, something awesome.”

4.3 Drought and Flood Resistant Farming Practices

Specifically concerning drought, there have been many studies in the wider agricultural context conducted on the feasibility of drought-tolerant and resistant crops. Especially as the temperature warms, there are likely to be dry spells in Georgia which can result in long periods of drought. For crops that require a high amount of water and moisture to grow, this can threaten their survival. Hence, drought-tolerant crops are a reasonable solution to the growing drought concerns in Georgia. An employee of the Georgia Water Planning and Policy Center (speaker 1591) agrees with this statement, saying that "dealing with drought means we need more drought tolerant crops." According to a research scientist in Georgia (speaker 2917), "sorghum is another one that is talked about because sorghum handles dry conditions better," showing support for the planting of sorghum in increasingly drought-prone conditions. These crops can further enable the exploitation of opportunities that may arise as a result of extended droughts. However, like all alternative crop and farming practices, there are tradeoffs associated with making the switch to drought-resistant crops. Farmers who have a substantial capital investment in crop-specific equipment, accumulated know-how, labor streams, and market networks may not be able to easily switch operations to a different crop in the short term. This means that while drought-resistant crops are a beneficial solution, it is not a simple switch for farmers but will instead require them to uproot their equipment and know-how to be replaced with another crop.

Furthermore, during droughts and warmer periods, farmers should investigate controlled and precision irrigation as a potential solution. A fresh-cut flower farmer in Georgia (speaker 1509) commented "You can just produce better, more productive crops with controlled irrigation, basically." This is because controlled irrigation allows farmers to limit the amount of water that crops are getting, which can help save water during dry spells and only give the crops what they need. This is well put by an agricultural research scientist in Georgia (speaker 2640) who said "really getting water to the plants that need it and only the amount of water they actually need" is important. This is because water often gets wasted when irrigation is not properly measured and can end up (overwatering) the soil. There is also literature to support the implementation of controlled/ precision agriculture. Shin et al., (2020), discuss the benefits of precision irrigation leading to enhanced resilience of agriculture to climate change. It could also improve water-use efficiency by adopting micro-irrigation technologies, such as sprinkler and drip irrigation along with soil moisture sensors to detect when agricultural fields have been watered enough. However, building irrigation systems requires a lot of infrastructure and can be very costly for small-scale farmers. In addition, controlled/ precision irrigation can only be applied to certain crops and on limited acreages, making this a more suitable solution for small-scale farms. There is also a need for farmers to be willing to learn how to use controlled/precision irrigation which could involve a steep learning curve and the time, and dedication required to understand how such systems work. Other water management systems such as catchments during high periods of rainfall could be helpful during drier spells and may reduce the need for irrigation systems.

Farm insurance programs could also significantly help small-scale farmers during extremely dry or extremely wet periods. This would allow farmers to insure certain crops that are especially vulnerable to climatic changes. Crop insurance payouts tend to be higher during periods of drought as compared to wetter periods, but there is still a need for insurance during wetter periods. For example, peanuts (as discussed in section 3.2.3) are very vulnerable to high rainfall and peanut farmers could risk losing their entire harvest if there is a particularly wet spell one season. Therefore, crop insurance would allow them to maintain their operations even when faced with significant crop damage. However, it is important to consider that not all crops are covered by crop insurance programs. Specifically for newer crops that are new to the market like drought or flood-resistant counterparts of cotton and corn, as well as other row crops, crop insurance programs may not exist yet. Therefore, the crop insurance argument is only applicable to a certain handful of crops being grown in Georgia.

Finally, it is important to consider that climate-smart agricultural practices are long-term solutions. Farmers looking for short-term gains and returns from their fields will struggle to see them with climate-smart practices as no-till and cover cropping are long-term solutions. The increased input costs (such as infrastructure or seeds) make the upfront cost of climate-smart practices higher than conventional practices in many cases. There is a possibility that farmers may operate at a loss until gains are made after adopting climate-smart practices. While they do make farms more resilient to climate change, the upfront financial barriers could potentially steer farmers away from adopting climate-smart practices. Such financial barriers demonstrate a need for financial support from agricultural stakeholders such as the USDA to help cover the cost of cover crop seeds to ensure that farmers can implement climate-smart practices at a lower cost. Finally, if climate-smart practices are adopted, there will need to be training programs conducted for farm employees to understand alternate practices which will likely be new and unfamiliar. This will cost farmers time and effort, which could lead to a tradeoff between spending time on other areas of their operations.

5 Conclusion

In conclusion, uncovering what the future of agriculture will look like in Georgia under climate change is a complex task. While this thesis focuses solely on extreme temperature and precipitation variability in Georgia, there are multiple other variables that could be analyzed in relation to climate change such as wind pattern and sea surface temperature. Due to the intersectional properties of temperature and precipitation, especially between extreme heat and drought, these two variables were chosen to understand how climate change is impacting agricultural systems and farmers in Georgia.

Overall, temperatures are likely to rise in the near future, especially in SSP585 (the highest emission scenario). Some agriculturally productive parts of the state including the Southeastern Plains and Southern Coastal Plains will face maximum temperatures hitting almost 100°F during the warmest month. This could give rise to extreme heat conditions that reduce crop yield, threaten farmer and farmworker health, and create drought-like conditions that affect irrigation supply. On the other hand, an overall warming trend could result in opportunities for farmers in the form of longer growing seasons. While the cold temperatures are also likely to drop more and become more extreme, warming temperatures are more of a concern for agriculture in Georgia.

Future precipitation levels in Georgia are going to be more unpredictable than temperature change; however, there is an overall positive trend that will create wetter conditions for Georgia's agricultural systems. Wetter conditions pertain to flooding, a higher likelihood of plant diseases, negative impacts on soil quality, and more. Whereas dry conditions could lead to drought, reducing crop yield and affecting farmer livelihoods. Both ends of the spectrum are possible regarding precipitation but looking at variables such as annual precipitation levels, there is a higher likelihood of seeing increased precipitation for Georgia over the next 80 years.

Given the impacts of climate change on its agricultural systems, Georgia should look at potential solutions and adopt sustainable farming practices within reason. While this paper highlights the challenges Georgia's agricultural system will face in the future due to climate change, it also highlights opportunities. It explicitly discusses the existence of viable options that could potentially satisfy agricultural stakeholders' interests including practices to increase farm resilience to climate change while simultaneously increasing productivity and yield. The potential solutions section discusses specific solutions and farming techniques that target issues caused by extreme temperatures and extreme precipitation such as drought.

Despite the many benefits that climate-smart solutions bring, adopting them is no easy feat. To implement sustainable farming practices, systems change from the ground up is needed more than ever. Everyone has a role to play in creating fully functioning and thriving agricultural systems in Georgia. Those at the table must be farmers, particularly small-scale and migrant farmers, as well as policymakers, government officials, and scientists. Future farm policy can help create a climate-smart agricultural system that reduces GHG emissions while increasing food production and security.

With the existence of many climate-smart solutions, and the acknowledgment of its tradeoffs, there is potential to achieve resilient and equitable agricultural systems that serve the community observed. Understanding the challenges, opportunities, and barriers will help researchers gain valuable insights to inform future studies.

Appendix

Future Direction and Next Steps

The future direction of this research will focus on interactions with farmers. It is important to discuss climate projections directly with farmers to understand why they have historically been skeptical of climate data. Therefore, in the future, the researchers and data collectors from this paper will conduct focus groups with farmers across Georgia to understand their perspectives and interpretations of this study. In addition, since the interviews used in this paper were primarily with farmers and not farmworkers, there is an opportunity to understand a firsthand farmworker perspective. Since farmworkers have less socioeconomic protections, they are more vulnerable to extreme temperatures and therefore may provide a unique perspective to this research. It will also be crucial to understand how to communicate the findings from this paper with different stakeholders including farmers and farmworkers. Not only are the education levels likely to be different, but there could be inherent biases that both groups have about climate change data which must be considered.

Eventually, this paper will be converted into an infographic that will combine the main findings of future temperature and precipitation in Georgia, with existing farm policy. Farm policy is crucial to understanding how climate change will affect agriculture in the state of Georgia, therefore it must be considered and well-researched. Overall, by communicating the information from this study with farmers and farmworkers, there can be a more holistic input on trends.

Figure A1

Minimum Temperature Coldest Month from 2021-2100 (SSP370)

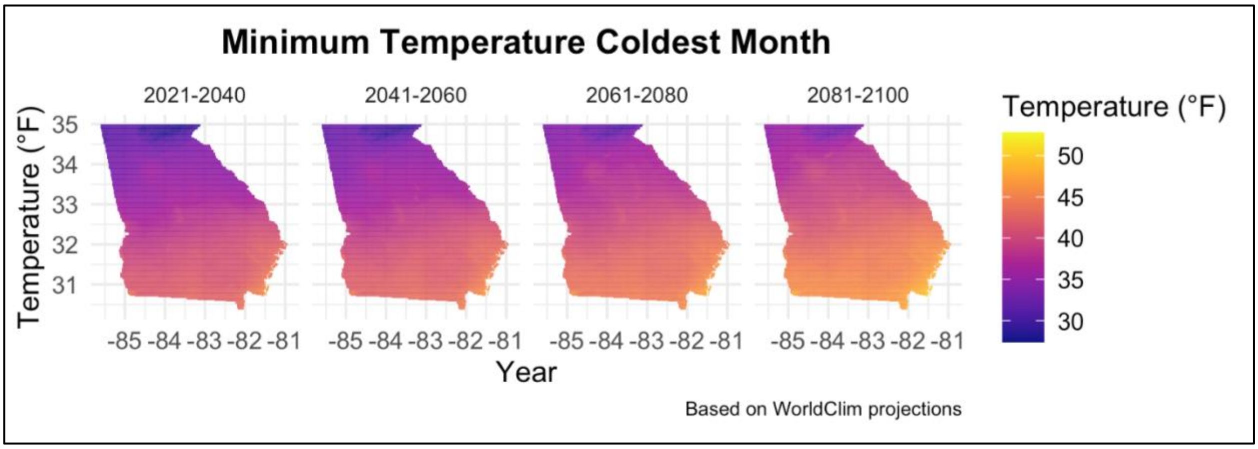


Figure A2

Average Annual Precipitation from 2021-2100 (SSP370)

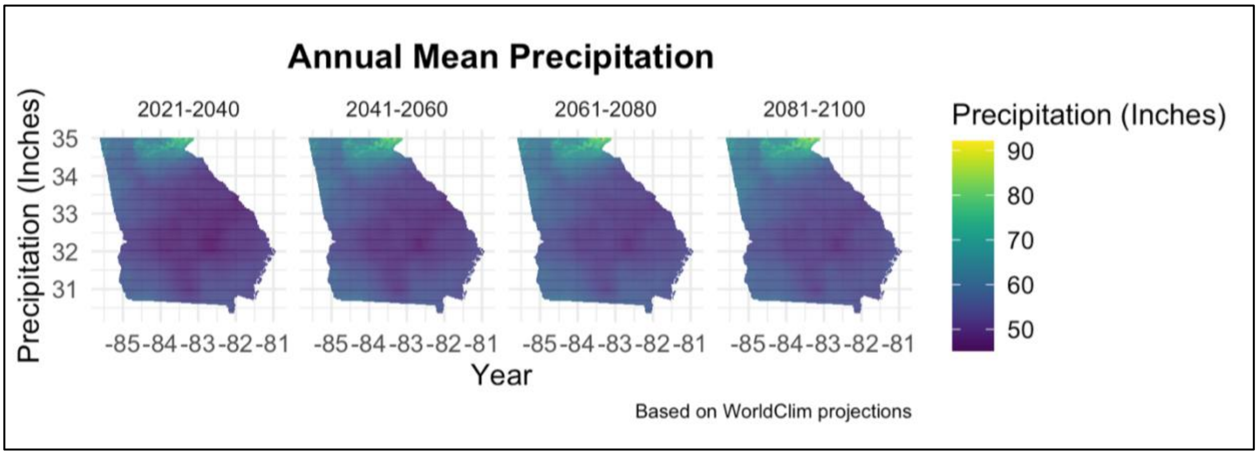


Figure A3

Precipitation in the Driest Month from 2021-2100 (SSP370)

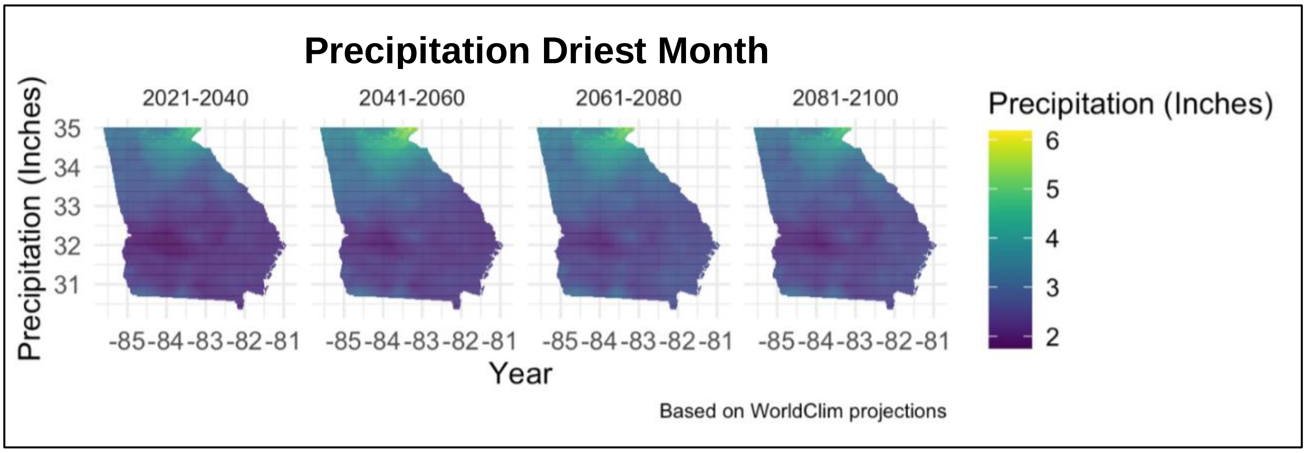
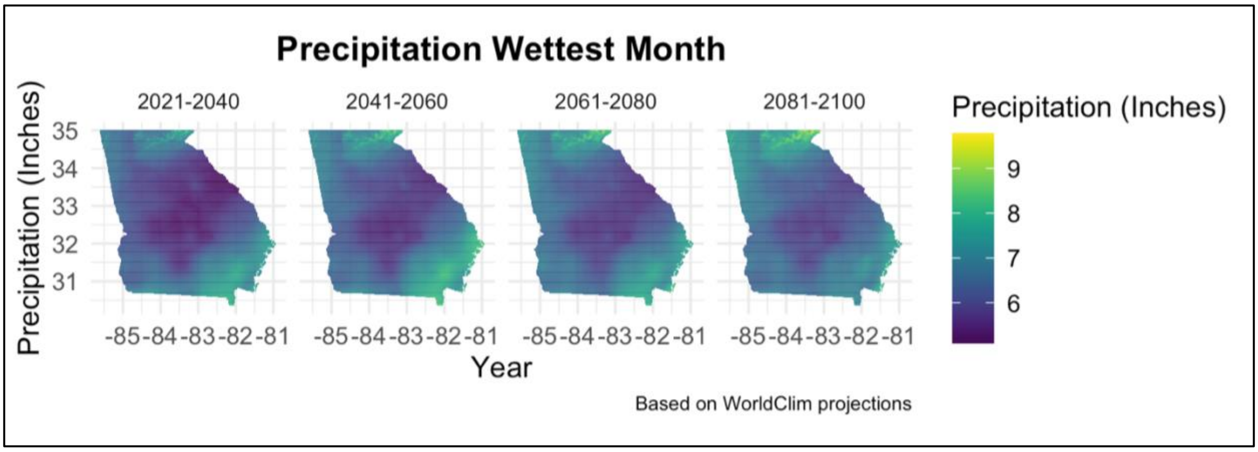


Figure A4

Precipitation in the Wettestt Month from 2021-2100 (SSP370)



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