ABSTRACT

Title of Thesis: CLIMATE CHANGE IMPACTS AND ADAPTATIONS IN EASTERN US CROP PRODUCTION

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Climate change is affecting crop production in the Eastern US and is expected to continue doing so unless adaptation measures are employed. In the first study, we conducted surveys and interviews to identify crop management practices currently used as adaptations in the Mid-Atlantic US. The results pointed to a variety of water and soil management practices, changes in crop characteristics, and changes in planting dates. In the second study, we used the Agricultural Policy/Environmental eXtender (APEX) model to evaluate future climate change impacts and adaptations in Eastern US corn-soybean rotation systems. The effects of climate change on yields ranged from decreases to increases, generally improving with latitude and worsening with time. Climate change affected corn yields more negatively or less positively than soybean yields. No-tillage and rye cover cropping did not serve as effective adaptations in regards to yields. In fact, planting rye after corn and soybeans reduced corn yields.

CLIMATE CHANGE IMPACTS AND ADAPTATIONS IN EASTERN US CROP PRODUCTION

by

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Dedication

I would like to dedicate my Master's studies and thesis to my Lord and Savior, Jesus Christ, to whom I owe everything; to my fiancé, Pablo Zalduondo; to my parents, Raúl Salazar and Teresa Lahera; and to my future parents-in-law, Alfonso Zalduondo and Ana María Jiménez. Without the emotional and financial support of these people, the completion of my Master's work would not have been possible.

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Chapter 1: Introduction

According to the Intergovernmental Panel on Climate Change (IPCC)'s Fifth Assessment Report, climate change is already negatively affecting global crop production and is expected to continue doing so unless adaptive measures are taken (IPCC, 2014a). After reviewing many studies covering a large number of crops and regions, the IPCC concluded that the negative effects of climate change on yields have been more common than the positive ones, the latter occurring mainly in high-latitude regions (IPCC, 2014a). The IPCC also concluded that, without adaptation, local temperature increases of 2°C or more will likely cause decreases in the yields of major crops in tropical and temperate regions (IPCC, 2014a).

A certain level of further climate change is unavoidable due to the lag between greenhouse gas emissions and global warming (IPCC, 2014a; USDA, 2013). Even if emissions were to currently cease, the Earth's land surfaces would continue to warm for decades and its oceans for centuries due to past emissions (USDA, 2013). Climate scientists refer to this phenomenon as committed warming (IPCC, 2014a). Global temperatures will continue to increase due to committed warming and future emissions (IPCC, 2014a). Therefore, crop production will need to adapt to the projected changes in climate in order to prevent or reduce future yield declines.

The main goal of this M.S. research was to identify practices that can serve as effective adaptations in crop production in the Eastern United States (US) using both social science and modeling approaches. The second chapter contains a literature review that provides background on global climate change research, projected changes in Eastern US climate, their expected effects on crop production, and agricultural models. The third and fourth chapters describe the two research studies conducted. The fifth chapter includes a brief summary of the methods and results of both studies.

In the first study, we surveyed crop producers and interviewed agricultural Extension agents to assess current climate change impacts and adaptations in crop production in the Mid-Atlantic US. This study had two objectives:

1. Identify the main weather-related conditions affecting crop production
2. Identify crop management practices that producers are using as climate change adaptations

In the second study, we used the Agricultural Policy/Environmental eXtender (APEX) model to evaluate future climate change impacts and adaptations in corn and soybean production in the Eastern US. This study had three objectives:

1. Calibrate and validate the APEX model for corn and soybean yields in the Eastern US
2. Determine the effects of future climate change on corn and soybean yields
3. Determine the effectiveness of no tillage and cover cropping as future climate change adaptations in corn and soybean production

Chapter 2: Literature Review

Intergovernmental Panel on Climate Change

The Intergovernmental Panel on Climate Change (IPCC)—established in 1988 by the United Nations—is dedicated to the task of providing global policymakers with regular assessments of the current state of scientific knowledge on climate change (IPCC, 2013c). Made up of representatives of 195 member states, the IPCC enlists thousands of scientific experts to write, review, and edit its assessment reports (IPCC, 2013c). These scientists assess the published literature and publish reports on the physical science basis of climate change, its impacts, and options for mitigation and adaptation (IPCC, 2013c).

In 2000, the IPCC published a Special Report on Emissions Scenarios (SRES), which established a series of possible future greenhouse gas emissions scenarios. These SRES scenarios were grouped into four families—A1, A2, B1, and B2—based on four main "storylines" of future global development, which encompassed patterns of demographic, economic, political, and technological development (IPCC, 2000). The SRES scenarios were used in the IPCC's Third Assessment Report (2001) and Fourth Assessment Report (2007). In the Fifth Assessment Report, the SRES scenarios were replaced with Representative Concentration Pathways (RCPs), a set of greenhouse gas concentration trajectories. There are four RCPs, each named after the approximate increase in radiative forcing (in W/m^2) that they project for 2100 relative to 1750: RCP2.6, RCP4.5, RCP6.0, and RCP8.5 (IPCC, 2013e). The IPCC's SRES scenarios and RCPs have been the basis by which future climate data have been generated using climate models.

Climate Models

Climate models are computer programs that use mathematical equations based on the laws of physics and chemistry to simulate the Earth's climate (USDA, 2013). These models use a three-dimensional grid to divide the atmosphere into cells, which serve as computational units (USDA, 2013). At each cell, the model computes atmospheric variables based on the exchange of matter and energy with neighboring cells (USDA, 2013).

There are two main types of climate models, global climate models and regional climate models. Global climate models (GCMs) couple an atmospheric model, or general circulation model (also abbreviated GCM), with an ocean model, so they are often referred to as coupled global models or atmosphere-ocean general circulation models (AOGCMs) (IPCC, 2001). They have a low resolution—their grid cells are hundreds of kilometers wide (IPCC, 2001). Regional climate models (RCMs), however, have a higher resolution—their grid cells are at most 50 kilometers wide—so they are used to generate weather data for climate change impact studies (IPCC, 2001). These high resolution data are produced by running an RCM within the boundary conditions set by a particular GCM, or "nesting" the RCM within a GCM (IPCC, 2001).

The North American Regional Climate Change Assessment Program (NARCCAP), an international program within the University Corporation for Atmospheric Research (UCAR), works to produce high resolution future climate data for North America. NARCCAP does this by running several RCMs within different GCMs, all of which have been forced with a greenhouse gas emissions scenario from the SRES A2 family (NARCCAP, n.d.). The A2 family of scenarios describes a world that is marked by regionalization and social, economic, and technological heterogeneity (IPCC, 2000). World population increases continuously and economic growth and technological change are slower than in the other scenario families (IPCC, 2000). Under these scenarios, the concentration of carbon dioxide (CO_2) in the atmosphere is projected to reach 527 ppm by 2050 and 846 ppm by 2100 (IPCC, 2013a). Although the emissions projected by the A2 family are at the high end of the SRES scenarios, they are not the highest (IPCC, 2000).

Future Changes in Eastern US Climate

In the Eastern United States (US), increased greenhouse gas concentrations in the atmosphere are expected to result in higher temperatures, longer growing seasons, higher precipitation, and more intense precipitation events (IPCC, 2014b; USDA, 2013).

Atmospheric Carbon Dioxide Concentration

The concentration of CO_2 in the atmosphere will very likely continue to increase during the 21st century because emissions will very likely continue for some time, even if their rate stabilizes or decreases (IPCC, 2013d). Under the RCP2.6 pathway, a mitigation scenario, the CO_2 concentration peaks in 2050 at 443 ppm and decreases thereafter, reaching 421 ppm by 2100 (IPCC, 2013a; IPCC, 2013e) (Fig. 1.1). Under the RCP4.5 pathway, a medium-low stabilization scenario, the CO_2 concentration reaches 487 ppm by 2050 and stabilizes in 2100 at 538 ppm (IPCC, 2013a; IPCC, 2013b; IPCC, 2013e). Under the RCP6.0 pathway, a medium-high stabilization scenario, the CO_2 concentration reaches 478 ppm by 2050 and 670 ppm by 2100, stabilizing in 2150 at approximately 750 ppm (IPCC, 2013a; IPCC, 2013b; IPCC, 2013e). Finally, under the RCP8.5 pathway, a very high emissions scenario, the CO_2 concentration reaches 541 ppm by 2050 and 936 ppm by

2100, stabilizing in 2250 at approximately 2000 ppm (IPCC, 2013a; IPCC, 2013b; IPCC, 2013e).

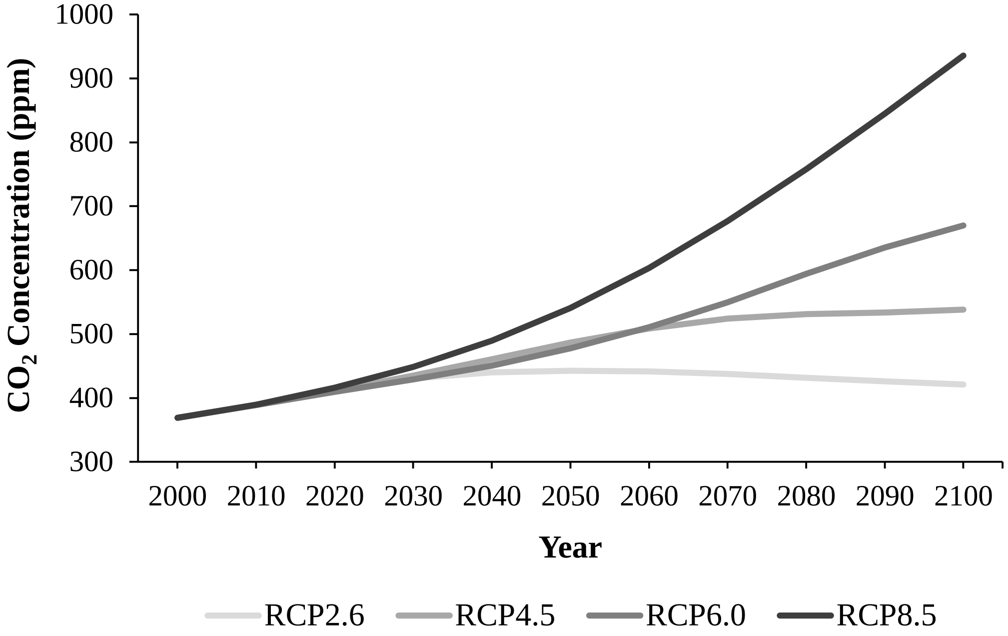

Figure 1.1. Atmospheric carbon dioxide (CO_2) concentrations projected by the Representative Concentration Pathways (RCPs) developed by the Intergovernmental Panel on Climate Change (IPCC). Data obtained from the Contribution of Working Group I to the Fifth Assessment Report of the IPCC (Annex II, Table AII.4.1).

Temperature

Relative to the late 20th century (1986–2005), the mean annual temperature in the Eastern US is projected to increase by 1–3°C by the mid-21st century (2046–2065) and 1–5.5°C by the late 21st century (2081–2100) (IPCC, 2014b). More relevant to crop production, the mean summer temperature is projected to increase by 1–2°C by the 2040s and 1.5–4.5°C by the 2080s, relative to the late 20th century (1970–1999) (USDA, 2013). The projected increase in summer temperature increases with latitude and distance from the coast (USDA, 2013).

Growing Season Length

The projected increase in temperature is expected to lengthen the growing season in the Eastern US by providing more growing degree days for crops. Under the A2 family of scenarios, the growing season length is projected to increase by 10–40 days by the end of the 21st century (USDA, 2013). As with temperature, the projected increase in growing season length increases with latitude and distance from the coast (USDA, 2013).

Precipitation

Relative to the late 20th century (1986–2005), the mean annual precipitation in the Eastern US is predicted to increase by 0–10% by the mid-21st century (2046–2065) and 0–20% by the late 21st century (2081–2100) (IPCC, 2014b). More importantly, the mean summer precipitation is expected to increase by 0–10% by the 2040s and remain the same until the 2080s, relative to the late 20th century (1970–1999) (USDA, 2013). Unlike in many other regions of the US, the length of dry spells and the occurrence of unusually dry summers are not expected to increase by an appreciable amount (IPCC, 2014b; USDA, 2013). However, the incidence of unusually heavy precipitation events is projected to increase by the mid-21st century (2046–2065) under the RCP4.5 pathway (IPCC, 2014b).

Climate Change Effects on Eastern US Crop Production

All of the changes in climate projected for the Eastern US are expected to affect crop production—some of them in more than one way—given the sensitivity of crops to CO_2 concentration, air and soil temperature, and soil moisture.

Atmospheric Carbon Dioxide Concentration

A higher atmospheric CO_2 concentration is expected to increase photosynthesis in C3 crops (e.g. soybeans, wheat, rice, cotton) but not in C4 crops (e.g. corn, sorghum, sugarcane) (USDA, 2013). The reason is that C4 plants have a higher CO_2-use efficiency and their photosynthetic rate is currently not limited by CO_2 concentration; i.e. they are already CO_2-saturated (USDA, 2013; IPCC, 2013d). A higher CO_2 concentration will also likely increase the water-use efficiency—or the amount of biomass produced per unit of transpired water—of both C3 and C4 crops. This is because at a higher CO_2 concentration, CO_2 enters the leaves through the stomata at a higher rate, allowing crops to keep their stomata open for shorter periods of time, thus reducing transpiration (USDA, 2013).

Temperature

All crops have minimum, maximum, and optimum temperatures for growth (USDA, 2013; IPCC, 2014b). In the Eastern US, summer daytime temperatures are already at the optimum level for most major crops, especially in the southern region of the Eastern US, so an increase in summer temperatures will likely lead to reduced summer growth. Higher summer temperatures could also reduce yields by increasing evapotranspiration, which would reduce water availability to crops (USDA, 2013). However, temperatures in the spring and fall are below the optimum for major crops, especially in the northern portion of the Eastern US, so an increase in spring and fall temperatures would be expected to increase growth during those months.

Growing Season Length

Higher temperatures in spring and fall would not only cause crops to grow more during those months, but would allow farmers to plant earlier and harvest later if soil conditions are appropriate (e.g. not too wet), thereby increasing the amount of time for crops to grow. However, if temperatures become too high or water too scarce in mid-summer, producers may need to switch to two short seasons with a mid-summer break (USDA, 2013).

Precipitation

The effects of precipitation on crop yields are more difficult to predict than those of carbon dioxide concentration and temperature because the connection between precipitation and soil moisture is relatively indirect. An increase in mean annual and summer precipitation would not necessarily lead to greater water availability to crops when they need it because of improper timing, increased evapotranspiration, and more intense rainfall events leading to greater runoff (USDA, 2013). Heavier rainfall events could also increase erosion, which selectively removes organic matter, fine soil particles, and nutrients from the soil, thus reducing soil fertility (Brady and Weil, 2008). For crops, more important than the total amount of rainfall during the growing season is its distribution throughout the season. For example, corn is sensitive to excess water at its early stages and to insufficient water during grain-filling (USDA, 2013).

Mitigation and Adaptation

There are two main strategies to reduce the expected negative effects from climate change: mitigation and adaptation. Mitigation is the process of reducing emissions or increasing sequestration of greenhouse gases in order to reduce or reverse further global warming (IPCC, 2014a). Adaptation is the process of making changes to human or natural systems in order to reduce the observed or expected negative effects of climate change and take advantage of the positive effects (IPCC, 2014a). These two strategies are complimentary and equally necessary (IPCC, 2014a). Mitigation is necessary because even the most effective adaptation efforts will not be able to counteract all the negative effects of climate change if greenhouse gas concentrations increase beyond a certain level (IPCC, 2014a). Adaptation is necessary because the planet will continue to warm for centuries unless current net CO_2 emissions are quickly replaced with net sequestration over a sustained period (IPCC, 2014a).

When describing adaptations in crop production, some authors have distinguished between long-term, major changes, which they define as adaptations, and short-term, minor ones, which they define as adjustments (Easterling, 1996). In this nomenclature system, adaptations are changes that transform crop production systems and require new research, technologies, market mechanisms, or government policies, including the introduction of new crops, the translocation of crops, and resource substitution (Easterling, 1996). Adjustments, on the other hand, are changes that maintain the basic structure of crop production systems while making them more resilient to future disturbances and are immediately available to producers, such as changes in the timing of operations and cultivars planted (Easterling, 1996). In this study, however, we will not distinguish between the two types of changes and refer to all of them as adaptations, as is standard practice.

Modeling Climate Change Impacts and Adaptations

In order to evaluate climate change impacts and adaptations in crop production, researchers rely on agricultural models, or computer programs that simulate agroecosystems. One of the most commonly used models is EPIC, which was developed in 1981 by researchers at the Blackland Research and Extension Center (BREC) in Temple, Texas. Initially EPIC stood for Erosion Productivity Impact Calculator since it was designed to predict the effects of soil erosion on productivity in agricultural systems (BREC, 2014). Since then, it has been greatly expanded with new routines and submodels that allow it to simulate the effects of weather, soil, topography, pests, and a large variety of management practices; thus, its name was changed to Environmental Policy Integrated Climate to reflect its broader capabilities (BREC, 2014). EPIC now includes a great number of components that allow it to predict soil properties and processes, hydrologic processes, nutrient and pesticide transport, crop yields for over 100 crop species, and farm economics, among other things (BREC, 2014). Each simulation is carried out on a field up to 100 hectares in area that is internally homogenous in terms of weather, soil, aspect and slope, cropping system, and management (BREC, 2014). Therefore, one limitation of EPIC is that it cannot simulate agricultural operations made up of different fields.

In 1993, the Agricultural Policy/Environmental eXtender, or APEX, model was developed to address this need (Williams et al., 2012). APEX was created using the EPIC field component, to which a routing component was added to simulate water, sediment, nutrient, and pesticide movement between the different fields (Williams et al., 2012). Thus, APEX is capable of simulating farms or small watersheds made up of more than one homogenous field, termed a “subarea” (Williams et al., 2012). Although in the modeling study described in Chapter 4 of this thesis we used the APEX model, all of the simulated farms consisted of only one subarea. Therefore, we only used the subarea component of APEX, not the routing component, which meant that we essentially used EPIC.

Both EPIC and APEX are process models that work on a daily time-step (BREC, 2014; Williams et al., 2012). Each day in the run, the field/subarea component simulates crop growth by first calculating the potential increase in biomass based on intercepted photosynthetically active radiation, which is dependent on solar radiation and leaf area index, and radiation use efficiency, which is dependent on CO_2 concentration (Williams et al., 2012). The model then reduces the potential growth using the most severe stress that day, determined by calculating a factor (ranging from 0 to 1) for each of five stresses: insufficient water, aeration, and nutrients (nitrogen, phosphorus, and potassium) and excess temperature and salt (Williams et al., 2012). The model then obtains the actual increase in biomass by multiplying the potential increase by the lowest stress factor (Williams et al., 2012).

Crop development in the field/subarea component is driven by the daily accumulation of growing degree days, also called growing degree units (GDUs) or heat units in EPIC and APEX (Williams et al., 2012). One of the parameters of each crop is its potential heat units (PHUs), or the number of accumulated GDUs the crop requires to reach physiological maturity. An annual crop will grow from planting until its PHUs have accumulated or the crop is harvested (Williams et al., 2012). Each day, the model computes a heat unit index (HUI) by dividing the number of GDUs accumulated until then by the crop’s PHUs and uses this HUI to simulate processes like leaf area growth, biomass partitioning between shoots and roots, and yield production (Williams et al., 2012). Yield is calculated by multiplying the biomass at harvest by the harvest index at harvest (the fraction of biomass made up by the yield), the machine harvest efficiency, and the simulated pest factor (Williams et al., 2012). The harvest index increases as the crop develops, as it is dependent on the HUI (Williams et al., 2012).

EPIC has been extensively tested for its ability to accurately simulate crop yields under a wide variety of conditions in several countries (Gassman et al., 2005). It has been validated for yields of several crops—including corn, soybeans, wheat, rice, barley, sorghum, and alfalfa—in many areas of North America, as well as in South America, Europe, and Asia (Gassman et al. 2005). However, successful validation sometimes requires adjusting model parameters (Gassman et al. 2005).

EPIC has been used to study a large variety of topics, including the effects of different management practices on soil erosion, nutrient cycling and losses, soil carbon sequestration, crop yields, and farm economics (Gassman et al. 2005). It has also been used to study the effects of climate change on crop yields in different regions of the US and other countries (Gassman et al. 2005). However, few of these studies have included the Eastern US. Moreover, few modeling studies have investigated climate change adaptations in crop production, in the Eastern US or elsewhere.

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Chapter 3: Identifying Practices Currently Used by Mid-Atlantic US Crop Producers in Response to Climate Change

Abstract

Climate change is expected to affect crop production in the Mid-Atlantic region of the United States (US) in multiple ways. Given that a certain level of climate change is currently unavoidable, crop production will need to adapt to the projected changes in order to reduce the risks and take advantage of the opportunities. The main objectives of this study were to: 1) identify the main weather-related conditions affecting crop production in the Mid-Atlantic US and 2) identify crop management practices that producers in the region are employing as climate change adaptations. We surveyed 193 producers at nine agricultural conferences held in Maryland, Delaware, New Jersey, and Pennsylvania and interviewed nine University of Maryland Extension agents between January and February, 2015. The results suggest that the most important weather-related challenges to crop production in the Mid-Atlantic are those related to precipitation—unpredictability in precipitation, low summer moisture, high spring moisture, and intense rainfall events—followed by those related to temperature—unpredictability in temperature, high summer temperatures, and low spring temperatures. The results also suggest that long growing seasons are providing an opportunity for crop production. Crop producers are managing for these challenges and opportunities using several practices in the areas of water management, soil management, crop and cultivar selection, and the timing of operations. In response to low moisture, mainly a challenge in summer, producers reported using increased irrigation, high-efficiency irrigation, conservation tillage, cover cropping, and

drought-tolerant crops. Producers reported using drainage to manage for high moisture, mainly a challenge in spring, and conservation tillage and cover cropping to manage for the effects of intense rainfall events. In response to high temperatures, mainly a challenge in summer, producers reported planting heat-tolerant crops and/or cultivars. When faced with long growing seasons, producers reported planting earlier with longer-season cultivars. Finally, to manage for unpredictability in precipitation and temperature, producers reported using crop rotations and an increased diversity of crops and/or cultivars. This information can help researchers determine what types of commonly-used practices to evaluate as climate change adaptations for crop production in the Mid-Atlantic US. It can also help university extension services in the region determine the types of information and support needed by the producers they serve.

Introduction

In the Mid-Atlantic region of the United States (US), which is loosely defined as the socio-political region that lies between New England and the South Atlantic states, crop production is an important part of the constituent states' economies. In New Jersey (NJ), Pennsylvania (PA), Maryland (MD), and Delaware (DE), over half of the total land area is under harvested cropland (NASS, 2014).

In these four Mid-Atlantic states, some of the primary climate variables that affect crop production—temperature and precipitation—have undergone changes over the last century. Between 1901 and 2012, the mean annual temperature increased by 0.5–1.0°C (IPCC, 2014b). However, each season of the year has been affected differently, with winter experiencing the greatest and most widespread warming while fall the least, even cooling in some areas (USDA, 2013). Between 1951 and 2010, the mean annual precipitation increased at a rate of 10–25 cm/year per century (IPCC, 2014b). However, again there have been seasonal differences, with almost the entire region experiencing a decrease in summer precipitation yet an increase in fall precipitation (USDA, 2013).

These trends are predicted not only to continue into the future, but to increase in rate. Relative to 1986–2005, the mean annual temperature in the Mid-Atlantic is projected to increase by 1–3°C by the mid-21st century (2046–2065) and by 1–5°C by the late 21st century (2081–2100) (IPCC, 2014b). The mean annual precipitation is predicted to increase by 0–10% by the mid-21st century and by 0–20% by the late-21st century (IPCC, 2014b). The frequency of unusually hot summers and heavy precipitation events is also expected to increase (IPCC, 2014b).

Higher summer temperatures would likely reduce growth of the main crops grown in the Mid-Atlantic—corn, soybeans, and small grains—by exceeding their optimum temperatures and increasing evapotranspiration, reducing the amount of water available to crops (USDA, 2013). However, higher temperatures in spring and fall could increase growth since crop growth during these months is often temperature-limited. Increases in precipitation could help meet the crops' greater water requirements in summer. However, an increase in annual precipitation would not necessarily result in an increased supply of water to crops in summer, when they need it most, and more intense rainfall episodes could increase water losses by surface runoff (USDA, 2013).

Given the sensitivity of crops to climate, crop production in the Mid-Atlantic will need to adapt to climate change in order to reduce the risks and take advantage of the opportunities. Several practices have been proposed as possible adaptations by different authors, including certain water management practices (e.g. increased irrigation efficiency, drainage), soil management practices (e.g. conservation tillage, cover cropping), changes in the timing of operations (e.g. earlier planting), changes in the selection of crops and cultivars (e.g. greater drought- and heat-tolerance, shorter- or longer-season requirements), and pest management practices (e.g. crop rotations) (Reilly and Schimmelpfennig 1999, Easterling 1996, Rosenberg 1992).

The implementation of adaptive practices by crop producers has been studied and documented in different areas of the world, including Canada, Europe, China, Australia, and New Zealand (USDA, 2013). For example, farmers in Canada have reported using adaptive practices in the areas of water management (tile drainage), soil management (no tillage, cover cropping, and applying manure), pest management (crop rotations), and crop selection (increased crop diversity, planting herbicide- and pest-resistant cultivars, and planting a variety of cultivars with different heat unit requirements) (Reid et al., 2007). In Europe, farmers have reported planting earlier, planting new crops suited to warmer climates (such as corn and sunflowers), planting drought-tolerant crops (such as grapes), and using water and soil conservation practices (Olesen et al., 2011). In the US, however, knowledge is lacking on how producers are adapting their practices to climate change (USDA, 2013). If available, this information would help guide adaptation efforts on behalf of researchers and university extension agents by suggesting practices to study as adaptations and pointing to the information and support needs of producers.

The objectives of this study were to survey producers and interview extension agents in order to:

1. Identify the main weather-related conditions affecting crop production in the Mid-Atlantic US

2. Identify crop management practices that producers in the Mid-Atlantic US are using as climate change adaptations

We were interested in four adaptation categories—water management, soil management, changes in the selection and planting of crops and cultivars, and changes in the timing of operations—and four crop sectors—agronomic crops (corn, soybeans, and small grains), vegetables, non-perennial fruits, and hay.

Materials and Methods

Producer Survey

We surveyed crop producers by distributing questionnaires at agricultural conferences held by university extension services and non-profit organizations. We surveyed at nine conferences held in MD, DE, NJ, and PA between January 13 and February 27, 2015 (Table 3.1, Fig. 3.1). A total of 193 producers participated in the survey out of approximately 600 who received a questionnaire, yielding a response rate of approximately 30%.

Table 3.1. Conferences where crop producers were surveyed.

Conference	Number of Producers Surveyed
Conferences held by university extension services	
University of Delaware	
1. Delaware Agricultural Week	18
University of Maryland, College Park	
2. Lower Shore Agronomy Day	27
3. Central MD Vegetable Growers Meeting	18
4. Harford County Midwinter Agronomy Meeting	22
5. Caroline County Agronomy Meeting	43
6. Central MD Agronomy Update	18
7. Queen Anne's County Agronomy Day	10
Conferences held by non-profit organizations	
8. Northeast Organic Farming Association-New Jersey Chapter (NOFA-NJ) Winter Conference	15
9. Pennsylvania Association for Sustainable Agriculture (PASA) Farming for the Future Conference	22

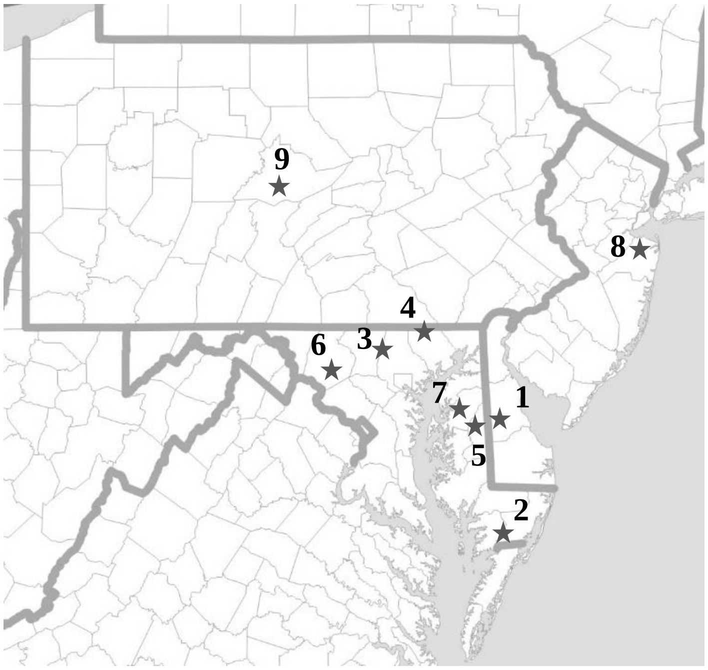

Figure 3.1. Locations of the conferences where crop producers were surveyed (numbers correspond to those in Table 3.1).

The questionnaire asked producers for three areas of information: 1) general information about themselves and their farm operations, 2) weather-related conditions that had affected their crop production the most, and 3) practices they had used to manage for such weather-related conditions (Appendix A). The general information collected was: 1) years spent managing crops, 2) average acres managed, 3) crops managed, and 4) location of managed lands. In addition to asking producers to name adaptive practices they had used, we asked them what weather-related conditions they had managed for with each practice. When naming the crops managed, weather-related conditions, and adaptive practices, producers were able to choose from several answer options, as well write down additional answers in the spaces provided. The question about weather-related conditions asked respondents to check off whether each condition they selected had a positive effect, negative effect, or both.

Extension Agent Interviews

We interviewed nine University of Maryland Extension agents representing ten MD counties between January 6 and 29, 2015. As with the surveyed producers, we asked the Extension agents for three areas of information: 1) general information about themselves and their counties' crop production, 2) weather-related challenges and opportunities faced by producers in their county, and 3) practices used by producers to manage for such challenges and opportunities. The general information collected was 1) number of years serving their county and 2) main crop sectors in their county. The interviews were conducted by telephone and were structured and open-ended.

Results

Producer Survey

General Information about Producers and Their Operations

Producer Experience

On average, surveyed producers had 25 years of experience managing crops at their respective locations. Over 80% of the producers had 40 years of experience or less and almost 90% had 50 years or less (Fig. 3.2).

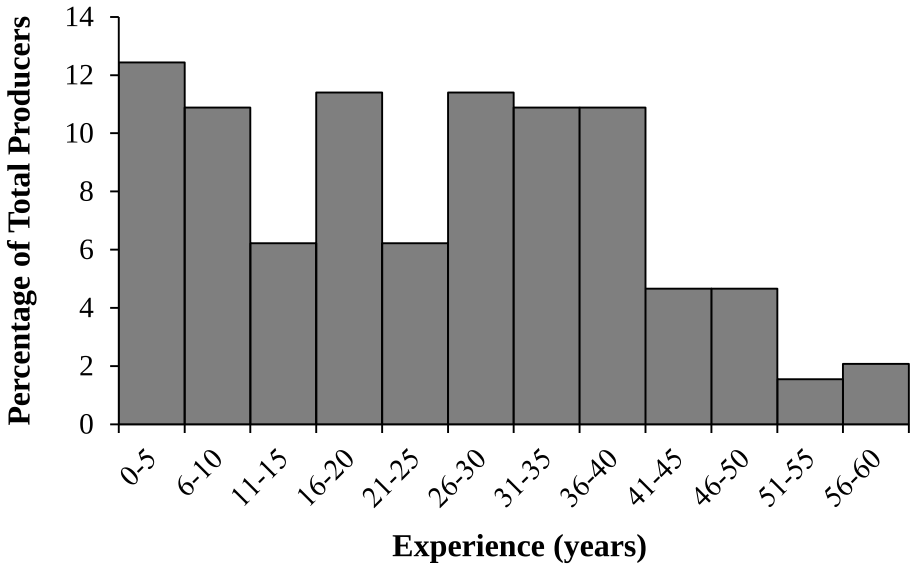

Figure 3.2. Number of years of experience that the 193 surveyed producers had managing crops.

Crop Area Managed

On average, surveyed producers managed 430 acres of crops at their respective locations. Over 55% of producers managed 200 acres of crops or less and over 75% managed 500 acres of less (Fig. 3.3).

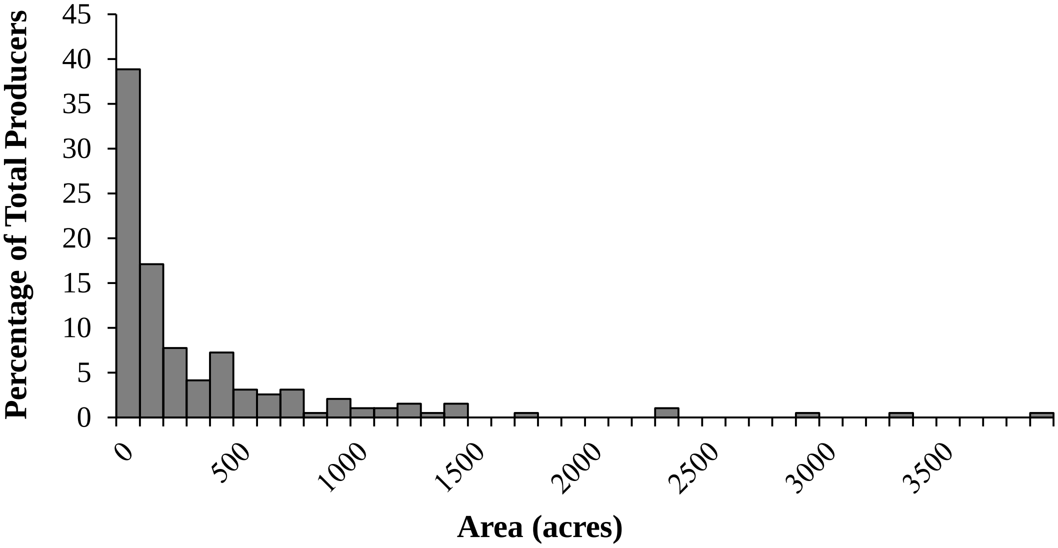

Figure 3.3. Average crop area managed by the 193 surveyed producers.

Crops Managed

The crop categories managed by the highest number of surveyed producers were corn (*Zea mays* L.) and soybeans (*Glycine max* (L.) Merr.), followed in decreasing order by small grains, vegetables, hay, and fruits (Table 3.2). The most commonly managed small grain was wheat (*Triticum aestivum* L.), followed by barley (*Hordeum vulgare* L.), rye (*Secale cereale* L.), and oats (*Avena sativa* L.). Within vegetables, market vegetables were the most commonly managed sector, followed by potatoes (*Solanum tuberosum* L.), and legumes.

Table 3.2. Crops managed by the 193 surveyed producers.

Crop	Percentage of Total Producers
Corn	68
Soybeans	68
Small grains	63
Wheat	54
Barley	28
Rye	12
Oats	6.2
Other small grain	3.1
Vegetables	46
Market vegetables	33
Potatoes	17
Legumes	7.8
Oilseeds	1.6
Sugar beets	1.0
Hay	39
Grass hay	30
Legume hay	19
Fruits	7.3

Location of Farm Operations

Most surveyed producers managed crops in MD, followed in decreasing order by NJ, PA, and DE (Table 3.3). Surveyed producers managed crops in 16 MD counties, 7 NJ counties, 13 PA counties, and all 3 DE counties (Fig. 3.4).

Table 3.3. States where the 193 surveyed producers managed crops.

State	Percentage of Total Producers*	Number of Counties
MD	87	16
NJ	8.8	7
PA	8.3	13
DE	6.7	3

* The sum of all percentages is greater than 100% because some producers managed crops in more than one state.

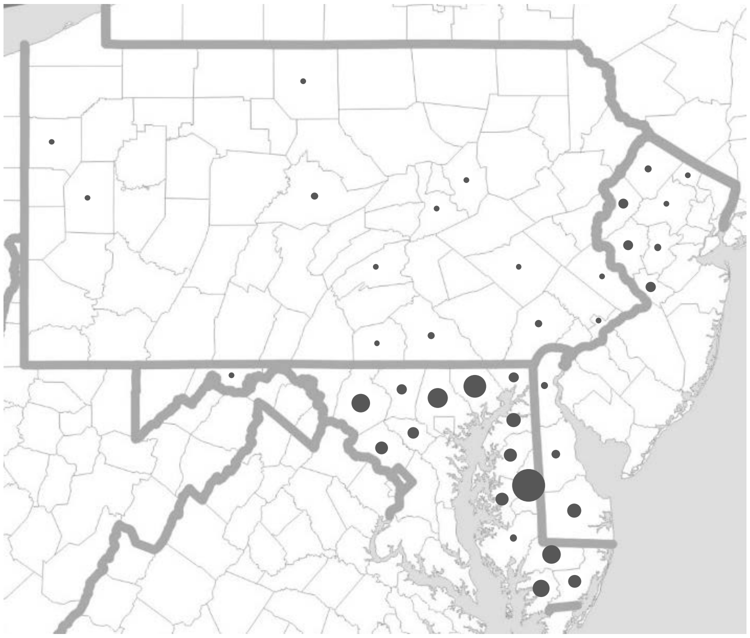

Figure 3.4. Number of surveyed producers that managed crops in each county (the area of each circle is proportional to the number of producers in the county, with the smallest size representing 1 producer and the largest size representing 43 producers).

Weather-Related Challenges and Opportunities

Of the weather-related conditions surveyed producers reported as affecting their production, all except a long growing season were cited by more producers as having a negative effect than a positive one (Fig. 3.5). The weather conditions that were most commonly reported as having a negative effect were those related to precipitation: unpredictability in precipitation, low moisture, and strong rainfall events. Although close to half of surveyed producers stated that short growing seasons are having a negative effect on production, over half of them stated that long growing seasons are having a positive effect.

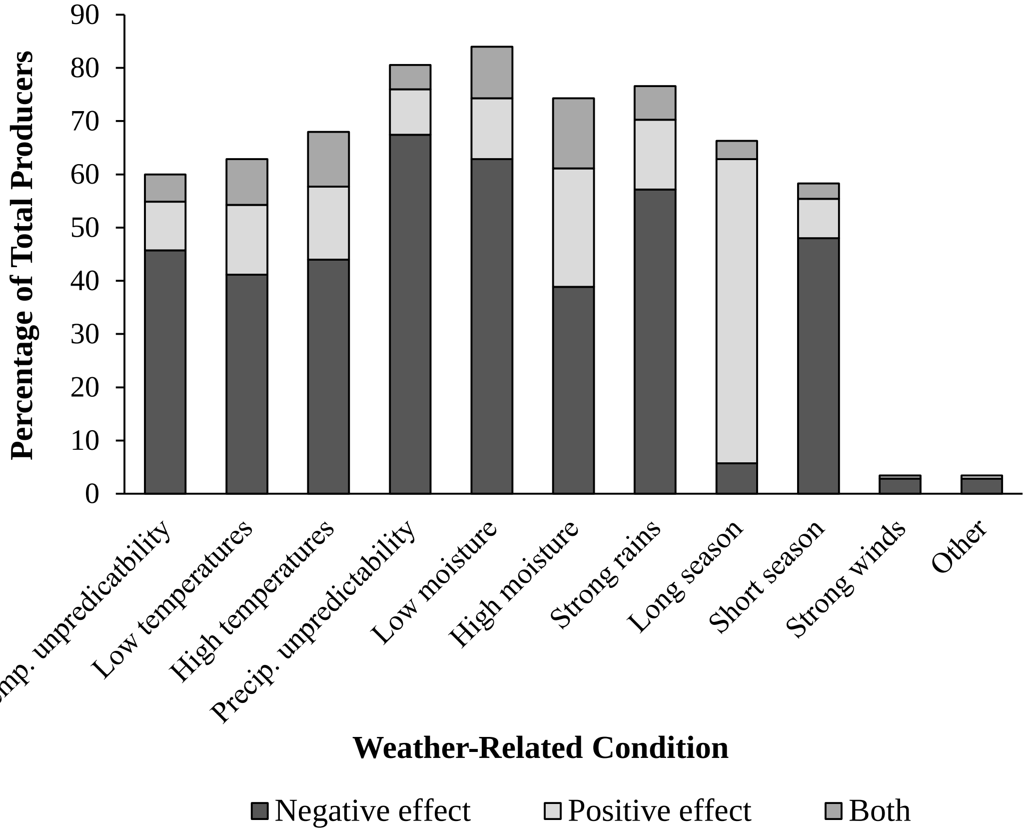

Figure 3.5. Weather-related conditions that the 193 surveyed producers reported having affected their crop production (bars are stacked).

Adaptive Practices

Water Management

High-efficiency irrigation was the water management practice that the largest percentage of surveyed producers reported using to manage for weather-related conditions, followed by increased irrigation inputs and drainage (Fig. 3.6). All three water management practices were used to manage for unpredictability in precipitation (Table 3.4). However, both high-efficiency irrigation and increased irrigation inputs were also used to manage for low moisture and high temperatures, while increased drainage was also used to manage for high moisture and strong rainfall events.

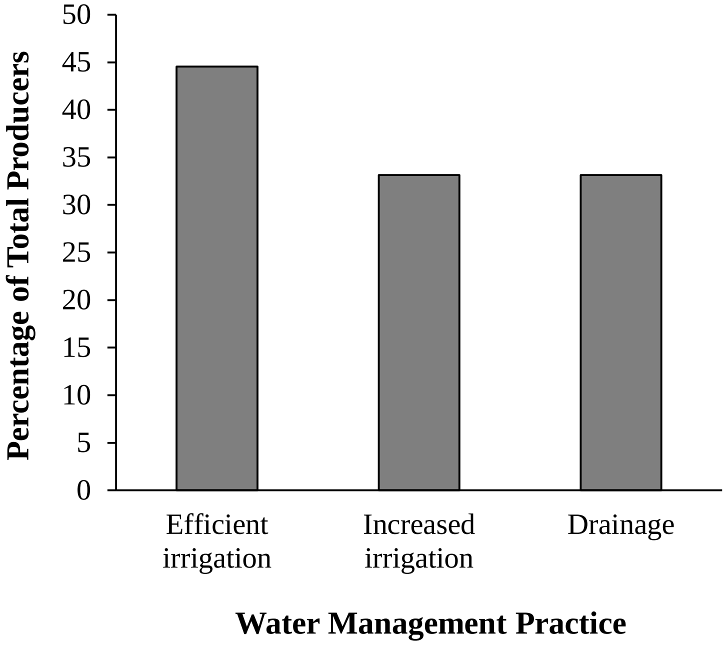

Figure 3.6. Water management practices that the 193 surveyed producers reported using in response to weather-related conditions that affected their crop production.

Table 3.4. Weather-related conditions that the 193 surveyed producers reported managing for with each of the following water management practices, as well as the percentage of producers that reported each weather-related condition out of the ones implementing the practice.

Water Management Practice	Weather-Related Condition	Percentage of Implementing Producers
High-efficiency irrigation	Low moisture	36
	Unpredictability in precipitation	27
	High temperature	13
Increased irrigation inputs	Low moisture	48
	Unpredictability in precipitation	23
	High temperature	14
Drainage	High moisture	30
	Strong rainfall events	22
	Unpredictability in precipitation	13

Soil Management

Conservation tillage was the soil management practice that the largest percentage of surveyed producers reported using to manage for weather-related conditions, followed in decreasing order by cover cropping, rotating crops, and partial or total use of organic wastes in place of inorganic fertilizers (Fig. 3.7). The type of conservation tillage most producers reported using was no tillage, followed by minimum tillage, mulch tillage, and strip tillage (Fig. 3.8). All four soil management practices were used to manage for unpredictability in precipitation, and all except crop rotations were also used to manage for low moisture and either strong rains or high moisture (Table 3.5).

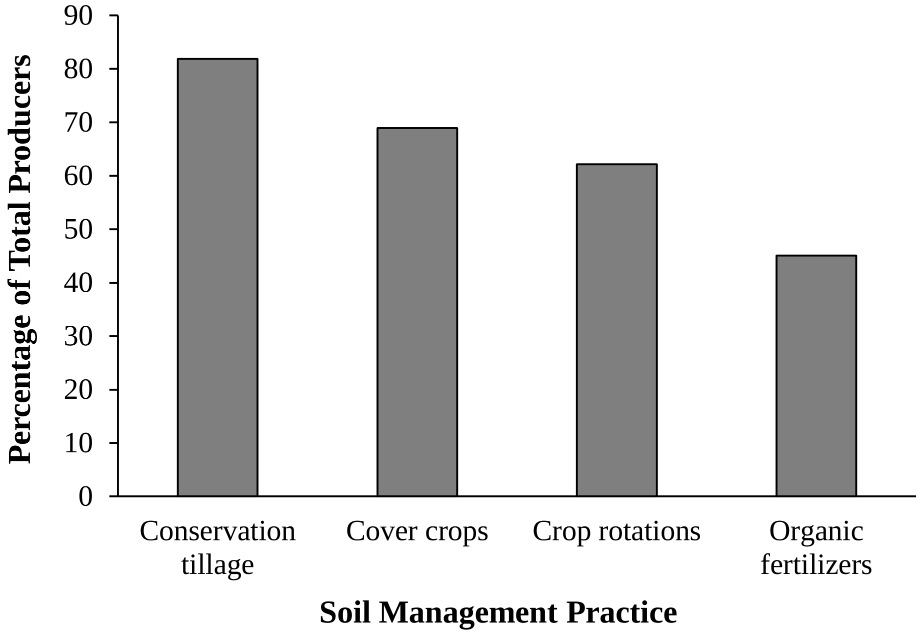

Figure 3.7. Soil management practices that the 193 surveyed producers reported using in response to weather-related conditions that affected their crop production.

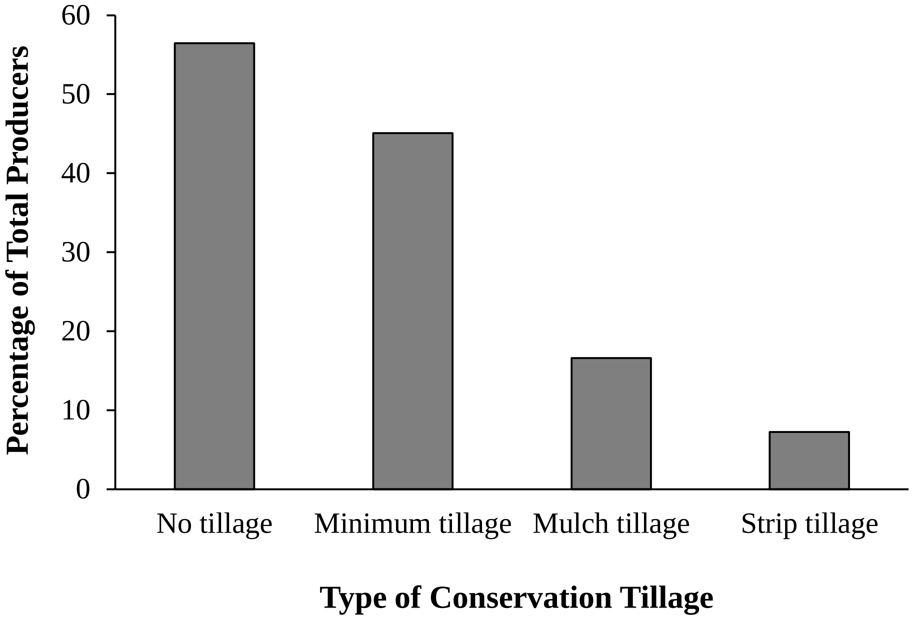

Figure 3.8. Types of conservation tillage that the 193 surveyed producers reported using in response to weather-related conditions that affected their crop production.

Table 3.5. Weather-related conditions the 193 surveyed producers reported managing for with each of the following soil management practices, as well as the percentage of producers that reported each weather-related condition out of the ones implementing the practice.

Soil Management Practice	Weather-Related Condition	Percentage of Implementing Producers
Conservation tillage	Low moisture	15
	Unpredictability in precipitation	11
	Strong rains	10
Cover crops	Low moisture	9.8
	Strong rains	7.5
	Unpredictability in precipitation	6.8
Crop rotations	Unpredictability in precipitation	5.8
Partial/total use of organic instead of inorganic fertilizers	Low moisture	9.2
	Unpredictability in precipitation	8.0
	High moisture	6.9

Changes in Crop and Cultivar Characteristics

Increased diversity was the change in crop or cultivar characteristics that the largest percentage of producers reported using to manage for weather-related conditions, followed in decreasing order by greater drought-tolerance, shorter-season crops and/or cultivars, longer-season crops and/or cultivars, greater heat tolerance, and both shorter and longer-season crops and/or cultivars (Fig. 3.9). Most of these changes were used to manage for unpredictability in precipitation and/or temperature (Table 3.6). Planting longer-season crops and/or cultivars was used to manage for high temperatures, while planting shorter-season crops and/or cultivars was used to manage for low temperatures.

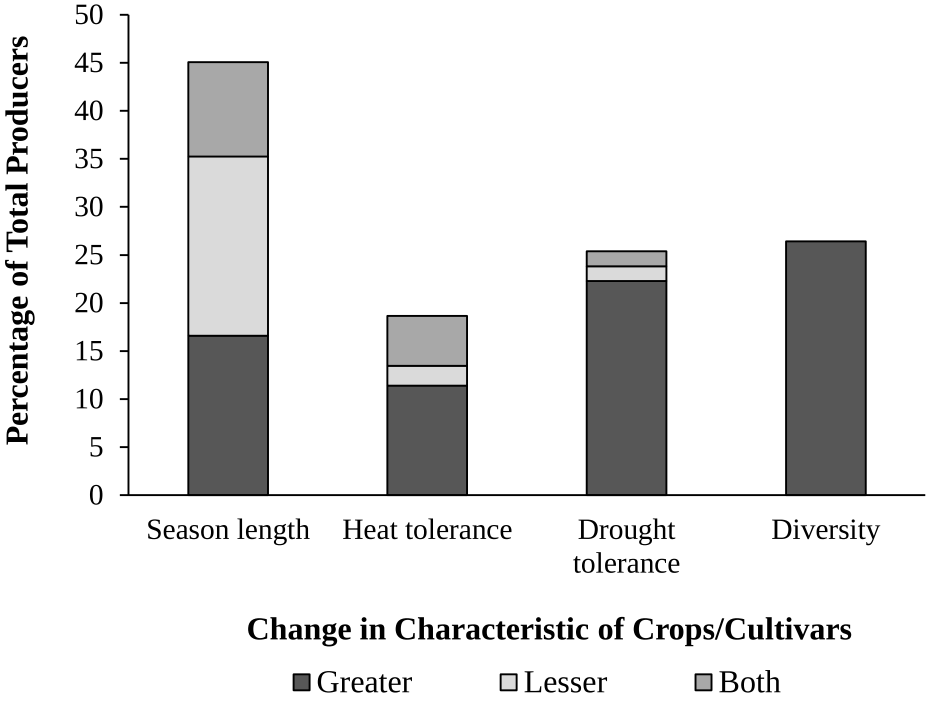

Figure 3.9. Changes in the characteristics of planted crops and/or cultivars that the 193 surveyed producers reported making in response to weather-related conditions that affected their production (bars are stacked).

Table 3.6. Weather-related conditions that the 193 surveyed producers reported managing for with each of the following changes in crop and/or cultivar characteristics, as well as the percentage of producers that reported each weather-related condition out of the ones implementing the change.

Change in Crop and/or Cultivar Characteristics	Weather-Related Condition	Percentage of Implementing Producers
Higher diversity in species/cultivars	Unpredictability in precipitation	24
	Unpredictability in temperature and low moisture	22
Change to species/ cultivars with higher drought tolerance	Low moisture	21
	Unpredictability in precipitation	9.3
Change to species/ cultivars with shorter maturity periods	Low temperature	17
	Short growing season	14
	Unpredictability in precipitation	11
Change to species/ cultivars with longer maturity periods	Long growing season	25
	Low moisture and high temperatures	13
Change to species/ cultivars with higher heat tolerance	High temperatures	50
Change to species/cultivars with both longer and shorter maturity periods	Unpredictability in precipitation	11

Changes in Planting Dates

Earlier planting was the change that the largest percentage of surveyed producers reported using to manage for weather-related conditions, followed by planting both earlier and later and finally by later planting (Fig. 3.10). Earlier planting was used to manage for low moisture and high temperature while later planting was used to manage for high moisture and low temperature (Table 3.7).

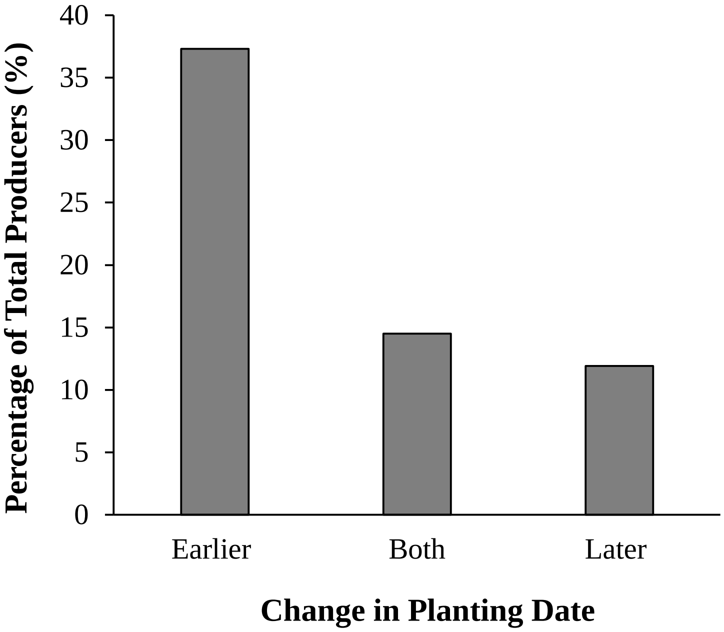

Figure 3.10. Changes in planting dates that the 193 surveyed producers reported making in response to weather-related conditions that affected their production.

Table 3.7. Weather-related conditions that the 193 surveyed producers reported managing for with each of the following changes in planting dates, as well as the percentage of producers that reported each weather-related condition out of the ones implementing the change.

Change in Planting Date	Weather-Related Condition	Percentage of Implementing Producers
Earlier planting	Low moisture	14
	High temperature	11
	Long growing season and unpredictability in precipitation	8.3
Both earlier and later planting	Unpredictability in temperature and low moisture	14
	Unpredictability in precipitation	11
Later planting	Low temperature	48
	Long growing season	26
	High moisture	22

Extension Agent Interviews

Weather-Related Challenges and Opportunities in Crop Production

Low moisture or drought was the weather-related condition interviewed agents reported most often as a challenge to crop production in their respective counties, followed in decreasing order by high moisture, low temperatures, and high temperatures (Table 3.8). Two agents reported low moisture as a challenge in summer and three agents reported high moisture as a challenge in the spring. Two agents said that high spring moisture is a problem because it leads to delayed planting, and thus a shorter growing season, as well as a higher incidence of crop diseases. According to one agent, hay production has been negatively affected by high moisture because the four consecutive dry days that are required prior to cutting hay are less likely to occur now than a few decades ago.

Only one Extension agent reported a weather-related opportunity faced by crop producers, and that was a long growing season (Table 3.8). The agent stated that vegetable producers have benefitted from early starts to the season because the ability to sell particular vegetables early in the season has given them a market advantage.

Table 3.8. Weather-related conditions reported by the nine interviewed Extension agents as affecting crop production the most in their respective Maryland counties and the number of agents who reported each condition.

Weather-Related Condition	Number of Agents
Challenges	
Low moisture/drought	8
High moisture	5
Low temperatures	3
High temperatures	2
Unpredictability in precipitation	1
Unpredictability in temperature	1
Strong rains and winds	1
Short growing season	1
Low sunlight	1
Opportunities	
Long growing season	1

Adaptive Practices in Crop Management

The water management practices Extension agents stated crop producers have used as adaptations were irrigation and drainage (Table 3.9). Irrigation was described as an adaptation to low moisture. However, only three of the eight agents that reported low moisture as a challenge named irrigation as an adaptation. Drainage was said to be an adaptation to high moisture and strong rains, but of the six agents that reported either high moisture or strong rains as a challenge, only two mentioned drainage as an adaptation.

The soil management practices agents reported as adaptations in use were cover cropping and no tillage (Table 3.9). Cover cropping and no tillage were said to be adaptations to low moisture because these practices increase soil moisture. No tillage was also said to reduce soil erosion and the time necessary to perform pre-planting operations, which allows farmers to plant earlier and therefore serves as an adaptation to short growing seasons.

Six of the nine agents reported an increase in the use of drought-tolerant crop species and cultivars as an adaptation to low moisture (Table 3.9). Four of these six agents named sorghum as the drought-tolerant species or one of such species producers are increasingly planting. Other drought-tolerant crops mentioned were soybeans (in place of corn) and millet. Three of the nine agents indicated that producers are planting corn, soybean, and small grain cultivars with shorter maturity periods as an adaptation to short growing seasons, which can be caused by low spring temperatures or high fall moisture. Other changes in crop selection and planting reported were an increase in cultivar diversity (as an adaptation to unpredictability in moisture), planting on areas with a relatively higher water table when drought is expected, and an increase in cultivars resistant to pests.

The agent who said that producers are using soybean cultivars with shorter maturity periods in response to a shorter growing season caused by wet falls stated that this practice has been accompanied by earlier harvesting (September rather than October) (Table 3.9). Another agent expressed that vegetable producers are building raised beds in the fall instead of the spring due to high spring moisture.

Table 3.9. Adaptive practices the nine interviewed Extension agents reported as being used by crop producers in their respective Maryland counties, the number of agents who reported each practice, and the weather-related conditions each practice was reported to manage for.

Adaptive Practice	Number of Agents	Weather-Related Condition
Water management		
Irrigation	3	Low moisture
Drainage	2	High moisture, strong rains
Soil management		
Cover cropping	3	Low moisture
No tillage	2	Low moisture, short season
Changes in crop selection and planting		
Drought-tolerant crop species and cultivars	6	Low moisture
Shorter-season cultivars	3	Short season
Diversity in cultivars	1	Unpredictability in precipitation
Precision agriculture	1	Low moisture
Cultivars resistant to pests	1	
Changes in timing of operations		
Earlier harvesting	1	High fall moisture
Building raised beds in fall instead of spring	1	High spring moisture

Discussion

Taken together, the results from the crop producer survey and Extension agent interviews suggest that currently the most important weather-related challenges to Mid-Atlantic crop production are those related to precipitation: unpredictability in precipitation, low moisture, high moisture, and strong rains. Given the information provided by the Extension agents, low moisture appears to be more of a challenge in summer, when temperatures and crops' water requirements are highest, whereas high moisture appears to be more of a challenge in spring because it delays planting and can increase the incidence of crop diseases. The results of both the survey and interviews suggest that low moisture has been a more important challenge to production than high moisture. Both sets of results also suggest that crop production has been negatively affected by temperature-related conditions: unpredictability in temperature, high temperatures, and low temperatures. Given the information provided by the Extension agents, high temperatures appear to be more of a challenge in summer, whereas low temperatures appear to be more of a challenge in spring because, like high moisture, they delay planting. The results of both the survey and interviews suggest that short growing seasons have been the result of high moisture and/or low temperatures in spring, whereas long-growing seasons have resulted from high temperatures and/or low moisture in spring. However, the results of the producer survey suggest that short growing seasons have been less prevalent than long growing seasons, which have presented an opportunity for crop production.

Both the survey and interview results suggest that producers have responded to all of these conditions through several adaptive practices. To manage for insufficient moisture brought about by low precipitation and high temperatures, producers appear to have used four strategies: 1) increasing water inputs through irrigation, 2) increasing irrigation water use efficiency, 3) increasing soil water retention through conservation tillage and cover cropping, and 4) reducing crop water requirements through the use of drought-tolerant species and/or cultivars, such as sorghum. Conversely, producers have responded to excess precipitation using drainage. Reducing erosion and leaching from strong rains seems to have been another reason why producers have used conservation tillage and cover cropping. In response to high temperatures, producers have selected heat-tolerant crop species and/or cultivars. The results of the survey and interviews together suggest that when warm, dry springs have allowed an early start to the growing season, producers have responded by planting earlier and using crop species and/or cultivars with longer maturity periods, as would be expected. Conversely, when colder, wet springs have caused a late start to the growing season, producers appear to have planted later and used crop species and/or cultivars with shorter maturity periods. Finally, due to unpredictability in precipitation and temperature, producers appear to have responded by increasing the spatial and temporal diversity of their crops. They have planted an increased diversity of crop species and/or cultivars and have used crop rotations.

From these results, it could be concluded that crop producers in the Mid-Atlantic are adapting to climate change using a wide variety of crop management practices already available to them. This study, however, did not investigate the effectiveness of the reported practices. Future research is required to assess the effects of these practices on yields, soil quality, nutrient losses, and other variables of interest under the expected changes in climatic conditions. Those practices that were reported by the highest percentages of producers—e.g. conservation tillage, cover cropping, crop rotations, irrigation, drainage, earlier planting, increased crop diversity, and drought-tolerant crops—could be tested first. Given that the use of drought-tolerant crops was a commonly reported practice, an important need may be the development of cultivars with greater drought-tolerance that are suited to the Mid-Atlantic US, as well as research on the introduction of more drought-tolerant crops from other areas.

Some limitations of this study must be kept in mind. The most important limitation is that, due to the general perception of producers in the Mid-Atlantic US that climate change is not occurring, the questionnaire did not ask respondents directly about changes in climate or adaptations to those changes. Instead, it asked producers about weather-related conditions that had affected their production the most and practices they had used to manage for such conditions. This may have led producers to select a large number of weather-related conditions as having had an important effect on their production, given that most producers had managed crops for over 20 years and in that time had likely observed every weather-related condition listed. Another major limitation is that, when answering the question about adaptive practices, some producers may have not read the question properly and selected all the practices they had used, regardless of whether they had used them to manage for weather-related challenges and opportunities or not. This is especially likely in the area of soil management, where a large percentage of producers reported using conservation tillage and cover cropping but a large percentage of these did not provide weather-related conditions that they managed for with those practices, suggesting that some of them did not implement those practices because of climate change but for other reasons (e.g. environmental benefits, government incentives, reducing production costs, increasing yields). For example, the Maryland Department of Agriculture provides financial incentives for farmers to plant cover crops, which may be the main reason why Maryland has the highest percentage of cropland planted to cover crops in the Eastern US (NASS, 2014). A third limitation of the producer survey is the small sample size (193 producers) used to represent all crop producers in the Mid-Atlantic region. In Maryland alone, there were 9,278 crop operations in 2012 (NASS, 2014). In addition, the large majority of the surveyed producers managed crops in Maryland and all of the Extension agents interviewed served only Maryland counties, making the results of this study more representative of Maryland than any other Mid-Atlantic state.

Conclusions

The results of this study suggest that crop producers in the Mid-Atlantic U.S. are responding to weather-related challenges and opportunities through changes in their management practices. The most important weather-related challenges appear to be those related to precipitation—unpredictability in precipitation, low summer moisture, high spring moisture, and intense rainfall events—followed by those related to temperature—unpredictability in temperature, high summer temperatures, and low spring temperatures. Although crop production has been affected by both short and long growing seasons, the results suggest that long seasons have been more prevalent, which has provided an opportunity for crop production. To manage for precipitation-related challenges, producers reported using increased irrigation, high-efficiency irrigation, conservation tillage, cover cropping, drought-tolerant crops, and drainage. To manage for high summer temperatures, producers reported planting heat-tolerant crops and/or cultivars. In response to long growing seasons, producers reported having planted earlier and having used longer-season cultivars. Conversely, in response to short growing seasons, producers reported having planted later and having used shorter-season cultivars. Finally, to manage for unpredictability in precipitation and temperature, producers reported having used crop rotations and an increased diversity of crops and/or cultivars.

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Chapter 4: Evaluating Climate Change Impacts and the Effectiveness of Soil Conservation Practices as Adaptations in Eastern US Corn-Soybean Production Using the APEX Model

Abstract

Climate change is projected to affect the atmospheric variables that control crop production in the Eastern United States (US). Given that changes in these variables over the next decades are currently unavoidable, crop production will need to adapt to the expected changes in order to prevent or reduce yield losses. The main objectives of this study were: 1) to evaluate the effects of climate change on yields in rainfed corn (*Zea mays* L.)-soybean (*Glycine max* (L.) Merr.) rotation systems in the Eastern US and 2) to test two soil conservation practices—no tillage and winter cover cropping with rye (*Secale cereale* L.)—for their effectiveness as climate change adaptations in these systems. We used the Agricultural Policy/Environmental eXtender (APEX) model to simulate corn-soybean rotation systems in the future (2041–2070) at nine land grant university research farms located throughout the Eastern US corn-soybean production belt from New York to Georgia. The simulated effects of climate change on yields varied depending on the climate model used, ranging from decreases to increases. Mean corn yields experienced decreases of 15–51% and increases of 14–85% while mean soybean yields experienced decreases of 7.6–13% and increases of 22–170%. Yield decreases were most common under the climate model predicting the highest increase in temperature and a reduction in precipitation, whereas yield increases were most common in the climate models predicting either a relatively small increase in temperature or a relatively large increase in precipitation. In many cases, the effects of climate change on yields worsened with time within the 30-year future period. The effects of climate change differed between the northern, central, and southern regions of the Eastern US, generally improving with latitude. Climate change generally affected corn yields more negatively or less positively than it did soybean yields. No tillage and rye cover cropping did not serve as effective climate change adaptations in regards to corn or soybean yields. In fact, planting rye after corn and soybeans reduced mean corn yields by 3.1–28% relative to the control (no cover crop). We speculate that this yield decrease occurred because the rye cover crop reduced the amount of soil water available to the following corn crop.

Introduction

In the Eastern region of the United States (US), crop production constitutes an important sector of the constituent states' economies. In the nine Atlantic states from New York to Georgia, between 30% and 80% of the total land area is under harvested cropland (NASS, 2014). Besides hay, the crops representing the largest percentages of total harvested cropland are corn (*Zea mays* L.) and soybeans (*Glycine max* (L.) Merr.) (NASS, 2014). In order to maximize yields, these two crops are most often grown in a two-year rotation rather than continuously (ERS, 2006). In addition, they are most commonly grown without irrigation. In the nine Atlantic states from New York to Georgia, the average percentage of cropland that is irrigated is 16% for corn and 6.5% for soybeans (NASS, 2014).

Climate change is expected to affect growing season conditions in the Eastern US by the mid-21st century. The projected changes include a higher atmospheric carbon dioxide (CO_2) concentration, higher temperatures, higher precipitation, and more intense precipitation events (IPCC, 2013a; USDA, 2013). The CO_2 concentration is expected to reach 443–541 ppm by 2050 (IPCC, 2013a). By the 2040s, the mean summer temperature is projected to increase by 1–2°C and the mean summer precipitation is projected to increase by 0–10%, both relative to the late 20th century (1970–1999) (USDA, 2013).

Predicting the effects that these changes will have on corn and soybean production is difficult due to the presence of both positive and negative effects. A higher CO_2 concentration is expected to increase photosynthesis in C3 crops (e.g. soybeans) but not in C4 crops (e.g. corn) (USDA, 2013). Higher temperatures in summer could reduce crop growth by exceeding the crops’ optimum temperatures and increasing evapotranspiration, thereby reducing the amount of water available to crops (USDA, 2013). However, higher temperatures in spring and fall could increase growth since crop growth during these months is often temperature-limited. Increases in precipitation would help supply part of the increase in crop water demand, but not necessarily all of it. In addition, more intense rainfall episodes could decrease the amount of effective precipitation by increasing the amount of water lost by surface runoff (USDA, 2013).

The expected negative effects of climate change on yields are largely due to the expected effects on agricultural soils. Plant growth is affected more by soil temperature than air temperature, so high summer air temperatures would reduce crop yields largely by increasing soil temperature (Brady and Weil, 2008). Higher soil temperatures in summer would increase soil evaporation, reducing the soil’s ability to supply water to crops when they need it most. More intense rainfall events would reduce soil fertility given that erosion selectively removes nutrients, organic matter, and clay from the soil (Brady and Weil, 2008). Warmer, drier soil conditions would increase soil organic matter (SOM) decomposition, which would in turn leave the soil more vulnerable to further erosion and nutrient deficiencies (Brady and Weil, 2008).

No tillage and cover cropping are crop management practices that offer promise as climate change adaptations due to their positive effects on soils. By increasing the amount of crop residue on the soil surface, these practices lower the soil temperature by shading and insulating and they increase soil moisture by reducing evaporation and increasing infiltration, thus reducing the negative effects of high temperatures and evapotranspiration in summer (SARE, 2007; Magdoff and Van Es, 2009). By increasing infiltration, surface cover, and SOM, no tillage and cover cropping reduce soil erosion and nutrient losses by runoff (SARE, 2007; Magdoff and Van Es, 2009). Winter cover crops also reduce nutrient losses by scavenging leftover nutrients in the fall and releasing them when they decompose in the spring (SARE, 2007). Other benefits of an increase in SOM include smaller variations in soil temperature, increased water and nutrient retention, and increased biological activity and diversity, which has numerous physical, chemical, and ecological benefits (SARE, 2007; Magdoff and Van Es, 2009).

Despite the benefits provided by no tillage and cover cropping, these practices are less prevalent in the Eastern US than their alternatives. Of the nine Atlantic states from New York to Georgia, all except Maryland have less than half of their harvested cropland under no tillage, the percentage ranging from 7% to 55% (NASS, 2014). Only three states have over half of their harvested cropland under any kind of conservation tillage (tillage that leaves at least 30% ground cover), including no tillage, the percentage ranging from 22% to 69% (NASS, 2014). None of the nine states have a quarter or more of their harvested cropland under cover cropping, the percentage ranging from 4% to 23% (NASS, 2014).

Process models that simulate crop ecosystems can be used to study climate change impacts and adaptations in crop production. One such model is the Agricultural Policy/Environmental eXtender (APEX) model, developed in 1993 at the Blackland Research and Extension Center (BREC) in Temple, Texas (Williams et al., 2012). APEX was built using routines from the Environmental Policy Integrated Climate (EPIC) model, which was developed in 1981, also at BREC, to simulate single fields that are internally homogenous in terms of weather, soil, aspect and slope, cropping system, and management (Williams et al., 2012; BREC, 2014). In order to provide a model that could simulate agricultural operations made up of one or more fields, APEX was built using EPIC’s routines for the field component, to which a routing component was added to simulate water, sediment, nutrient, and pesticide movement between the different fields. Although in this study we used the APEX model, all of the simulated farms consisted of only one field. Therefore, we only used the field component of APEX, not the routing component, which meant that we essentially used EPIC. Although for our purposes we could have used EPIC, we used APEX simply as a matter of convenience.

Models like EPIC and APEX have been used in a large number of studies to investigate climate change impacts and adaptations in crop production in different countries throughout the world (White et al. 2011). The most commonly studied crops are those that occupy the greatest agricultural land areas globally: wheat, corn, rice, and soybeans (White et al. 2011). The U.S has been the focus of the largest number of modeling studies by far, followed by countries like China, India, the UK, and Australia (White et al.

2011). However, few studies have focused on the Eastern U.S. at a regional scale. In addition, studies have concentrated more on impacts than adaptations and those that have examined adaptations have usually focused on changes in planting dates and cultivars rather than on changes in cropping systems or tillage (White et al. 2011). To our knowledge, no modeling studies have yet investigated the effectiveness of soil conservation practices as adaptations in the Eastern U.S.

In this study, we used the APEX model to evaluate the effects of climate change on yields in rainfed corn-soybean rotation systems in the Eastern US and the effectiveness of no tillage and cover cropping as adaptations in these systems. We chose to test these two practices not only because of their expected effects on soils under climate change, but also because in a previous study (described in Chapter 3 of this thesis), no tillage and cover cropping were the two practices most commonly reported by surveyed producers as being used to manage for weather-related challenges in the Mid-Atlantic US. We chose to test cereal rye (*Secale cereale* L.) as the cover crop given that rye was the cover crop reported in use by the highest percentage of producers. The research objectives were the following:

1. Validate the APEX model for rainfed corn and soybean yields in the Eastern US
2. Determine the effects of climate change on corn and soybean yields
3. Determine the effects of no tillage and rye cover cropping on yields under climate change

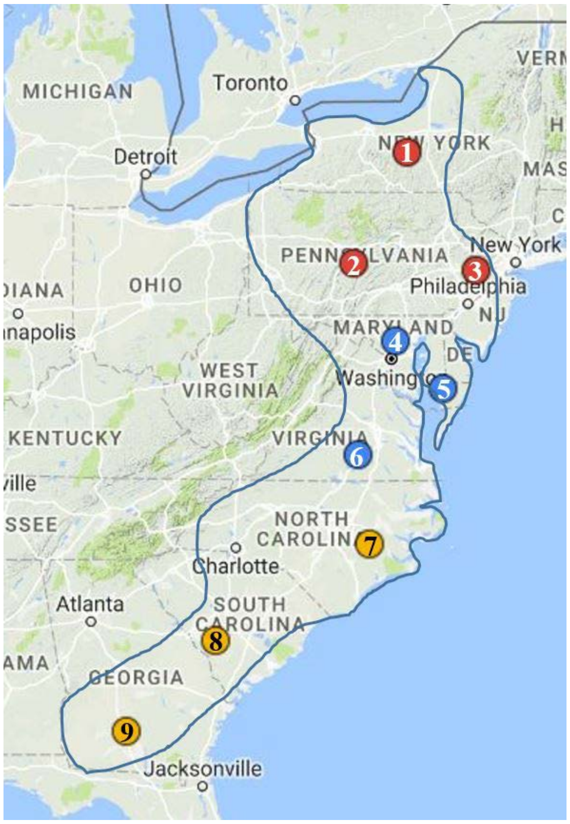
Materials and Methods

Study Area

The study area consisted of the corn-soybean production belt in the Eastern US, which lies mainly in the piedmont and coastal plain regions east of the Appalachian

Mountains, extending in a roughly north-south direction from New York to Georgia (Fig. 4.1). Because we anticipated the effects of climate change, cover cropping, and no tillage to vary with latitude, we divided the study area into three regions: North (New York, Pennsylvania, and New Jersey), Central (Maryland, Delaware, and Virginia), and South (North Carolina, South Carolina, and Georgia).

We selected nine farms to represent the study area, three farms in each region, using an approach similar to that used by Easterling et al. (1993) (Fig. 4.1). There was one farm in each state except in Delaware, where there were none, and Maryland, where there were two. All nine farms were research farms used by the land grant universities in the region to carry out corn and soybean variety trials. This allowed us to validate APEX for corn and soybean yields using the yield data from the variety trials. It also provided us with farms that were representative of farms in their area in terms of weather and soil map unit given that land grant universities establish research farms in the main agricultural areas within their state and in locations with soil map units typically used for crop production. Of the multiple research farms in each state where corn and soybean variety trials had been conducted, we selected the farm(s) that had the greatest number of years between 2000 and 2015 with both corn and soybean yield data available. Table 4.1 provides information on the nine selected farms' soil and geographic characteristics. For the purposes of this study, we named each farm after the state it was located in. In Maryland, we named the Clarksville farm MD1 and the Quantico farm MD2.



North Region

1. Musgrave Research Farm, Aurora, NY
2. Russel E. Larson Agricultural Research Center, Pennsylvania Furnace, PA
3. Snyder Research & Extension Farm, Pittstown, NJ

Central Region

4. Central Maryland Research & Education Center, Clarksville, MD
5. Lower Eastern Shore Research & Education Center, Quantico, MD
6. Southern Piedmont Agricultural Research & Extension Center, Blackstone, VA

South Region

7. Lower Coastal Plain Tobacco Research Station, Kinston, NC
8. Edisto Research & Education Center, Blackville, SC
9. University of Georgia Tifton Agricultural Experiment Station, Tifton, GA

Figure 4.1. Study region (area within solid line) and the nine research farms (numbered circles) used in the model simulations (base map courtesy of Google Maps).

Table 4.1. Soil descriptive information and geographic characteristics of the nine farms used in the model simulations.

Farm	Web Soil Survey Map Unit	Soil Subgroup	Hydrologic Group	Physical Region	Elevation (m)
NY	Lima silt loam 0–3%	Oxyaquic Hapludalfs	B	Central lowland interior plains	253
PA	Hagerstown silt loam, 3–8%	Typic Hapludalfs	B	Valley and ridge highlands	372
NJ	Quakertown silt loam, 2–6%	Typic Hapludults	C	Piedmont	79
MD1	Delanco silt loam, 3–8%	Aquic Hapludults	C	Piedmont	97
MD2	Mattapex silt loam, 0–2%	Aquic Hapludults	C	Coastal plain	2
VA	Durham sandy loam, 2–5%	Typic Hapludults	B	Piedmont	101
NC	Goldsboro loamy sand, 0–2%	Aquic Paleudults	B	Coastal plain	29
SC	Orangeburg loamy sand, 0–2%	Typic Kandiudults	B	Coastal plain	97
GA	Tifton loamy sand, 2–5%	Plinthic Kandiudults	B	Coastal plain	102

Model Description

The subarea component in APEX works on a daily time-step (BREC, 2014; Williams et al., 2012). Each day in the run, APEX simulates crop growth by first calculating the potential increase in biomass based on intercepted photosynthetically active radiation, which is dependent on solar radiation and leaf area index, and radiation use efficiency, which is dependent on CO_2 concentration (Williams et al., 2012). The model then reduces the potential growth using the most severe stress that day, determined by calculating a factor (ranging from 0 to 1) for each of five stresses: insufficient water, aeration, and nutrients (nitrogen, phosphorus, and potassium) and excess temperature and salt (Williams et al., 2012). The model then obtains the actual increase in biomass by multiplying the potential increase by the lowest stress factor (Williams et al., 2012).

Crop development in the subarea component is driven by the daily accumulation of growing degree days, also called growing degree units (GDUs) or heat units in APEX (Williams et al., 2012). One of the parameters of each crop is its potential heat units (PHUs), or the number of accumulated GDUs the crop requires to reach physiological maturity. An annual crop will grow from planting until its PHUs have accumulated or the crop is harvested (Williams et al., 2012). Each day, the model computes a heat unit index (HUI) by dividing the number of GDUs accumulated until then by the crop's PHUs and uses this HUI to simulate processes like leaf area growth, biomass partitioning between shoots and roots, and yield production (Williams et al., 2012). Yield is calculated by multiplying the biomass at harvest by the harvest index at harvest (the fraction of biomass made up by the yield), the machine harvest efficiency, and the simulated pest factor

(Williams et al., 2012). The harvest index increases as the crop develops, as it is dependent on the HUI (Williams et al., 2012).

EPIC has been extensively tested for its ability to accurately simulate crop yields under a wide variety of conditions in several countries (Gassman et al., 2005). It has been validated for yields of several crops—including corn and soybeans—in many areas of North America, as well as in South America, Europe, and Asia (Gassman et al. 2005). However, successful validation sometimes requires adjusting model parameters (Gassman et al. 2005).

Model Calibration and Validation (Research Objective One)

We calibrated and validated APEX for rainfed corn and soybean yields using the data from the non-irrigated variety trial reports published for each of the nine research farms except the NJ farm, for which there were only two years of soybean variety trial reports available. We collected information on the yields and management practices (planting and harvesting dates, planting density, row spacing, and type of tillage) during each year's variety trial. We collected information for all available years between 1997 and 2015, which resulted in 3–21 years of corn variety trial data and 3–18 years of soybean variety trial data per farm. When available in the variety trials reports, we also collected information on the soil series on which the trials took place and the soil's physical and chemical properties. When soil information was not available, we obtained it from the United States Department of Agriculture (USDA) Natural Resource Conservation Service (NRCS)'s Web Soil Survey database. We collected daily weather data from weather stations that were operated by the National Oceanic and Atmospheric Administration (NOAA) and research organizations, as well as from the APEX databases provided by the modeling team at BREC. When run, APEX filled in any gaps in the weather data by stochastically generating daily weather data using monthly weather statistics included in the APEX databases (Williams et al., 2012).

We used the information collected on yields, management practices, soils, and weather to produce input files for APEX with the objective of replicating (in a simplified manner) the variety trials at each farm. We set APEX to automatically fertilize with nitrogen and phosphorus in the amounts required by the simulated corn and soybeans, given that nitrogen and phosphorus fertilizers were used during the variety trials in the amounts necessary to meet crop requirements.

Out of the eight farms for which we had variety trial data available, we used four for calibration and four for validation. The four farms chosen for calibration were those that had the greatest number of years with data available and were approximately evenly distributed throughout the study area: PA, MD2, NC, and GA. To calibrate APEX, we ran the input files for these four farms and compared the mean simulated yields with the mean variety trial yields, i.e. the observed yields. For each farm, we calculated the absolute difference between the mean simulated yield and the mean observed yield as a percentage of the mean observed yield, as described in equation 1:

$$\Delta\overline{\mathrm{Y}} = \frac{\left|\frac{\sum_1^n Oi}{n} - \frac{\sum_1^n Si}{n}\right|}{\frac{\sum_1^n Oi}{n}} \cdot 100 \qquad (1)$$

where Oi is the observed mean yield in year i, Si is the simulated yield in year i, and n is the number of years. $\Delta\overline{\mathrm{Y}}$ quantifies the model’s accuracy in predicting multi-year mean yields, which is what we intended to use APEX for. Our objective was to obtain a mean value for $\Delta\overline{\mathrm{Y}}$ of 10% or less given that this is approximately the level of error obtained in other studies using EPIC and APEX (Bhattarai et al., 2017; Farina et al., 2011; Mudgal et al., 2012; Senaviratne et al., 2013). To achieve this, we determined which stress factors were limiting growth most often and adjusted two parameters in the APEX parameter file: the water stress weighting coefficient (parameter 38) and the upper nitrogen fixation limit (parameter 28). We set water stress to be strictly a function of soil water content (rather than actual evapotranspiration divided by potential evapotranspiration), given that water stress was the main stress limiting corn and soybean growth in the simulations. We set the upper nitrogen fixation limit at the maximum value of 20 kg/ha/day (instead of 10 kg/ha/day) in order to minimize nitrogen stress in the simulated soybeans.

After calibrating APEX for corn and soybean yields, we validated it using the four remaining farms: NY, MD1, VA, and SC. To validate APEX, we ran the calibrated model with the input files for these four farms and compared the simulated yields with the observed yields, again using $\Delta\overline{\mathrm{Y}}$ to quantify the model's accuracy in simulating yields.

In addition to quantitatively comparing the simulated yields with the variety trial yields, we graphically compared the simulated yields with the county-wide mean yields—obtained from the USDA's National Agricultural Statistics Service (NASS) "Quick Stats" database—at both the calibration farms and the validation farms. We did this because we expected the variety trial yields to be higher than the simulated yields given that the varieties tested during variety trials are those provided by seed companies, who submit their highest-yielding varieties for testing.

Data Generation[1]

Climate Change Effects (Research Objective Two)

To evaluate the effects that climate change will have on corn and soybean yields in the Eastern US (without any adaptations), we simulated a rainfed two-year corn-soybean rotation under reduced tillage and without cover cropping at each of the nine farms in the future (2041–2070) both with and without a change in climate relative to 1970–2000. We simulated reduced tillage because this type of tillage has replaced conventional tillage (intensive tillage that leaves less than 15% ground cover) as the most commonly practiced form of non-conservation tillage in the Eastern US.

All the necessary future weather data were obtained using data from the North American Regional Climate Change Assessment Program (NARCCAP). NARCCAP provides high (50 km) resolution daily weather data produced by different regional climate models (RCMs), which have been run under the boundary conditions set by different global climate models (GCMs) (NARCCAP, n.d.). All the GCMs have been forced with a greenhouse gas emissions scenario from the SRES A2 family, which projects relatively high emissions (NARCCAP, n.d.). NARCCAP chose to use this emissions scenario because, from an impacts and adaptations perspective, a higher emissions scenario provides more information than a lower emissions scenario and because the current actual emissions trajectory corresponds to a relatively high emissions scenario (NARCCAP, n.d.). Each RCM-GCM pair has been run to produce daily weather data for two periods: 1970–2000 (referred to as the “current” period) and 2041–2070 (referred to as the “future” period).

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[1] Although this modeling study was not a controlled experiment or an observational study, we borrowed terminology from these types of studies (e.g. “effect”, “treatment”, “factor of interest”, “interaction”) for lack of better terminology.

Due to the variability in future climate projections, we chose to use weather data from four different RCM-GCM pairs, which together encompassed a variety of future changes in temperature and precipitation. The four model pairs were the following:

1. Regional Climate Model version 3 (RCM3) nested within the Third Generation Coupled Global Climate Model (CGCM3)
2. Regional Climate Model version 3 (RCM3) nested within the Geophysical Fluid Dynamics Laboratory (GFDL) global climate model
3. Weather Research and Forecasting Model (WRFG) nested within the Community Climate System Model (CCSM)
4. Weather Research and Forecasting Model (WRFG) nested within the Third Generation Coupled Global Climate Model (CGCM3)

From each of these RCM-GCM pairs, we obtained daily data on the six weather variables required by APEX: maximum and minimum temperature, precipitation, solar radiation, relative humidity, and wind speed. To represent climate change, we used the daily weather data produced by each RCM-GCM pair for the “future” period and fed them directly into APEX. For the baseline climate, we used the daily weather data produced by each RCM-GCM pair for the “current” period to produce monthly weather statistics. We then set APEX to generate daily weather data for 2041–2070 using those monthly statistics. Therefore, we carried out simulations using eight different future climates at each farm, four representing no change in climate between 1971–2000 and 2041–2070 and four representing climate change. The differences in maximum temperature, minimum temperature, and precipitation predicted by each RCM-GCM pair between 1971–2000 and 2041–2070 are shown in Tables 4.2–4.4. For the baseline climate treatments, we set the atmospheric CO_2 concentration to 345 ppm, the concentration observed in 1985 (IPCC, 2013a). For the climate change treatments, we set the CO_2 concentration to 550 ppm, the concentration projected for 2055 under the A2 family of scenarios (IPCC, 2013a).

Table 4.2. Change in mean daily maximum temperature (°C) from 1970–2000 to 2041–2070 predicted by each of the four regional climate model-global climate model pairs at each of the nine farms, as well as the mean changes in each of the three regions of the Eastern US and in the entire Eastern US.

	NY	PA	NJ	MD1	MD2	VA	NC	SC	GA	North Mean	Central Mean	South Mean	Entire Area Mean
RCM3-CGCM3	+2.6	+2.5	+2.5	+2.6	+2.3	+2.4	+2.1	+2.0	+2.1	+2.5	+2.4	+2.1	+2.3
RCM3-GFDL	+2.2	+2.3	+2.2	+2.3	+2.2	+2.3	+2.1	+2.0	+2.1	+2.2	+2.3	+2.1	+2.2
WRFG-CCSM	+2.5	+2.9	+2.6	+2.8	+2.1	+2.8	+2.7	+3.0	+2.8	+2.7	+2.6	+2.8	+2.7
WRFG-CGCM3	+1.8	+1.8	+1.8	+2.0	+1.8	+1.8	+1.6	+1.6	+1.7	+1.8	+1.9	+1.6	+1.8

Table 4.3. Change in mean daily minimum temperature (°C) from 1970–2000 to 2041–2070 predicted by each of the four regional climate model-global climate model pairs at each of the nine farms, as well as the mean changes in each of the three regions of the Eastern US and in the entire Eastern US.

	NY	PA	NJ	MD1	MD2	VA	NC	SC	GA	North Mean	Central Mean	South Mean	Entire Area Mean
RCM3-CGCM3	+2.8	+2.6	+2.6	+2.6	+2.3	+2.4	+2.2	+2.0	+1.9	+2.7	+2.4	+2.0	+2.4
RCM3-GFDL	+2.3	+2.4	+2.4	+2.4	+2.3	+2.3	+2.2	+2.1	+1.9	+2.4	+2.3	+2.1	+2.3
WRFG-CCSM	+2.6	+2.7	+2.6	+2.6	+1.9	+2.5	+2.2	+2.2	+2.2	+2.6	+2.3	+2.2	+2.4
WRFG-CGCM3	+2.2	+2.0	+2.0	+1.9	+1.9	+1.9	+1.7	+1.8	+1.7	+2.1	+1.9	+1.7	+1.9

Table 4.4. Change in mean annual precipitation (mm) from 1970–2000 to 2041–2070 predicted by each of the four regional climate model-global climate model pairs at each of the nine farms, as well as the mean changes in each of the three regions of the Eastern US and in the entire Eastern US.

	NY	PA	NJ	MD1	MD2	VA	NC	SC	GA	North Mean	Central Mean	South Mean	Entire Area Mean
RCM3-CGCM3	+48	+35	+33	+41	+23	+53	+84	+137	+90	+39	+39	+104	+60
RCM3-GFDL	+11	+53	+54	+17	+41	+76	+179	+74	+12	+39	+45	+88	+57
WRFG-CCSM	-8.4	-38	-0.6	+33	-40	-19	-49	-19.9	-59	-16	-9	-43	-22
WRFG-CGCM3	+42	-34	+48	+3.4	+57	+26	+106	+123	+77	+19	+29	+102	+50

In order to produce 30 years of corn yields and 30 years of soybean yields at each farm under each of the eight future climates, we simulated first a corn-soybean rotation that started with corn and ended with soybeans and then one that started with soybeans and ended in corn. Therefore, we ran 144 simulations in total (nine farms x eight climates x two rotations). Reduced tillage was simulated by a chisel plow operation, a tandem disk operation, and a field cultivator operation 3, 2, and 1 days before planting, respectively. Cumulatively, these three operations leave 22% ground cover in APEX. Corn and soybean planting were scheduled to occur when a specified fraction of the year's total growing degree days (GDDs) had accumulated. To determine this fraction for each farm, we recorded the planting dates used during the variety trials between 1997 and 2015. For each year, we then calculated the number of GDDs that accumulated between January 1st and planting and the number of GDDs that accumulated over the entire year using the historic weather data collected when calibrating APEX. Finally, we divided the first number of GDDs by the second and averaged the resulting fraction across all the years. We also used the variety trial reports to determine the values to which to set planting density, row spacing, and potential heat units (PHUs) for corn and soybeans at each farm. Corn and soybean harvest were each scheduled to occur at the same specified date each year. The date used for each farm was the average harvest date during the variety trials. Like when calibrating APEX, we set fertilization to occur automatically so as to prevent any nitrogen or phosphorus stress in the simulated corn and soybeans. Likewise, we used the same values for the physical and chemical properties of each farm's soil as during APEX calibration.

After running each simulation, we recorded the simulated annual corn and soybean yields during the 30-year future period. We divided this period into six five-year periods (2041–2045, 2046–2050, 2051–2055, 2056–2060, 2061–2065, and 2066–2070) and averaged the yields within each five-year period, separately for corn and soybeans, in order to test whether the effect of climate change changed with time. The resulting data set for analysis was therefore comprised of six five-year mean yields for each of the two crops at each farm and under each of the eight climates.

Climate Change Adaptations (Research Objective Three)

In order to evaluate the effectiveness of no tillage and rye cover cropping as climate change adaptations, we simulated a rainfed two-year corn-soybean rotation at each of the nine farms in the future (2041–2070) under each of the following six management treatments:

1. Reduced tillage; no cover crop (RT NC)
2. Reduced tillage; rye cover crop after corn (RT CC1)
3. Reduced tillage; rye cover crop after corn and soybeans (RT CC2)
4. No tillage; no cover crop (NT NC)
5. No tillage; rye cover crop after corn (NT CC1)
6. No tillage; rye cover crop after corn and soybeans (NT CC2)

At each farm, we simulated a corn-soybean rotation and a soybean-corn rotation under each of the six management treatments and under each of the four future climates, for a total of 432 simulations (nine farms x six management treatments x four climates x two rotations). Reduced tillage was simulated in the same manner as for the second research objective. The corn and soybean planting and harvest dates, planting density, row spacing, and PHUs used were also the same as those used then. In the four treatments with a cover crop, rye was planted three days after corn or soybean harvest and was killed (without harvesting) two weeks before planting the following main crop. As before, we set APEX to automatically fertilize with nitrogen and phosphorus in the amounts required by the simulated corn and soybeans. Finally, the soil properties used at each farm were the same as those previously used.

After running each simulation, we averaged the annual yields within each five-year period, separately for corn and soybeans, as for the second research objective. Therefore, the resulting data set for analysis was comprised of six five-year mean yields for each crop at each farm and under each of the six management treatments.

Data Analysis

We analyzed the simulated corn and soybean yields as if they were measured or observed data obtained from an experimental/observational study. We analyzed the yields separately for each of the four RCM-GCM pairs as we were not interested in studying the effect of climate model. The purpose of using four different model pairs was simply to extend the scope of the study to a variety of possible future climates. Therefore, for the second research objective, we had three factors of interest: 1) region, with three levels (north, central, and south), 2) climate change, with two levels (no climate change and climate change), and 3) period, with six levels (the six five-year time periods). For the third research objective, we had four factors of interest: 1) region, 2) tillage, with two levels (RT and NT), 3) cover crop, with three levels (NC, CC1, and CC2), and 4) period.

All statistical analyses were carried out using SAS 9.3 for Windows (SAS Institute, 2011). We used ANOVA (with the PROC MIXED procedure) to determine if each of the factors and interactions had a significant effect on mean corn and soybean yields (Appendices B and C). When the cover cropping factor had a significant effect, we used Tukey's adjustment of P-values to conduct pairwise comparisons between the means of the three levels. The significance level (α) used in all statistical tests was 0.05.

Results

Model Calibration and Validation

During calibration, the mean error committed by APEX in simulating multi-year mean yields was 6.8% for corn and 8.9% for soybeans (Table 4.5). During validation, the mean error was 11% for corn and 15% for soybeans (Table 4.6). In general, APEX underpredicted yields more often than it overpredicted them, as expected. One possible explanation for the higher mean errors during validation than calibration is that fewer years of data were used for the first than for the second. Although the mean error during validation was over 10% for both corn and soybeans, it was less than or equal to 15%. When observed over time, the simulated yields replicated to a certain extent the trends in the variety trial and county-wide yields (Fig. 4.2–4.5). For these reasons, we concluded that APEX was simulating corn and soybean yields with a sufficient level of accuracy and considered it validated.

Table 4.5. Absolute differences between the mean simulated yields and mean observed yields, as a percentage of the mean observed yields, obtained when using variety trial data to calibrate APEX for rainfed corn and soybean yields at four land grant university research farms in Pennsylvania Furnace, PA, Quantico, MD, Kinston, NC, and Tifton, GA, as well as the number of years of calibration data used from each farm.

Farm	Corn		Soybeans	
	Years	Absolute Difference (%)	Years	Absolute Difference (%)
PA	16	10	18	17
MD2	16	3.4	15	1.3
NC	7	13	13	13
GA	19	0.7	5	3.8
Mean	15	6.8	13	8.9

Table 4.6. Absolute differences between the mean simulated yields and mean observed yields, as a percentage of the mean observed yields, obtained when using variety trial data to validate APEX for rainfed corn and soybean yields at eight land grant university research farms in Aurora, NY, Pennsylvania Furnace, PA, Clarksville, MD, Quantico, MD, Blackstone, VA, Kinston, NC, Blackville, SC, and Tifton, GA, as well as the number of years of validation data used from each farm.

Farm	Corn		Soybeans	
	Years	Absolute Difference (%)	Years	Absolute Difference (%)
NY	5	18	7	26
MD1	16	4.0	13	25
VA	8	4.6	8	7.1
SC	3	15	3	3.6
Mean	8	11	8	15

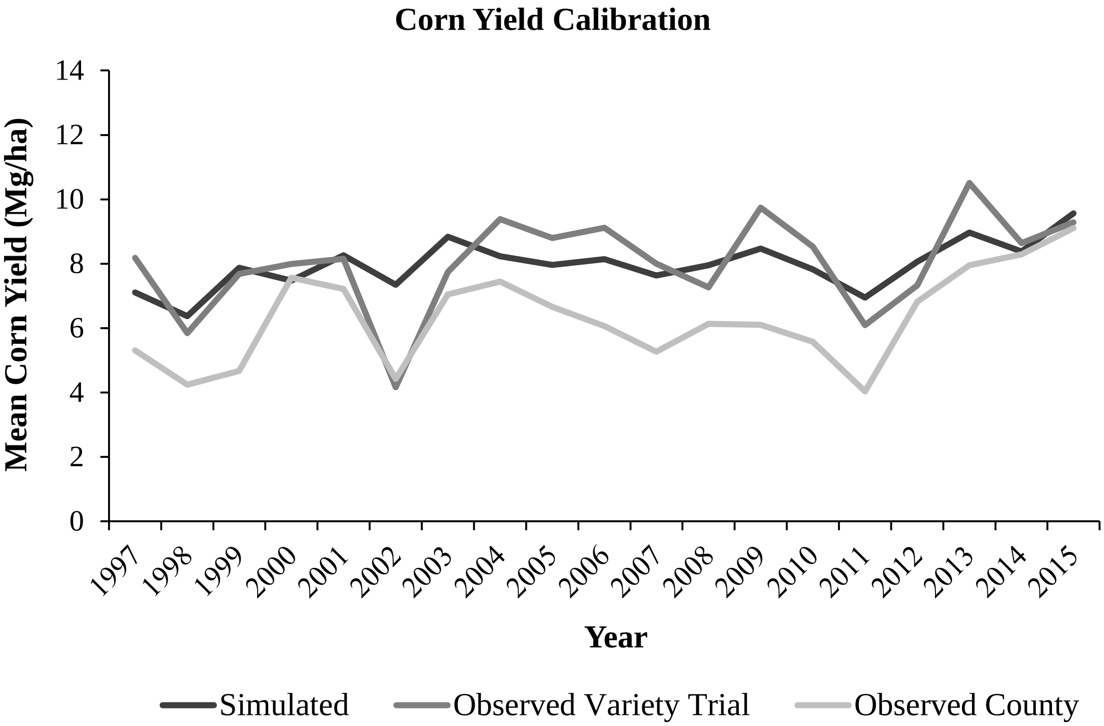


Figure 4.2. Mean simulated corn yields (dry weight basis) generated when calibrating APEX using the mean corn yields observed during variety trials carried out in four land grant university research farms in Pennsylvania Furnace, PA, Quantico, MD, Kinston, NC, and Tifton, GA, as well as the mean corn yields observed in the counties where the four farms where located.

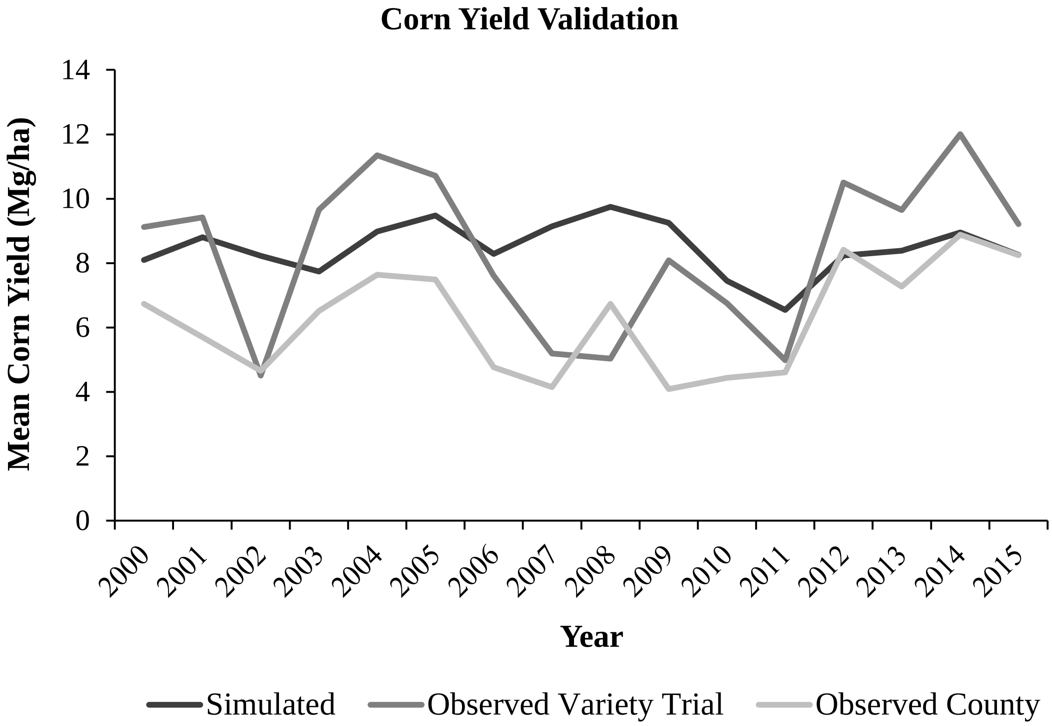


Figure 4.3. Mean simulated corn yields (dry weight basis) generated when validating APEX using the mean corn yields observed during variety trials carried out in four land grant university research farms in Aurora, NY, Clarksville, MD, Blackstone, VA, and Blackville, SC, as well as the mean corn yields observed in the counties where the four farms where located.

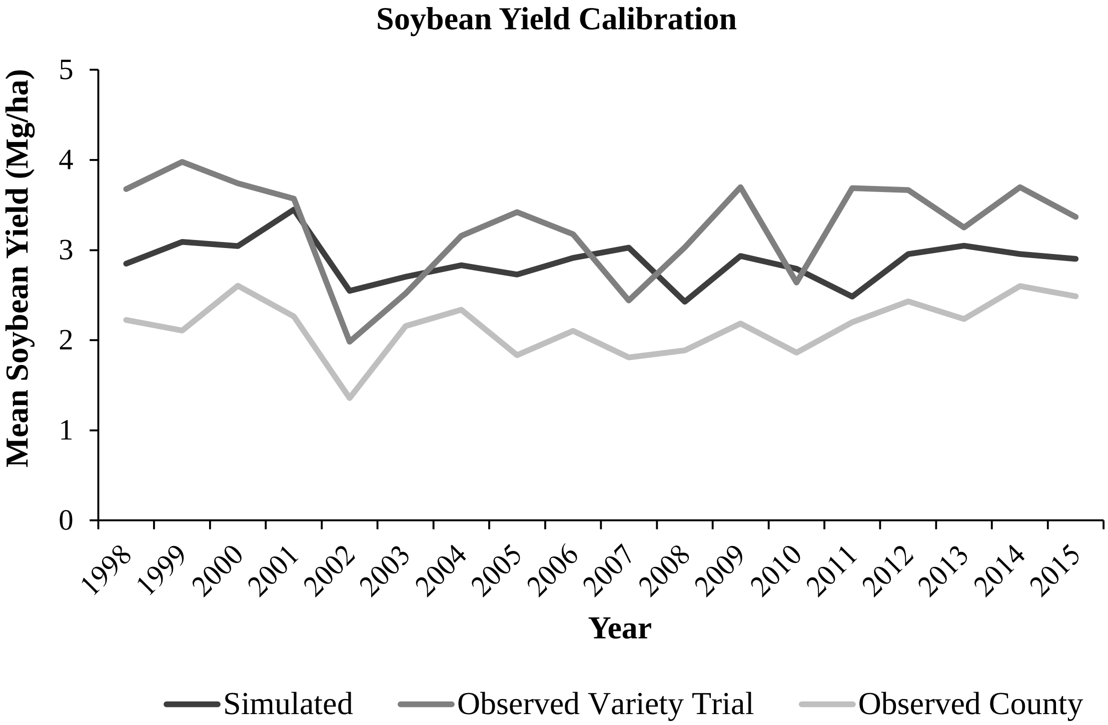


Figure 4.4. Mean simulated soybean yields (dry weight basis) generated when calibrating APEX using the mean soybean yields observed during variety trials carried out in four land grant university research farms in Pennsylvania Furnace, PA, Quantico, MD, Kinston, NC, and Tifton, GA, as well as the mean soybean yields observed in the counties where the four farms where located.

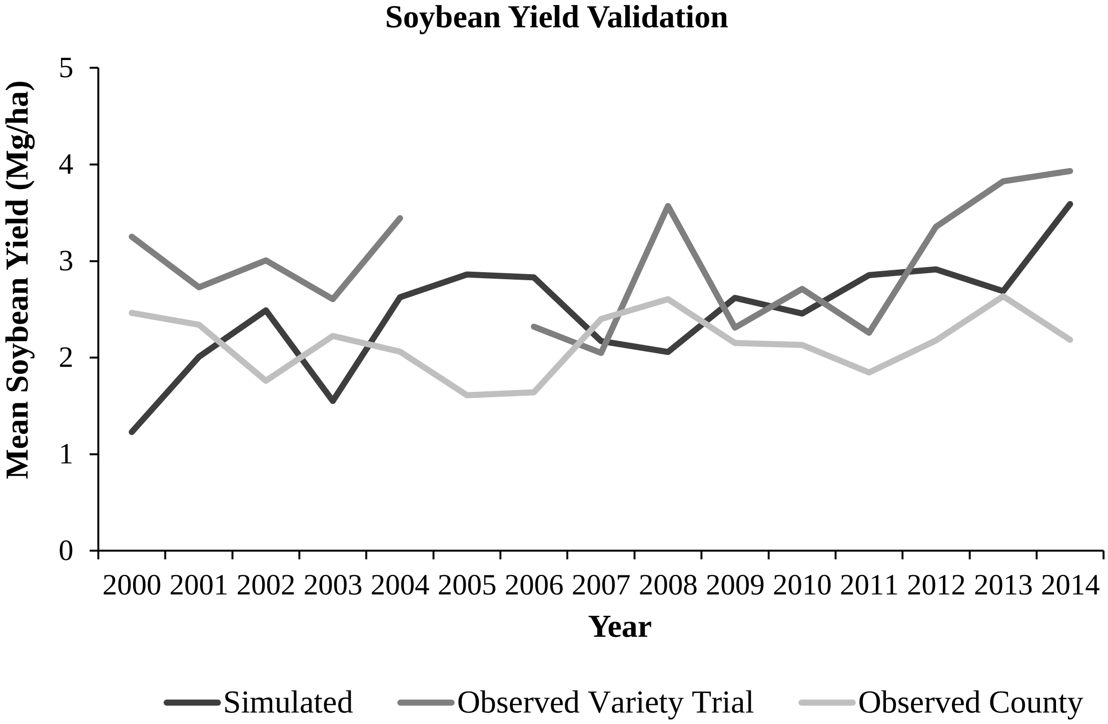
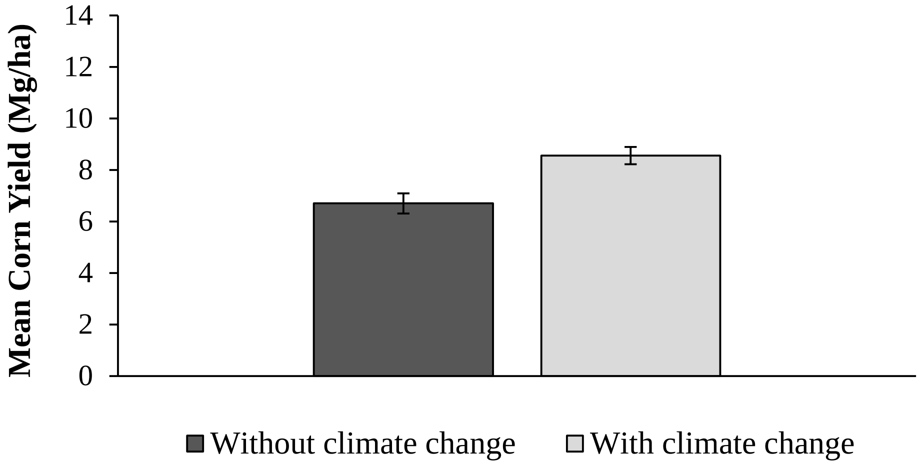


Figure 4.5. Mean simulated soybean yields (dry weight basis) generated when validating APEX using the mean soybean yields observed during variety trials carried out in four land grant university research farms in Aurora, NY, Clarksville, MD, Blackstone, VA, and Blackville, SC, as well as the mean soybean yields observed in the counties where the four farms where located.

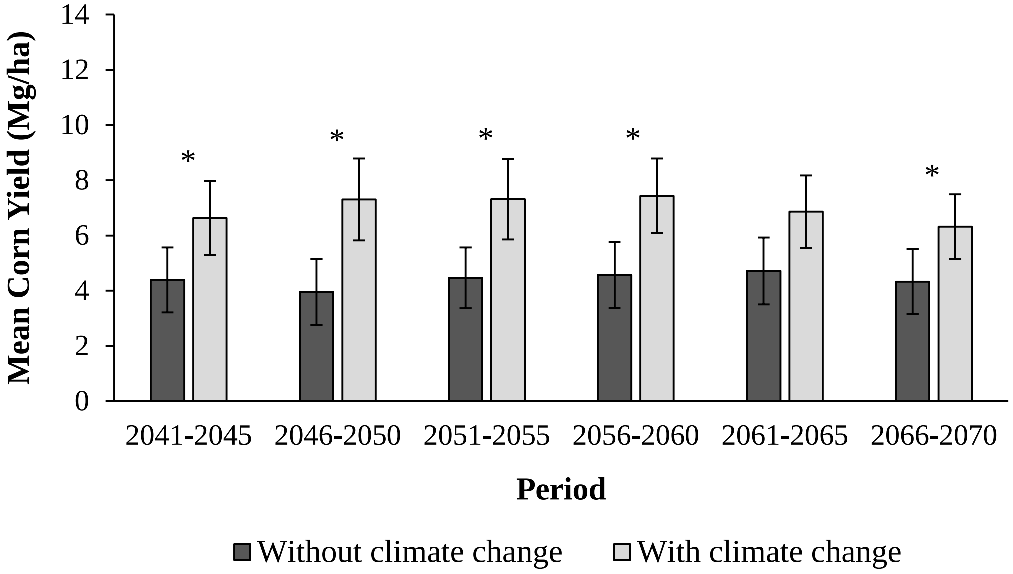
Climate Change Effects

Corn Yields

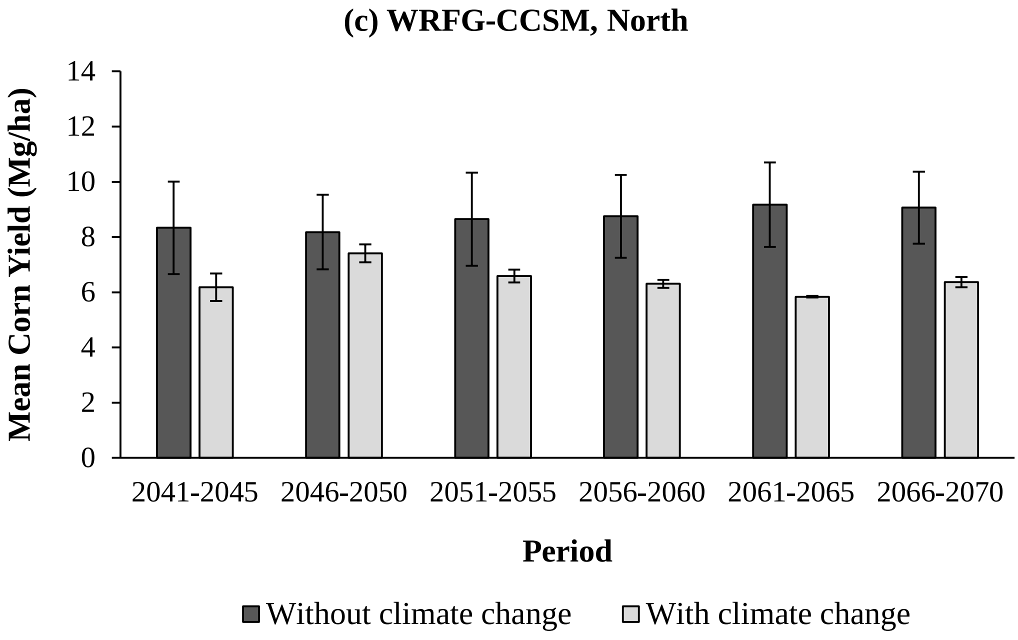
The simulated effect of climate change on mean corn yields varied by region within the Eastern US. In the northern region, climate change had a significant effect on mean yields only under the RCM3-GFDL and WRFG-CGCM3 climate models (Fig. 4.6). Under both climate models, the effect of climate change varied by five-year period within the 30-year period (2041–2070). Under RCM3-GFDL, climate change significantly increased mean yields in every five-year period by 2.0–3.4 Mg/ha (46–85%), except in 2061–2065, where it had no significant effect (Fig. 4.6b). Under WRFG-CGCM3, climate change significantly increased mean yields in 2041–2045 by 1.1 Mg/ha (18%) and decreased them in 2061–2065 and 2066–2070 by 2.5–3.1 Mg/ha (37–51%) (Fig. 4.6d).



(a) RCM3-CGCM3. North



(b) RCM3-GFDL, North


(c) WRFG-CCSM, North

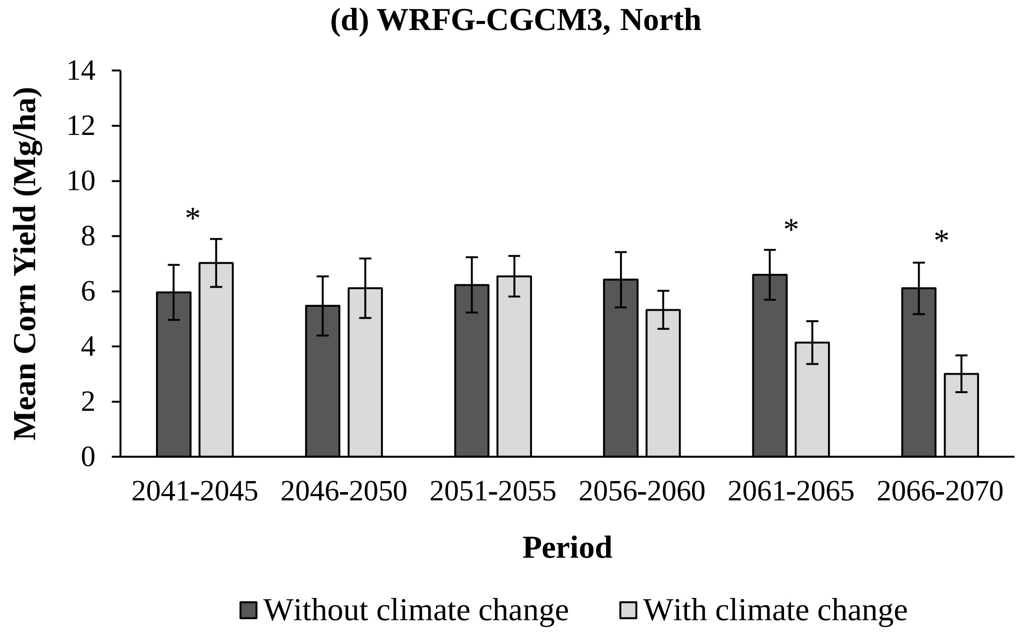
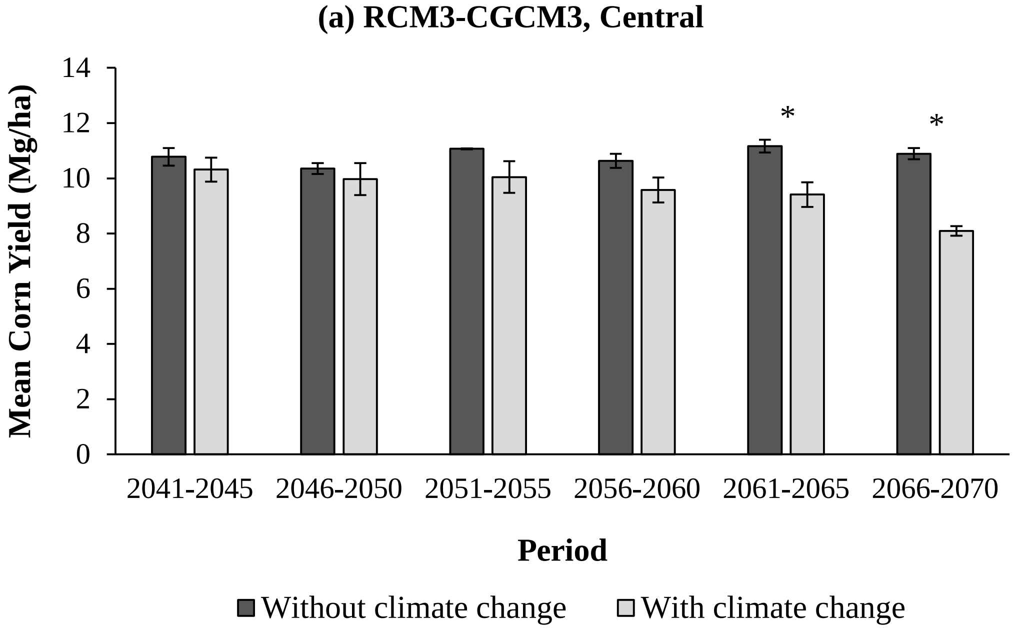
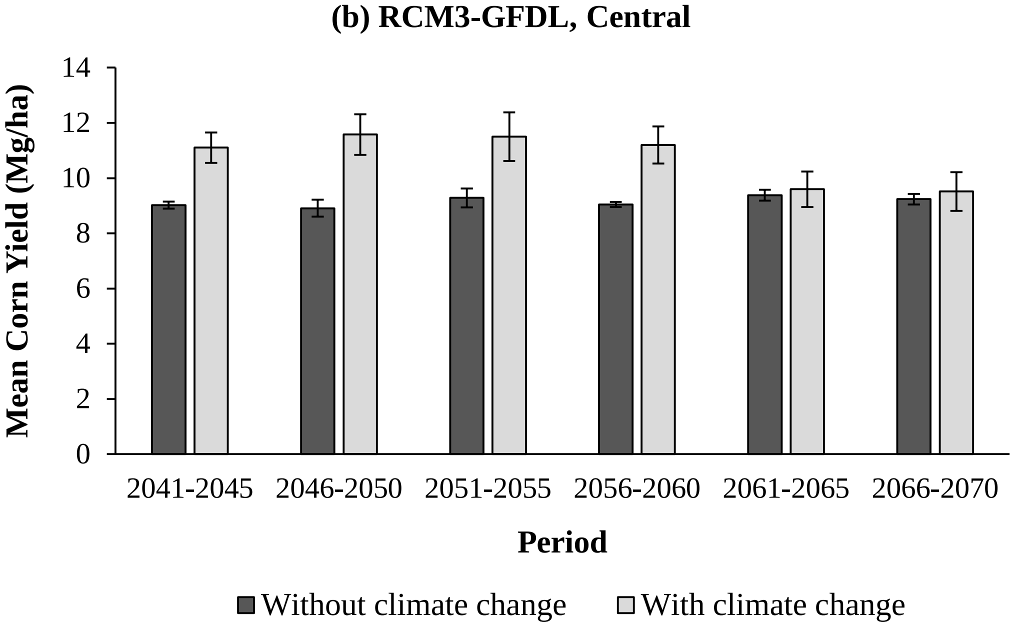

(d) WRFG-CGCM3, North

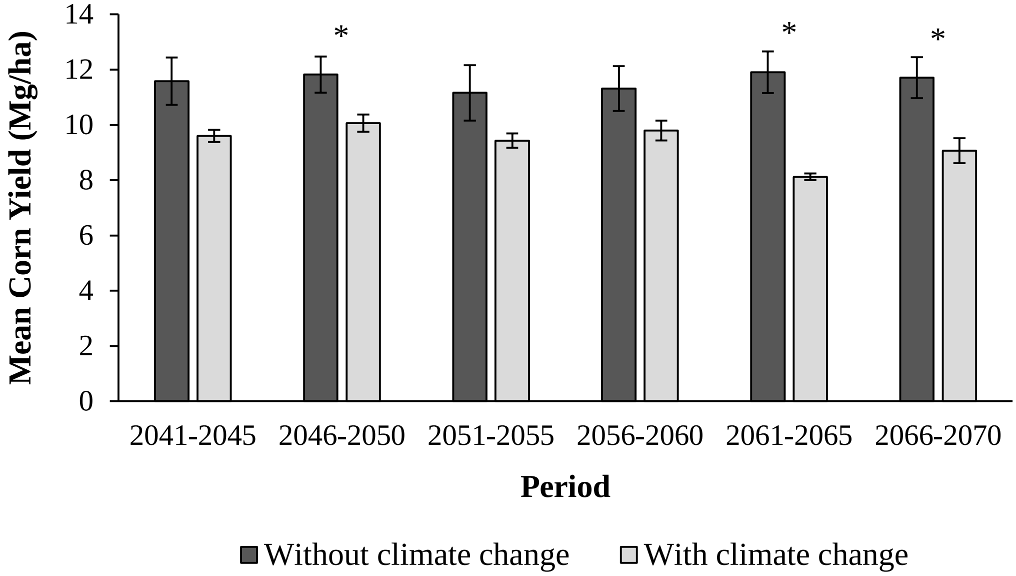
Figure 4.6. Mean corn yields (dry weight basis) in a rainfed corn-soybean rotation in the future (2041–2070) in the northern region of the Eastern US with and without climate change, as simulated by APEX under four different climate models. Error bars indicate standard errors. Asterisks above pairs of bars indicate significant differences between the two means at α=0.05.

In the central region, climate change had a significant effect on mean corn yields under the RCM3-CGCM3, WRFG-CCSM, and WRFG-CGCM3 climate models (Fig. 4.7). Under all three climate models, the effect of climate change varied by five-year period. Under RCM3-CGCM3, climate change significantly decreased mean yields in 2061–2065 and 2066–2070 by 1.8–2.8 Mg/ha (16–26%) (Fig. 4.7a). Under WRFG-CCSM, climate change significantly decreased mean yields in 2046–2050, 2061–2065, and 2066–2070 by 1.8–3.8 Mg/ha (15–32%) (Fig. 4.7c). Under WRFG–CGCM3, climate change significantly increased mean yields in 2041–2045, 2046–2050, and 2056–2060 by 1.5–2.3 Mg/ha (14–22%) (Fig. 4.7d).


(a) RCM3-CGCM3, Central
Mean Corn Yield (Mg/ha)
0
2
4
6
8
10
12
14
*
*
2041-2045
2046-2050
2051-2055
2056-2060
2061-2065
2066-2070
Period
Without climate change
With climate change


(b) RCM3-GFDL, Central
Mean Corn Yield (Mg/ha)
0
2
4
6
8
10
12
14
2041-2045
2046-2050
2051-2055
2056-2060
2061-2065
2066-2070
Period
Without climate change
With climate change

(c) WRFG-CCSM, Central



(d) WRFG-CGCM3, Central

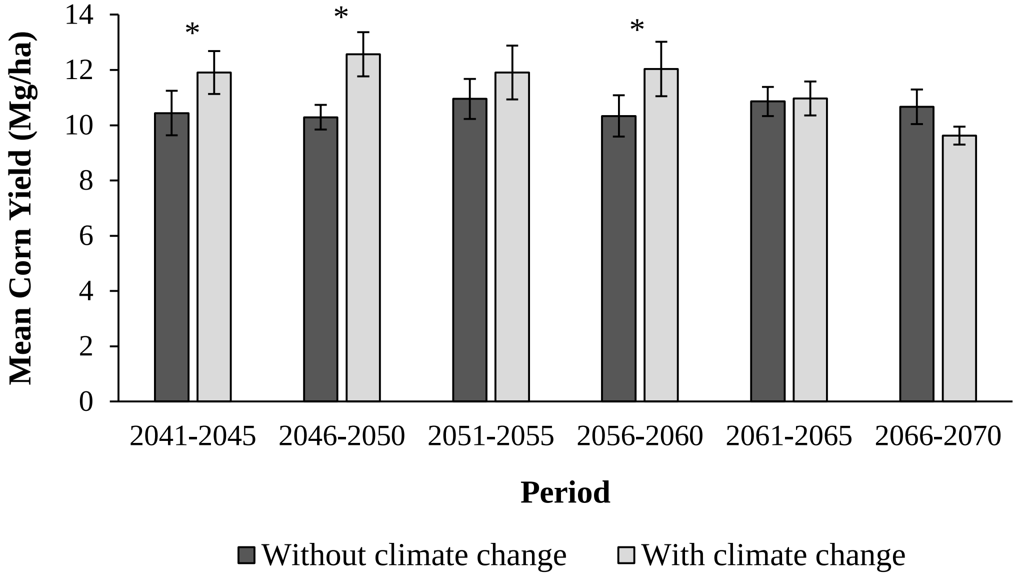
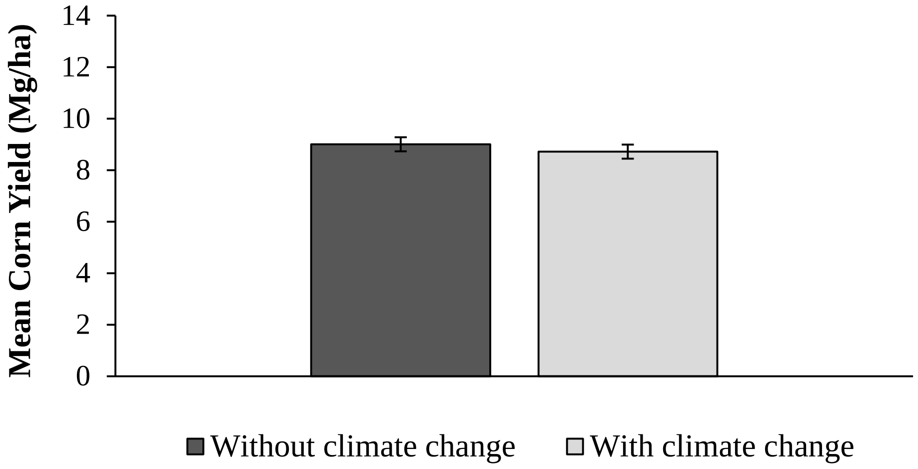


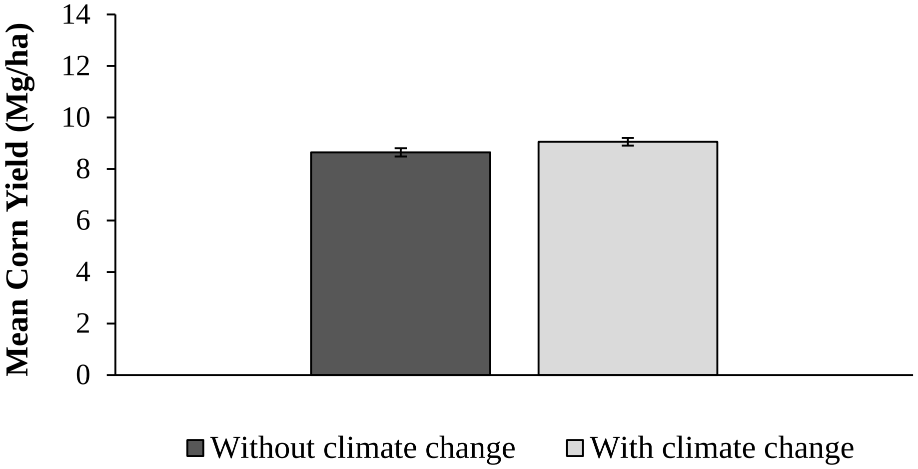
Figure 4.7. Mean corn yields (dry weight basis) in a rainfed corn-soybean rotation in the future (2041–2070) in the central region of the Eastern US with and without climate change, as simulated by APEX under four different climate models. Error bars indicate standard errors. Asterisks above pairs of bars indicate significant differences between the two means at α=0.05.

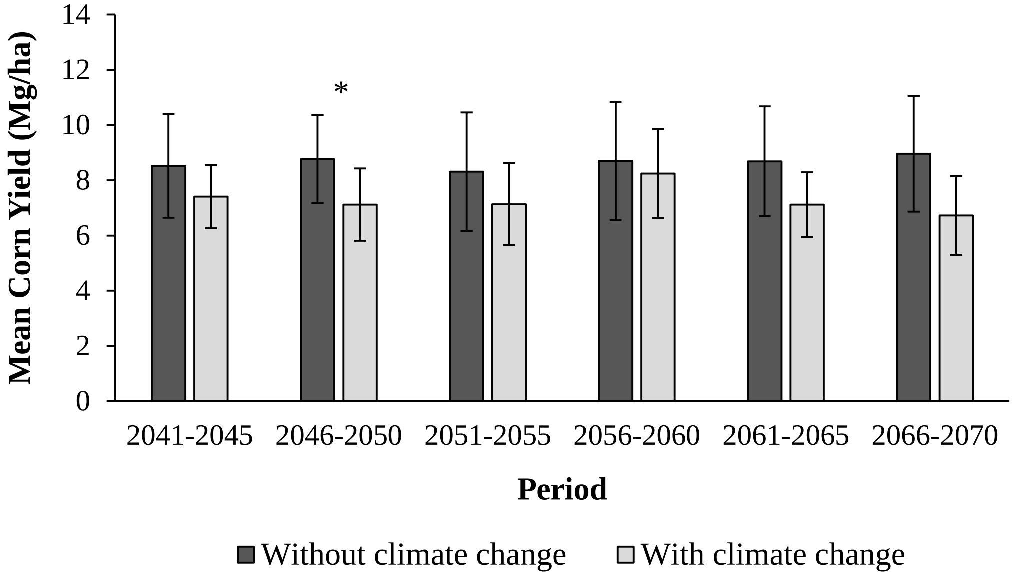
In the southern region, climate change had a significant effect on mean corn yields only under the WRFG-CCSM climate model (Fig. 4.8). Under this climate model, the effect of climate change varied by five-year period. Climate change significantly decreased mean yields in 2046–2050 by 1.6 Mg/ha (19%) (Fig. 4.8c).

(a) RCM3-CGCM3, South

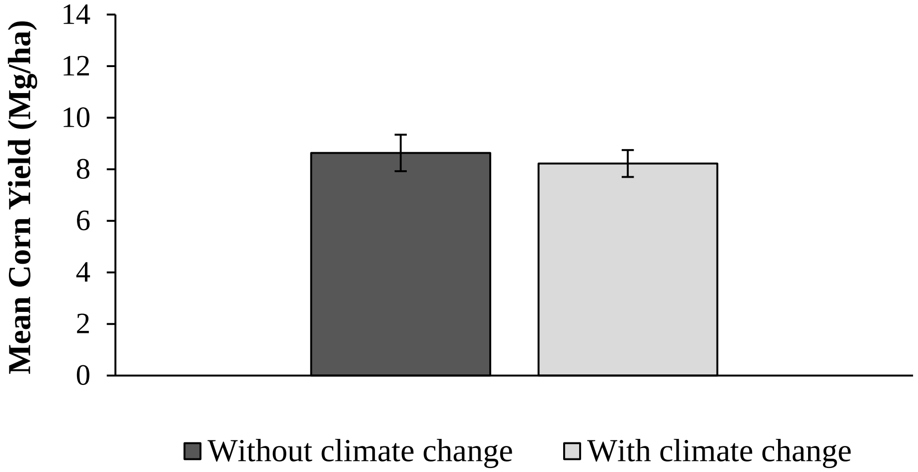


(b) RCM3-GFDL, South





(c) WRFG-CCSM, South



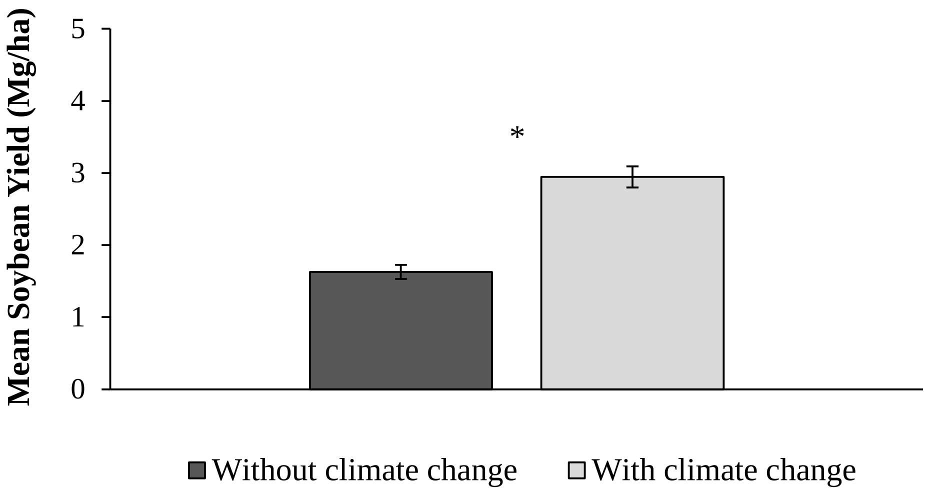
(d) WRFG-CGCM3, South

Figure 4.8. Mean corn yields (dry weight basis) in a rainfed corn-soybean rotation in the future (2041–2070) in the southern region of the Eastern US with and without climate change, as simulated by APEX under four different climate models. Error bars indicate standard errors. Asterisks above pairs of bars indicate significant differences between the two means at α=0.05.

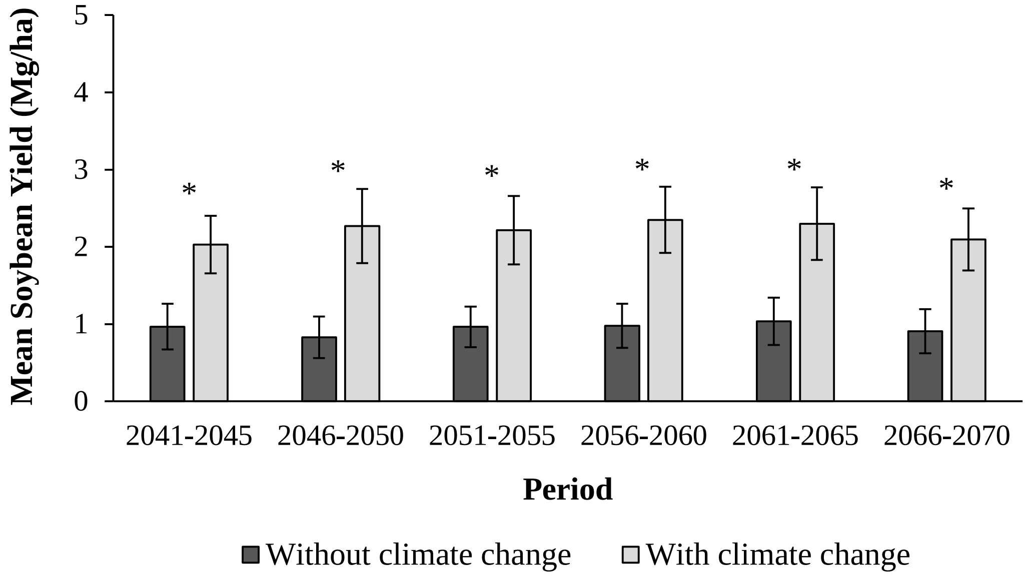
Soybean Yields

The simulated effect of climate change on mean soybean yields varied by region within the Eastern US. In the northern region, climate change had a significant effect on mean yields under the RCM3-CGCM3, RCM3-GFDL and WRFG-CGCM3 climate models (Fig. 4.9). Under the first climate model, the effect of climate change was the same throughout the 30-year period, while under the second two climate models, the effect varied by five-year period. Under RCM3-CGCM3, climate change significantly increased mean yields by 1.3 Mg/ha (81%) (Fig. 4.9a). Under RCM3-GFDL, climate change significantly increased mean yields during every five-year period by 1.1–1.4 Mg/ha (110–170%) (Fig. 4.9b). Under WRFG-CGCM3, climate change significantly increased mean yields in 2046–2050 and 2051–2055 by 0.71–0.79 Mg/ha (55–57%) (Fig. 4.9d).

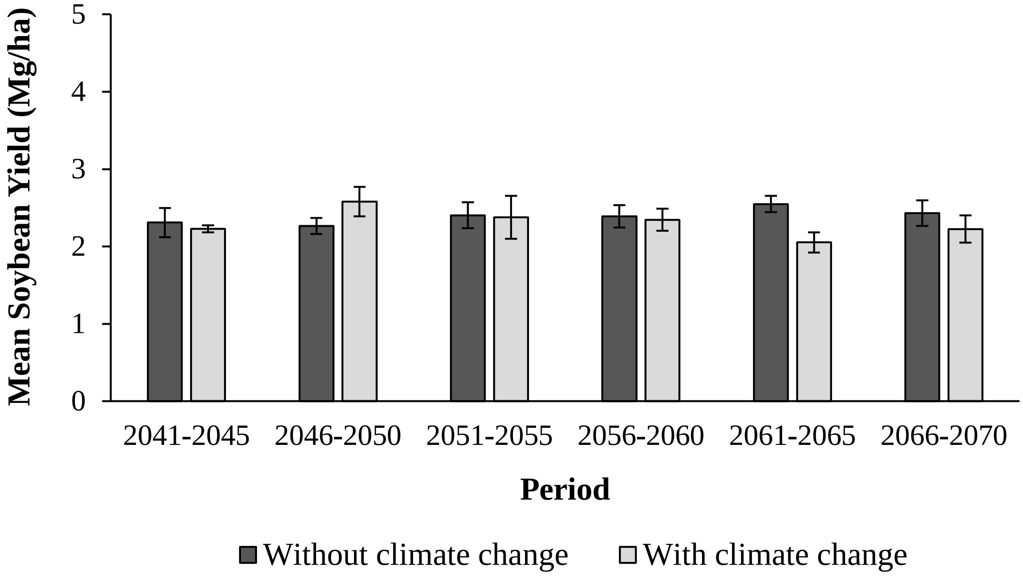
(a) RCM3-CGCM3, North



(b) RCM3-GFDL, North



(c) WRFG-CCSM, North



(d) WRFG-CGCM3, North

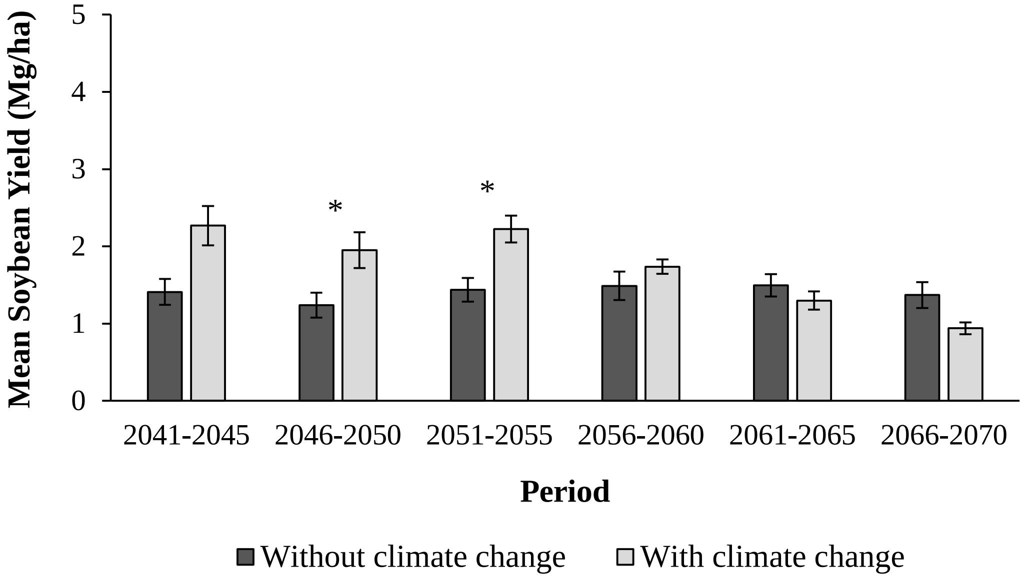
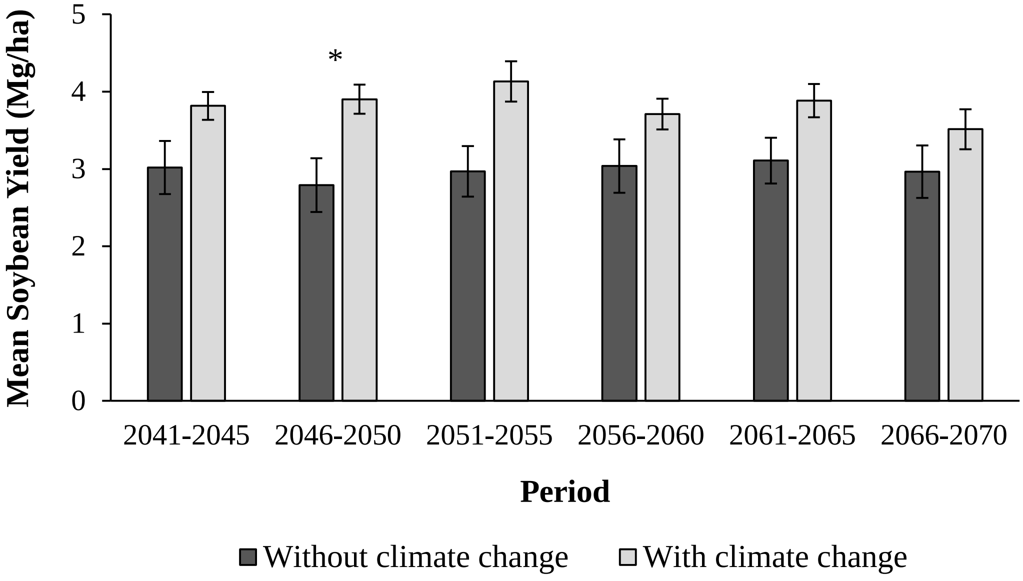


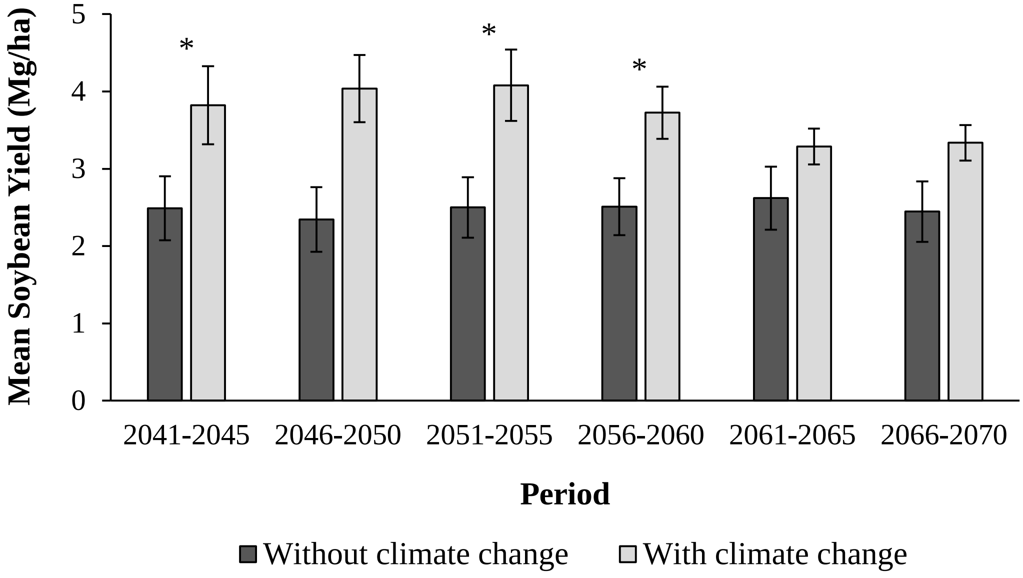
Figure 4.9. Mean soybean yields (dry weight basis) in a rainfed corn-soybean rotation in the future (2041–2070) in the northern region of the Eastern US with and without climate change, as simulated by APEX under four different climate models. Error bars indicate standard errors. Asterisks above pairs of bars indicate significant differences between the two means at α=0.05.

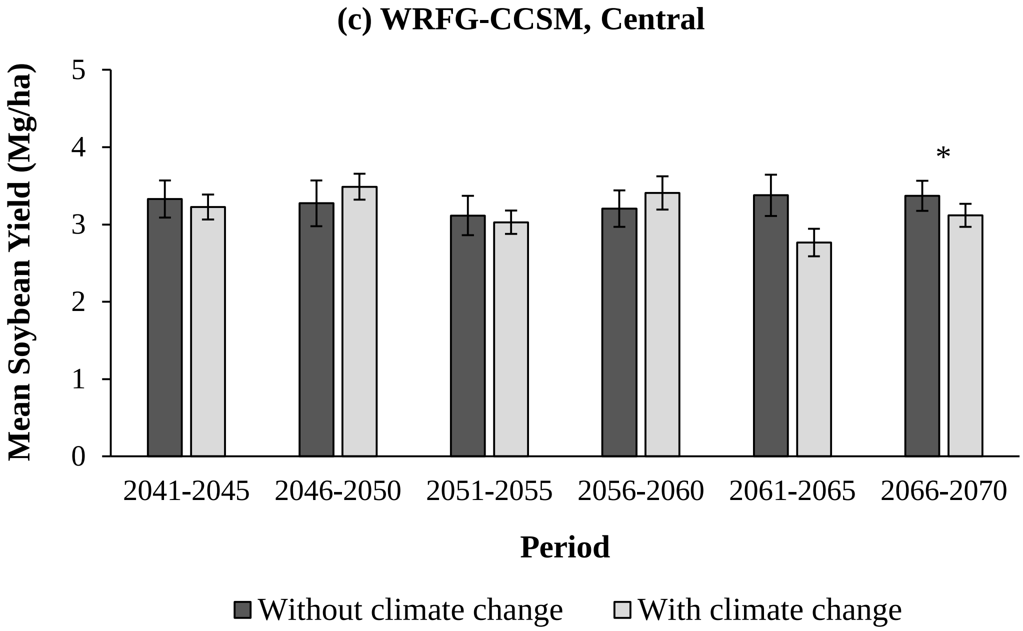
In the central region, climate change had a significant effect on mean soybean yields under all four climate models (Fig. 4.10). Under all four climate models, the effect of climate change varied by five-year period. Under RCM3-CGCM3, climate change significantly increased mean yields in 2046–2050 by 1.1 Mg/ha (40%) (Fig. 4.10a). Under RCM3-GFDL, climate change significantly increased mean yields in 2041–2045, 2051–2055, and 2056–2060 by 1.2–1.6 Mg/ha (48–63%) (Fig. 4.10b). Under WRFG-CCSM, climate change significantly decreased mean yields in 2066–2070 by 0.25 Mg/ha (7.6%) (Fig. 4.10c). Lastly, under WRFG-CGCM3, climate change significantly increased mean yields in 2041–2045, 2046–2050, 2051–2055, and 2056–2060 by 1.3–1.9 Mg/ha (44–69%) (Fig. 4.10d).

(a) RCM3-CGCM3, Central



(b) RCM3-GFDL, Central




(c) WRFG-CCSM, Central

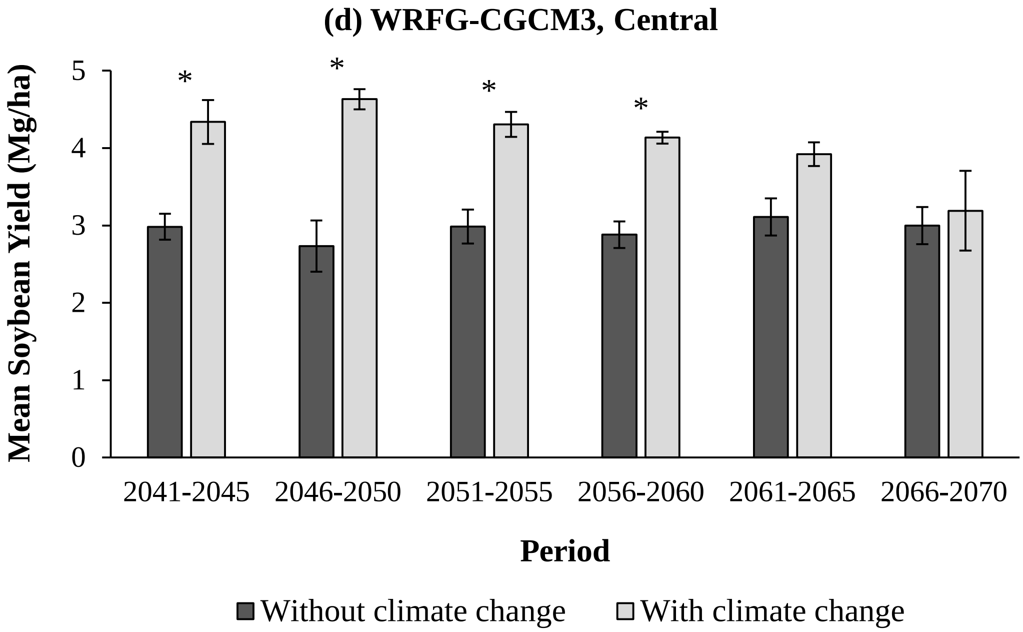
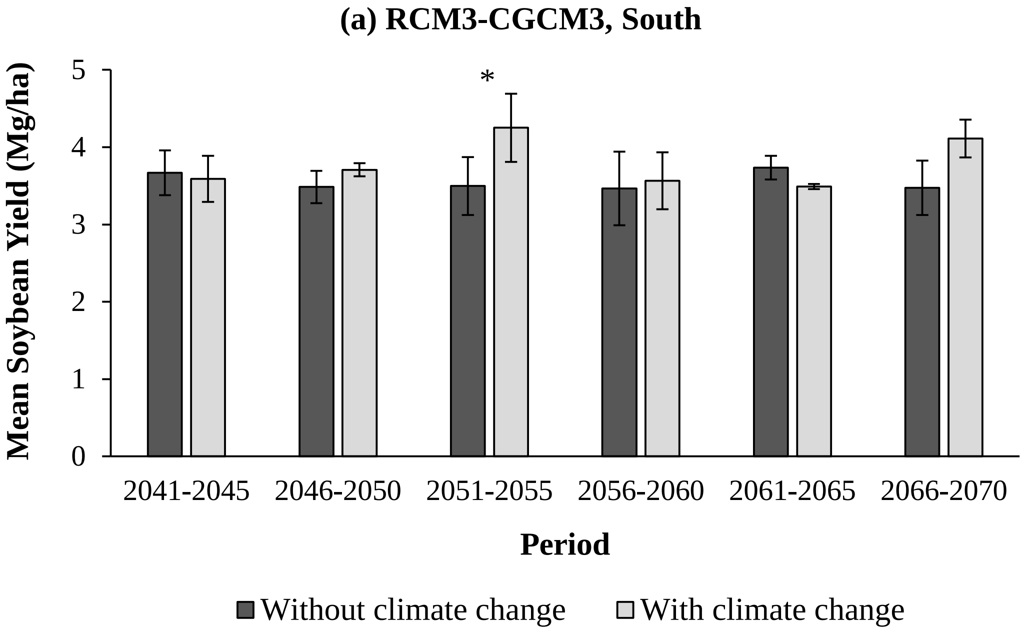
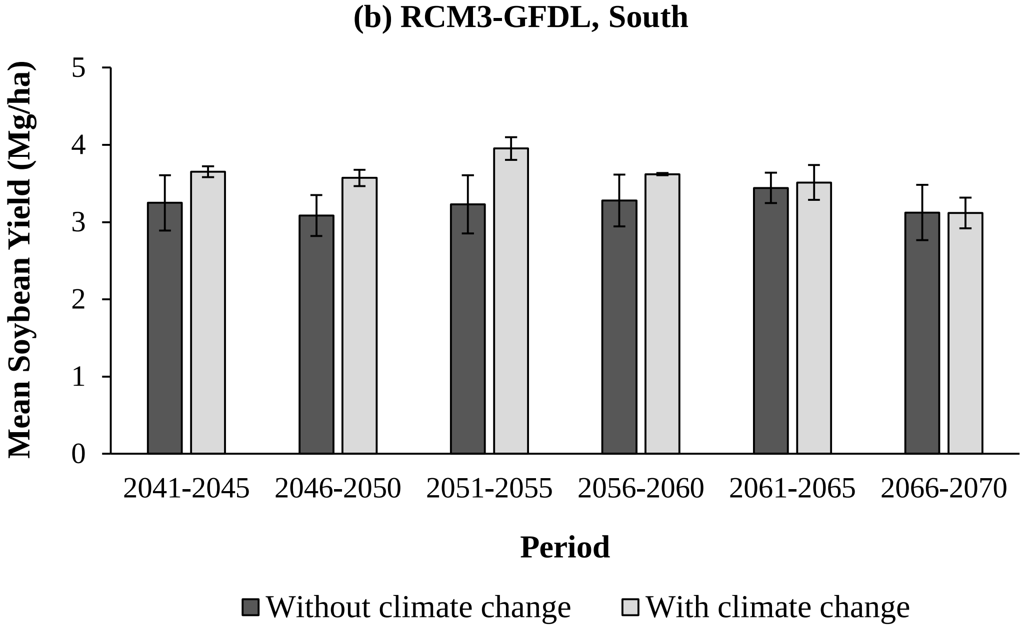

(d) WRFG-CGCM3, Central

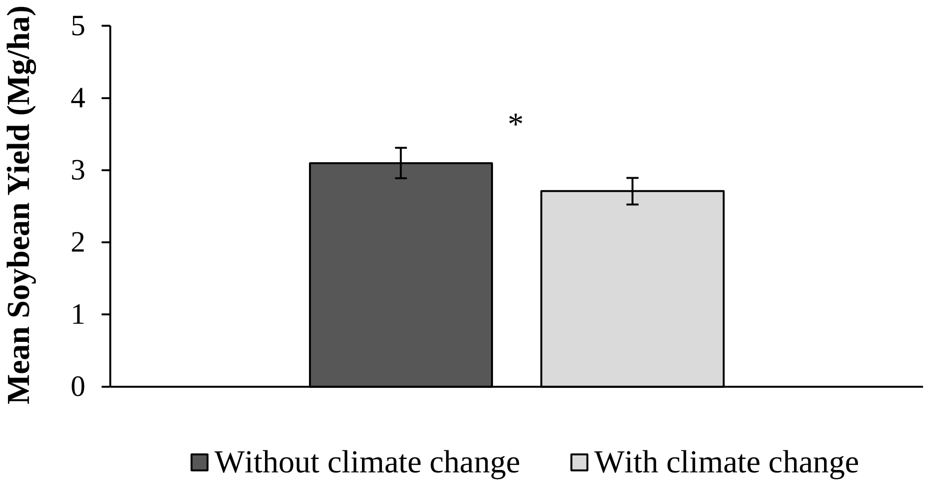
Figure 4.10. Mean soybean yields (dry weight basis) in a rainfed corn-soybean rotation in the future (2041–2070) in the central region of the Eastern US with and without climate change, as simulated by APEX under four different climate models. Error bars indicate standard errors. Asterisks above pairs of bars indicate significant differences between the two means at α=0.05.

In the southern region, climate change had a significant effect on mean soybean yields under the RCM3-CGCM3 and WRFG-CCSM climate models (Fig. 4.11). Under the first climate model, the effect of climate change varied by five-year period, while under the second climate model, the effect was the same throughout the 30-year period. Under RCM3-CGCM3, climate change significantly increased mean yields in 2051–2055 by 0.75 Mg/ha (22%) (Fig. 4.11a). Under WRFG-CCSM, climate change significantly decreased mean yields by 0.39 Mg/ha (13%) (Fig. 4.11c).


(a) RCM3-CGCM3, South
Mean Soybean Yield (Mg/ha)
0
1
2
3
4
5
*
2041-2045
2046-2050
2051-2055
2056-2060
2061-2065
2066-2070
Period
■ Without climate change
□ With climate change


(b) RCM3-GFDL, South
Mean Soybean Yield (Mg/ha)
0
1
2
3
4
5
2041-2045
2046-2050
2051-2055
2056-2060
2061-2065
2066-2070
Period
■ Without climate change
□ With climate change

(c) WRFG-CCSM, South



(d) WRFG-CGCM3, South

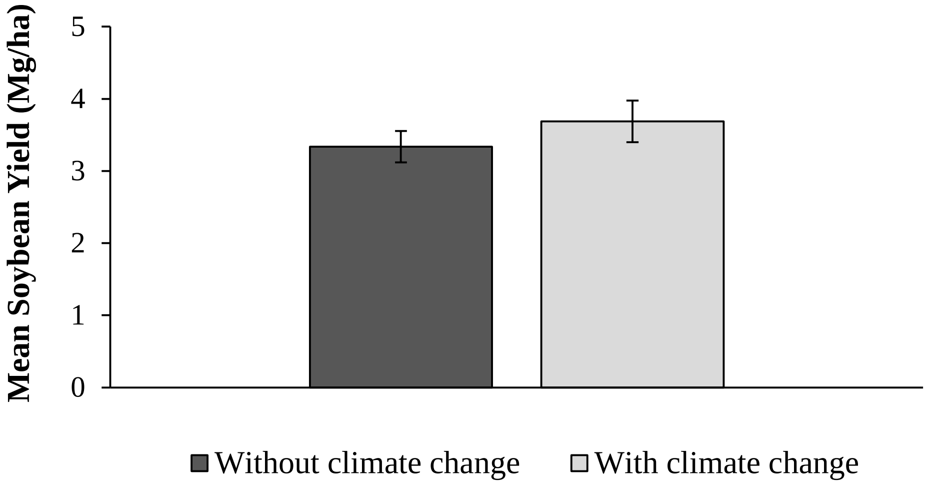


Figure 4.11. Mean soybean yields (dry weight basis) in a rainfed corn-soybean rotation in the future (2041–2070) in the southern region of the Eastern US with and without climate change, as simulated by APEX under four different climate models. Error bars indicate standard errors. Asterisks above pairs of bars indicate significant differences between the two means at α=0.05.

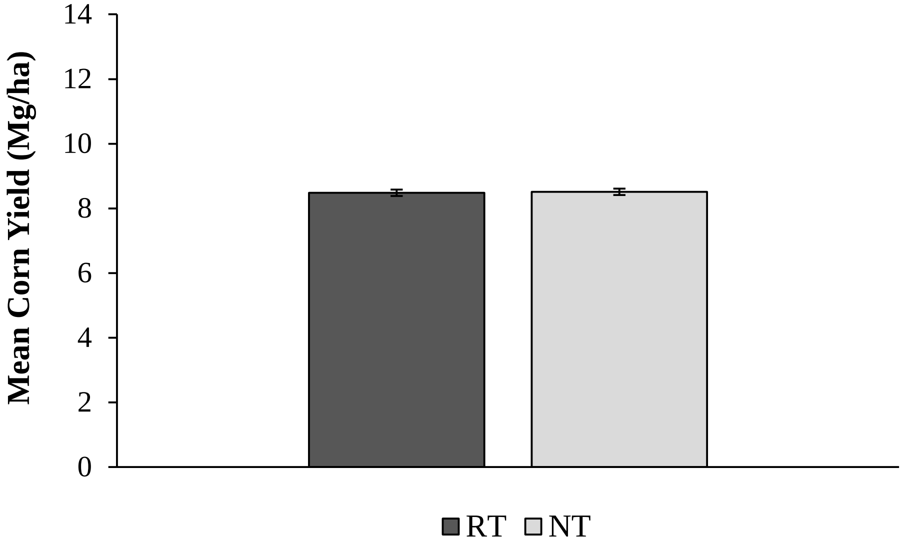
Climate Change Adaptations

No Tillage

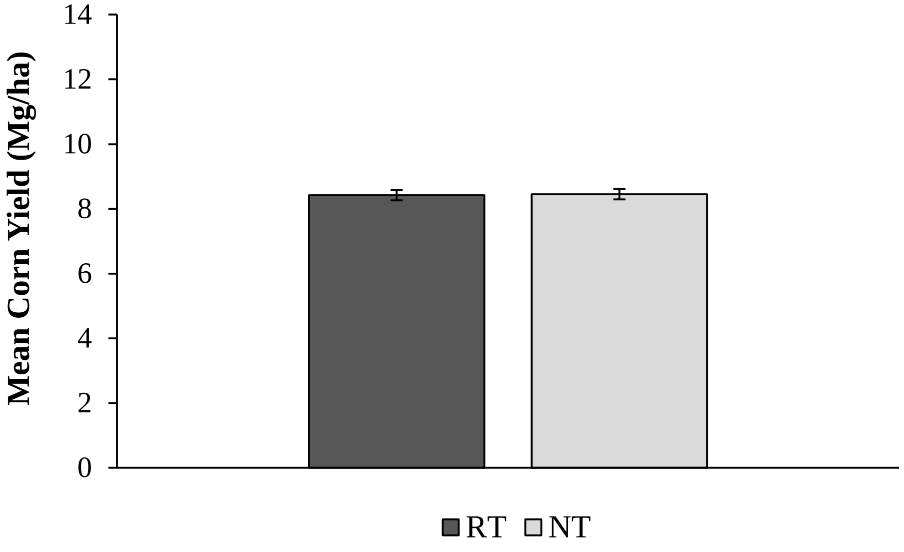
Corn Yields

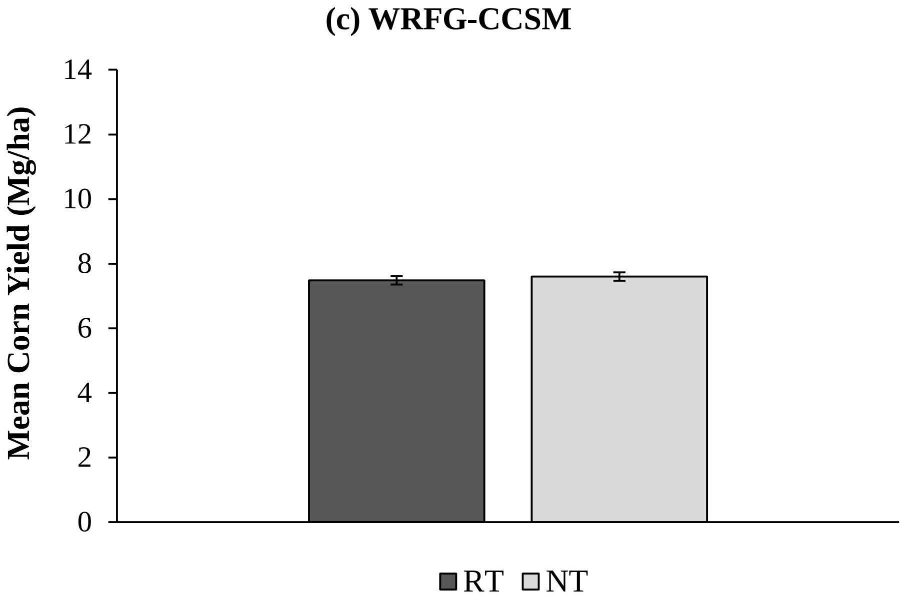
The simulated effect of no tillage on mean corn yields under climate change did not vary by region within the Eastern US or by five-year period within the thirty-year period (2041–2070) under any of the four climate models. No tillage did not have a significant effect on mean yields under any of the four climate models (Fig. 4.12).

(a) RCM3-CGCM3

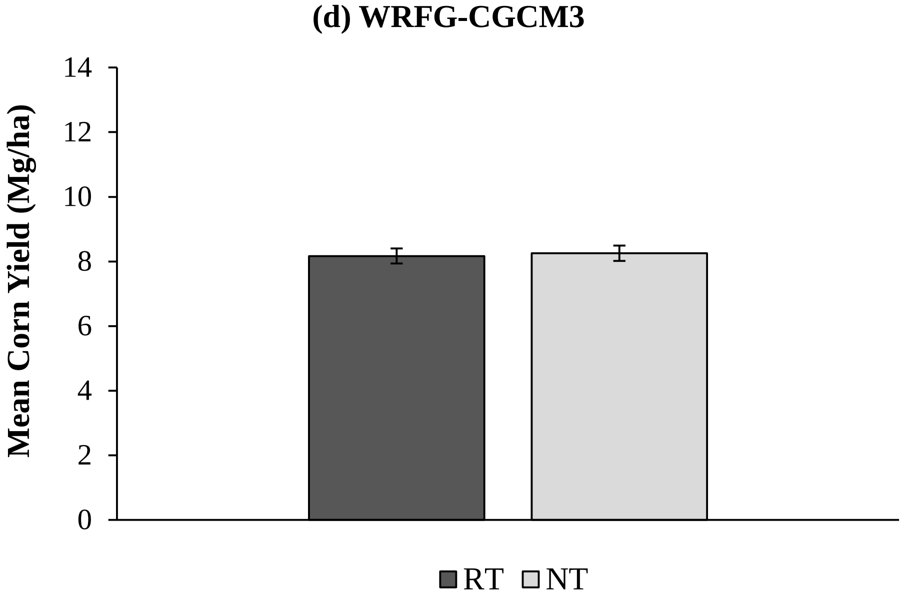


(b) RCM3-GFDL





(c) WRFG-CCSM



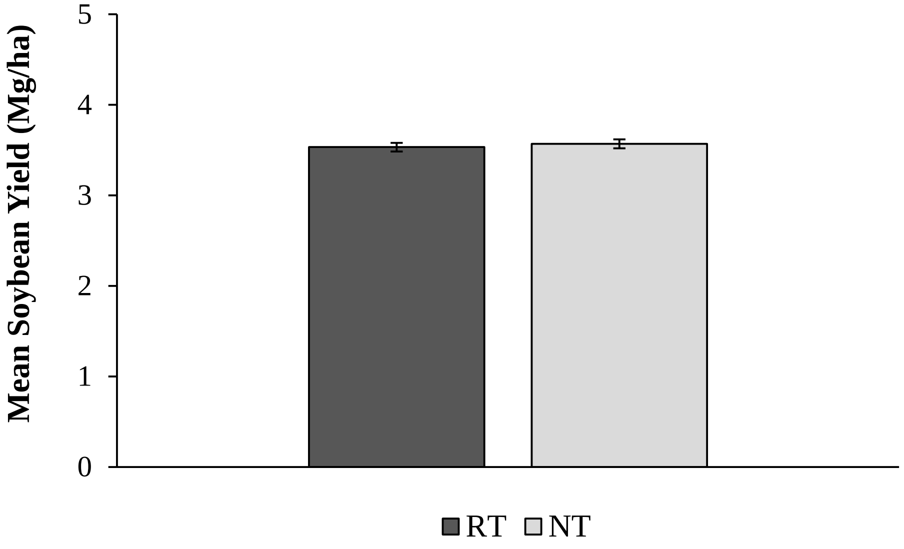
(d) WRFG-CGCM3

Figure 4.12. Mean corn yields (dry weight basis) in a rainfed corn-soybean rotation under future (2041–2070) climate change in the Eastern US, under reduced tillage (RT) and under no tillage (NT), as simulated by APEX under four different climate models. Error bars indicate standard errors. An asterisk above each pair of bars indicates a significant difference between the two means at α=0.05.

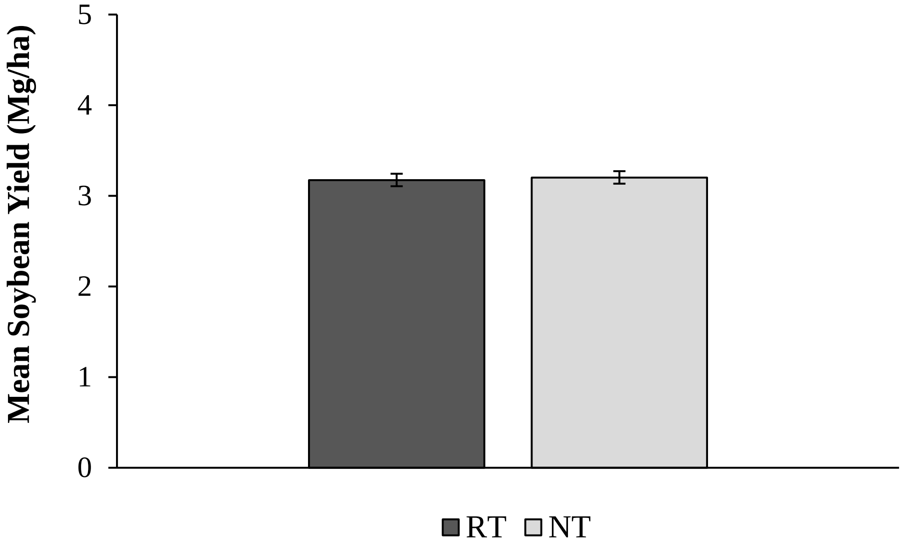
Soybean Yields

The simulated effect of no tillage on mean soybean yields under climate change did not vary by region within the Eastern US or by five-year period under any of the four climate models. No tillage did not have a significant effect on mean yields except under the WRFG-CCSM climate model (Fig. 4.13). Under this climate model, no tillage significantly increased the mean yield relative to reduced tillage. However, this increase was of only 0.07 Mg/ha (2.7%).

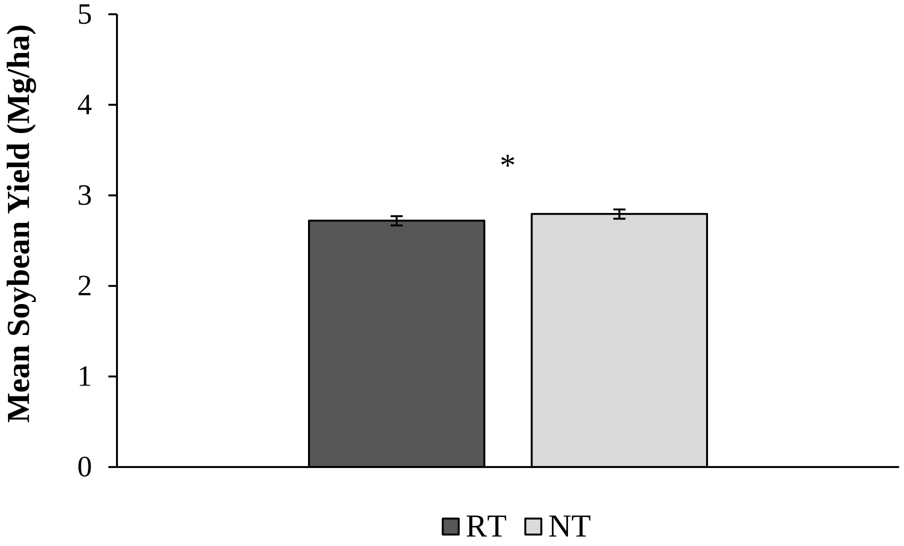
(a) RCM3-CGCM3



(b) RCM3-GFDL



(c) WRFG-CCSM



(d) WRFG-CGCM3

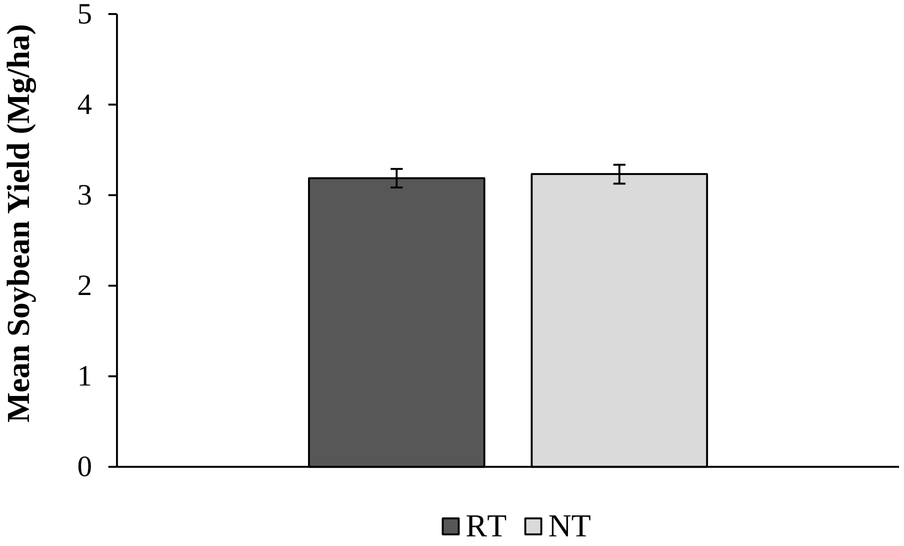


Figure 4.13. Mean soybean yields (dry weight basis) in a rainfed corn-soybean rotation under future (2041–2070) climate change in the Eastern US, under reduced tillage (RT) and under no tillage (NT), as simulated by APEX under four different climate models. Error bars indicate standard errors. An asterisk above the bars indicates a significant difference between the two means at α=0.05.

Rye Cover Cropping

Corn Yields

The simulated effect of rye cover cropping on mean corn yields under climate change varied by region within the Eastern US except under the WRFG-CCSM climate model. Under this climate model, the effect of cover cropping on mean yields did not vary by five-year period. In addition, under this climate model, planting a rye cover crop after corn did not have a significant effect on mean yields relative to the control (no cover crop), but planting a rye cover crop after both corn and soybeans significantly decreased mean yields by 0.65 Mg/ha (8.4%) (Fig. 4.14).

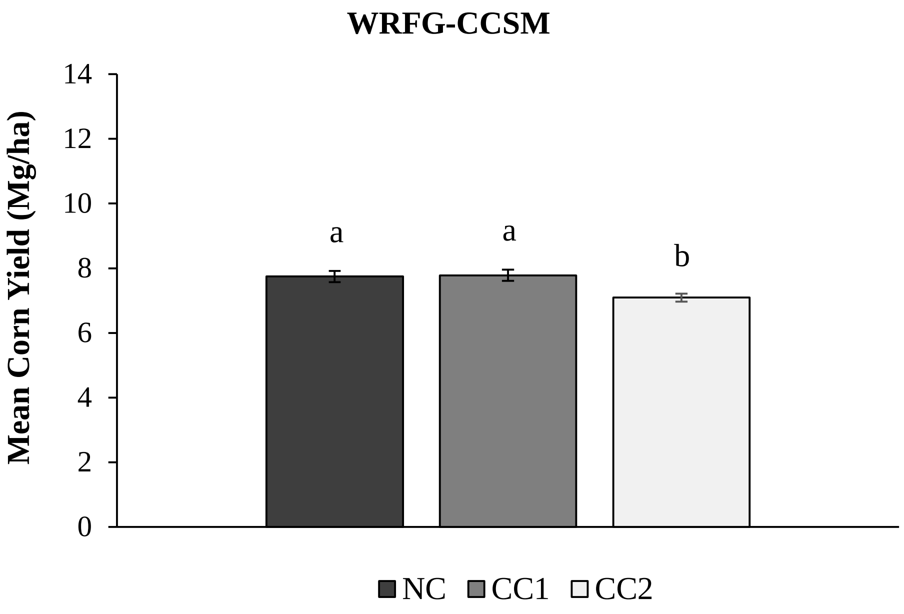
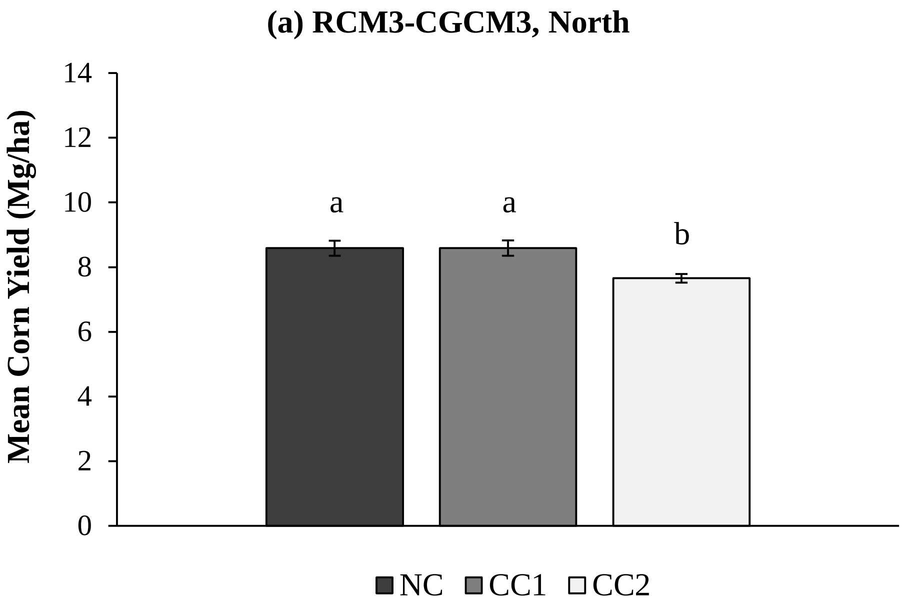
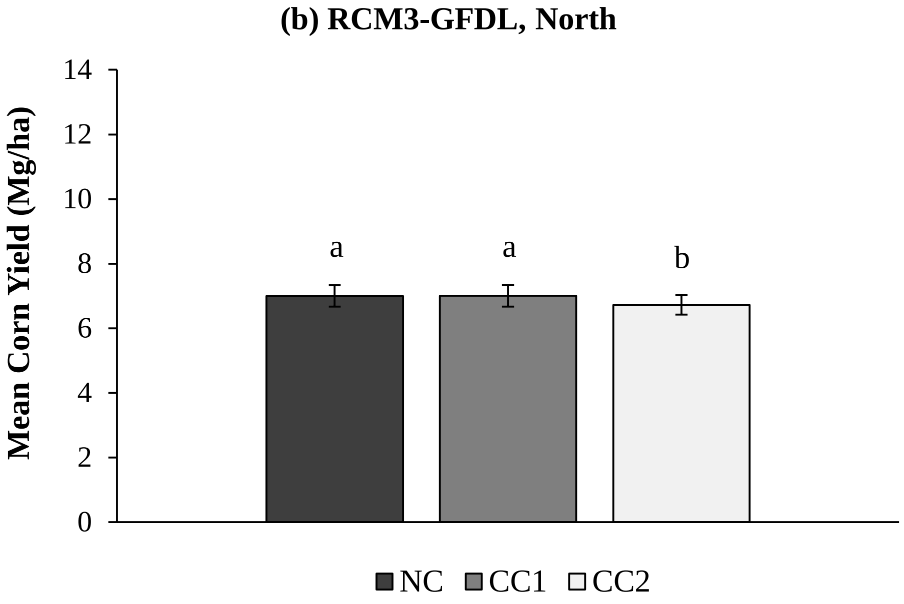


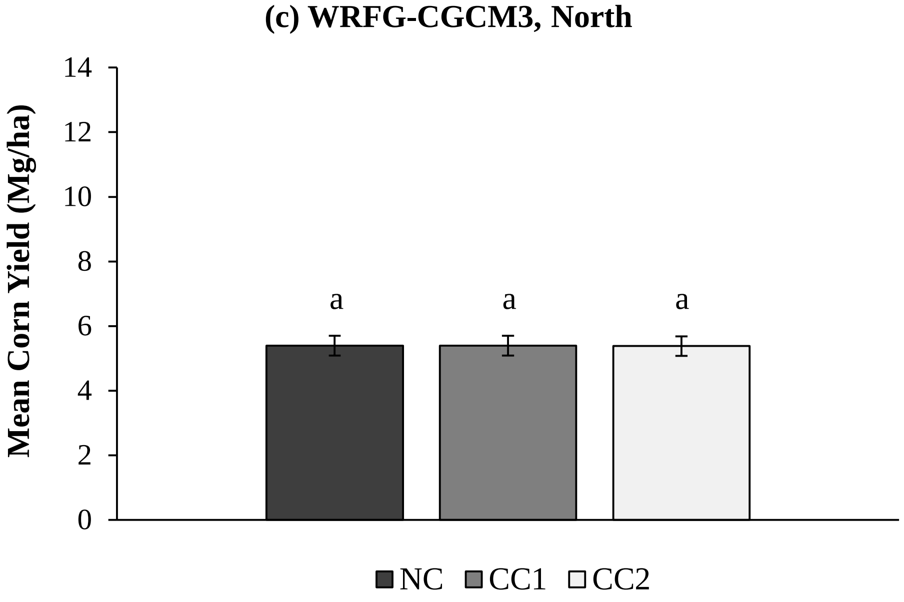
Figure 4.14. Mean corn yields (dry weight basis) in a rainfed corn-soybean rotation under future (2041–2070) climate change in the Eastern US, with no cover crop (NC), with a rye cover crop after corn (CC1), and with a rye cover crop after both corn and soybeans (CC2), as simulated by APEX under the WRFG-CCSM climate model. Error bars indicate standard errors. Different letters above the trio of bars indicate significant differences between the three means at α=0.05.

Under the RCM3-CGCM3, RCM3-GFDL, and WRFG-CGCM3 climate models, the effect of cover cropping on mean corn yields varied by region. In the northern region, the effect of cover cropping on mean yields did not vary by five-year period under any of the three climate models. Under the RCM3-CGCM3 and RCM3-GFDL climate models, planting a rye cover crop after corn did not have a significant effect on mean yields relative to the control, but planting a rye cover crop after both corn and soybeans significantly decreased mean yields by 0.93 Mg/ha (11%) under RCM3-CGCM3 and 0.28 Mg/ha (4.0%) under RCM3-GFDL (Fig. 4.15).


(a) RCM3-CGCM3, North



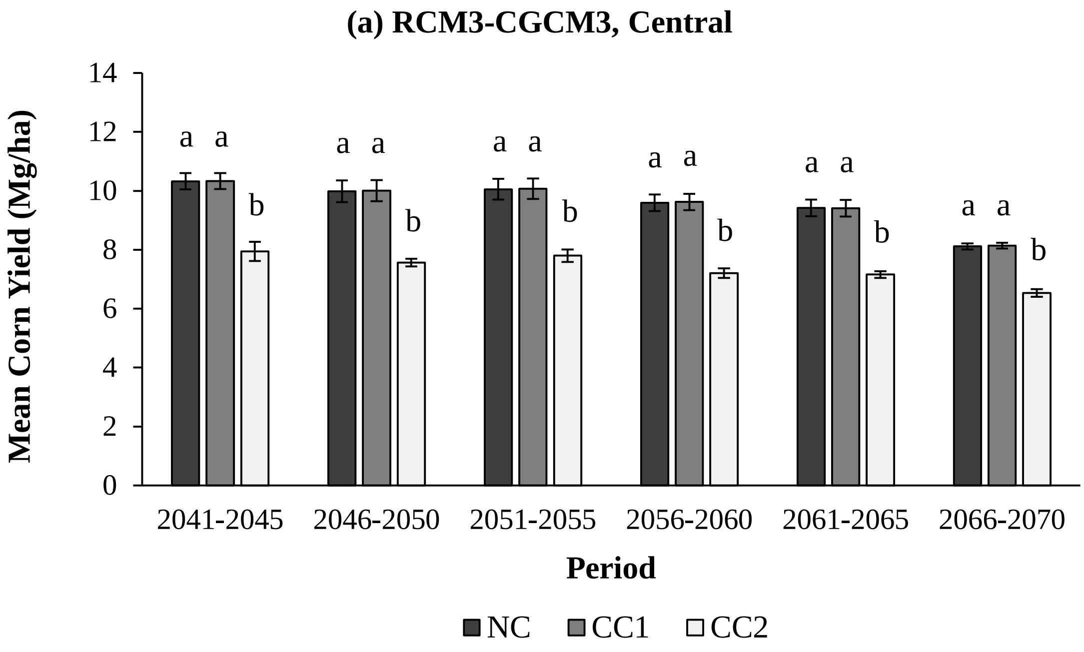
(b) RCM3-GFDL, North



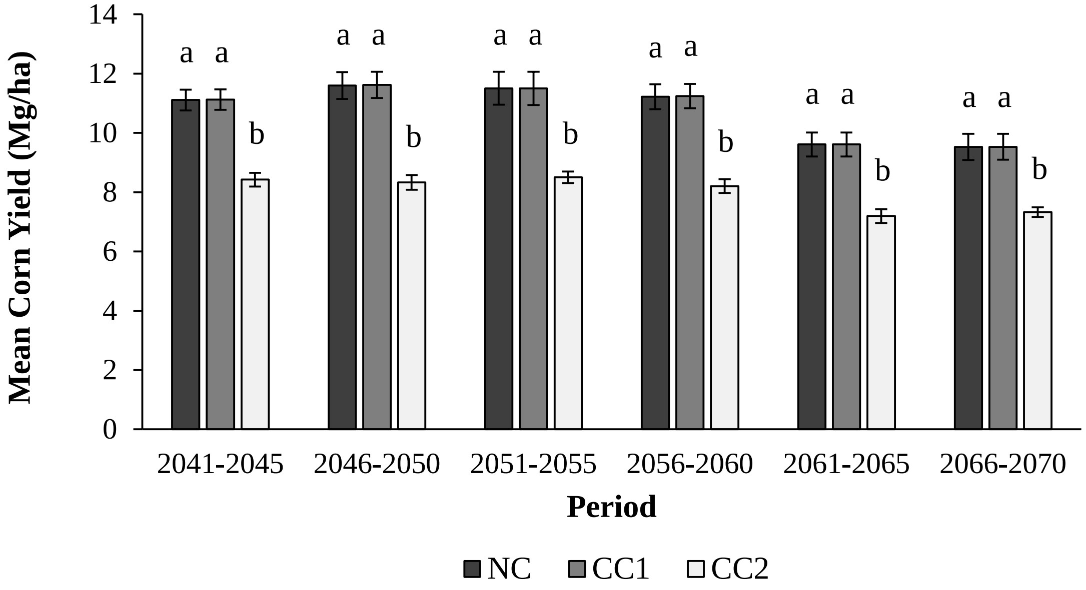
(c) WRFG-CGCM3, North

Figure 4.15. Mean corn yields (dry weight basis) in a rainfed corn-soybean rotation under future (2041–2070) climate change in the northern region of the Eastern US, with no cover crop (NC), with a rye cover crop after corn (CC1), and with a rye cover crop after both corn and soybeans (CC2), as simulated by APEX under three different climate models. Error bars indicate standard errors. Different letters above each trio of bars indicate significant differences between the three means at α=0.05.

In the central region, the effect of cover cropping on mean corn yields varied by five-year period under the RCM3-CGCM3, RCM3-GFDL, and WRFG-CGCM3 climate models. Under all three climate models, planting a rye cover crop after corn did not have a significant effect on mean yields relative to the control, but planting a rye cover crop after both corn and soybeans significantly reduced mean yields in all six five-year periods (Fig. 4.16). These decreases in mean yields were 1.6–2.4 Mg/ha (20–25%) under RCM3-CGCM3, 2.2–3.3 Mg/ha (23–28%) under RCM3-GFDL, and 0.30–1.7 Mg/ha (3.1–14%) under WRFG-CGCM3.



(b) RCM3-GFDL, Central



(c) WRFG-CGCM3, Central

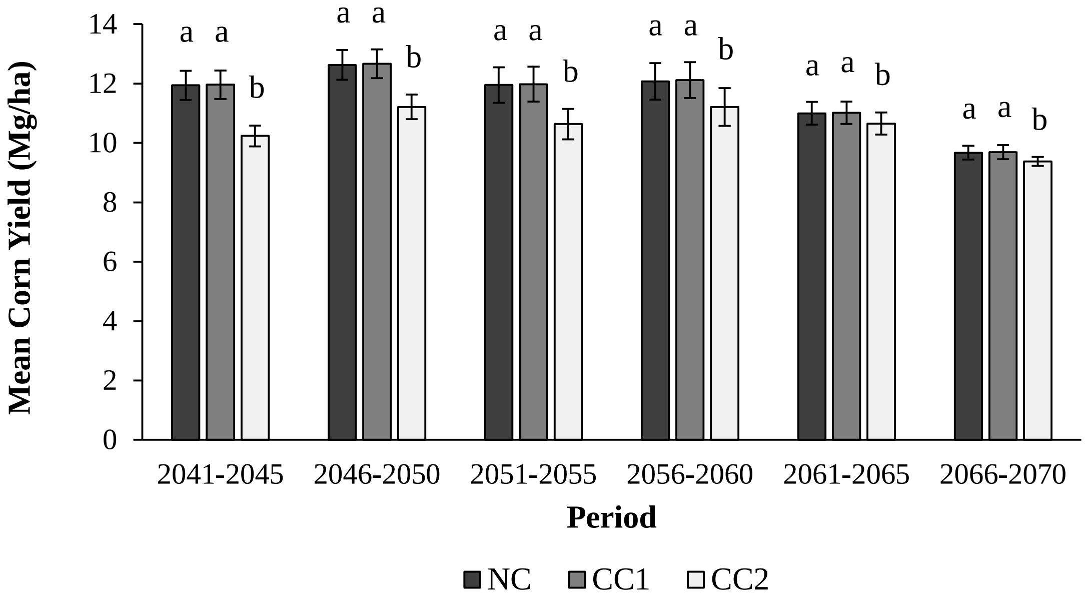
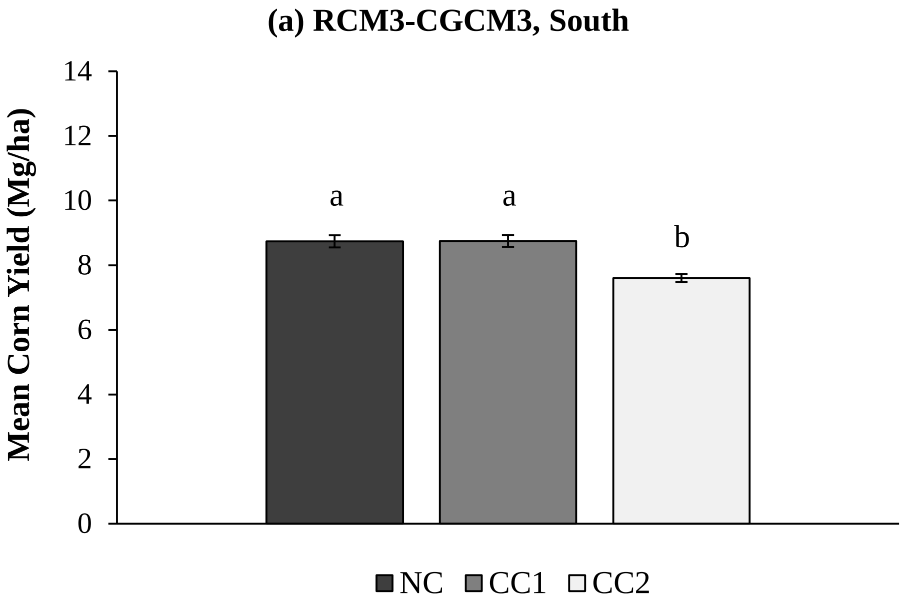
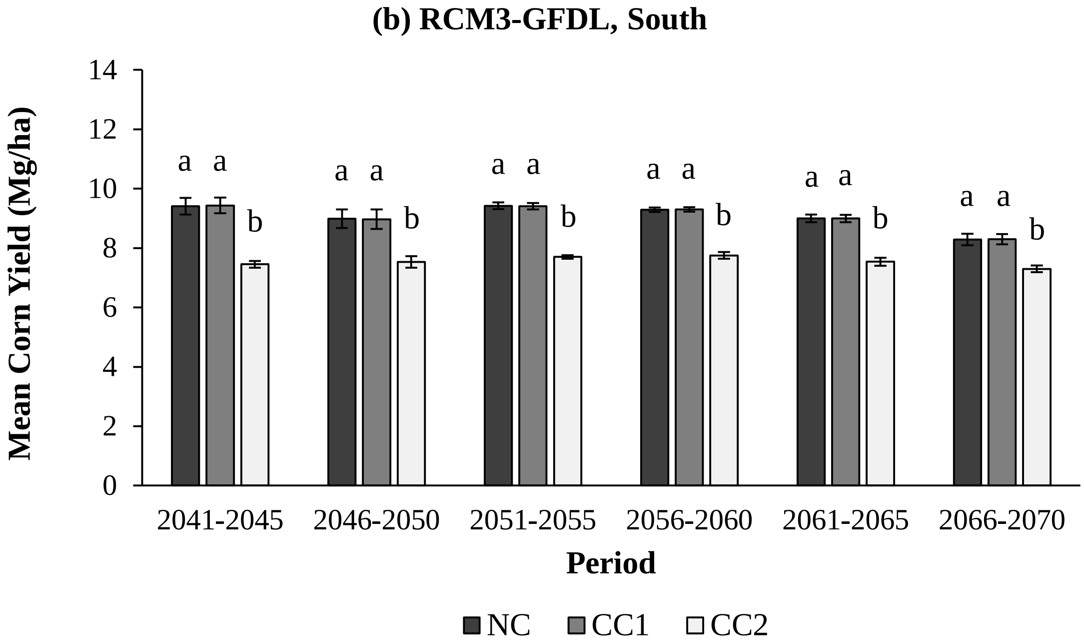


Figure 4.16. Mean corn yields (dry weight basis) in a rainfed corn-soybean rotation under future (2041–2070) climate change in the central region of the Eastern US, with no cover crop (NC), with a rye cover crop after corn (CC1), and with a rye cover crop after both corn and soybeans (CC2), as simulated by APEX under three different climate models. Error bars indicate standard errors. Different letters above each trio of bars indicate significant differences between the three means at α=0.05.

In the southern region, the effect of cover cropping on mean corn yields did not vary by five-year period except under the RCM3-GFDL climate model. Under the RCM3-CGCM3 and RCM3-GFDL climate models, planting a rye cover crop after corn did not have a significant effect on mean yields relative to the control, but planting a rye cover crop after both corn and soybeans significantly reduced mean yields by 1.1 Mg/ha (13%) under RCM3-CGCM3 and 0.99–2.0 Mg/ha (12–21%) under RCM3-GFDL (Fig. 4.17).




(b) RCM3-GFDL, South

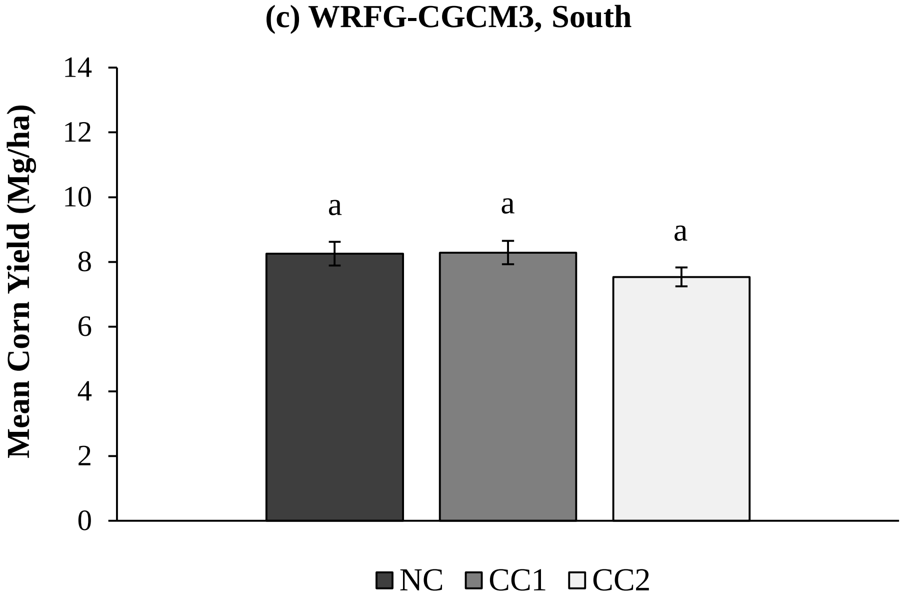
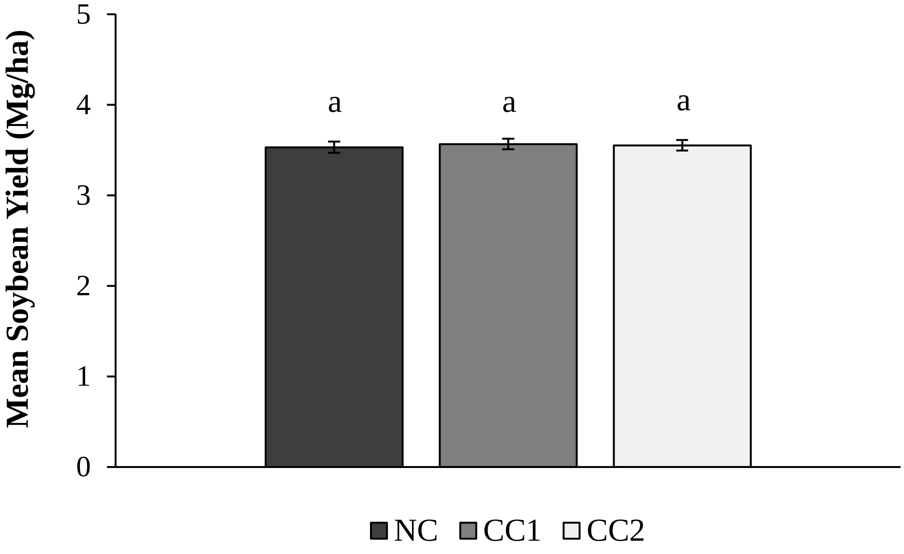

(c) WRFG-CGCM3, South

Figure 4.17. Mean corn yields (dry weight basis) in a rainfed corn-soybean rotation under future (2041–2070) climate change in the southern region of the Eastern US, with no cover crop (NC), with a rye cover crop after corn (CC1), and with a rye cover crop after both corn and soybeans (CC2), as simulated by APEX under three different climate models. Error bars indicate standard errors. Different letters above each trio of bars indicate significant differences between the three means at α=0.05.

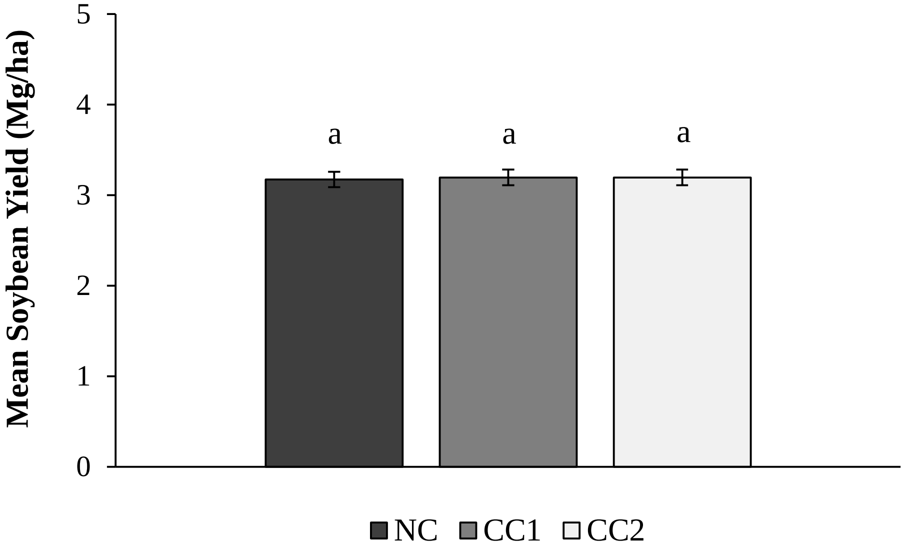
Soybean Yields

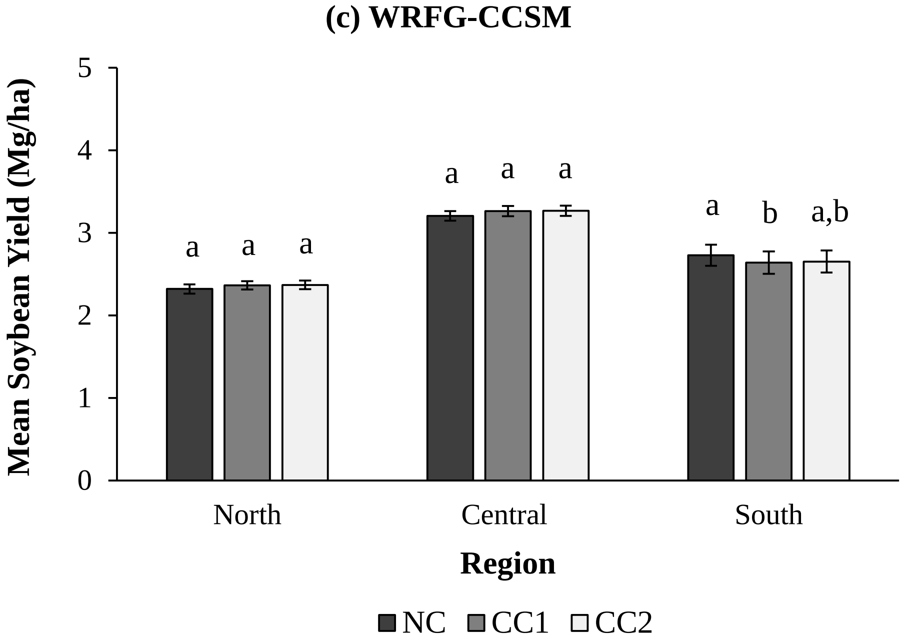
The simulated effect of rye cover cropping on mean soybean yields under climate change did not vary by region within the Eastern US except under the WRFG-CCSM climate model. Under this climate model, planting a rye cover crop after both corn and soybeans did not have a significant effect on mean yields relative to the control (no cover crop), but planting a rye cover crop after corn significantly reduced mean yields in the southern region (Fig. 4.18). However, this decrease was of only 0.09 Mg/ha (3.2%).

(a) RCM3-CGCM3



(b) RCM3-GFDL





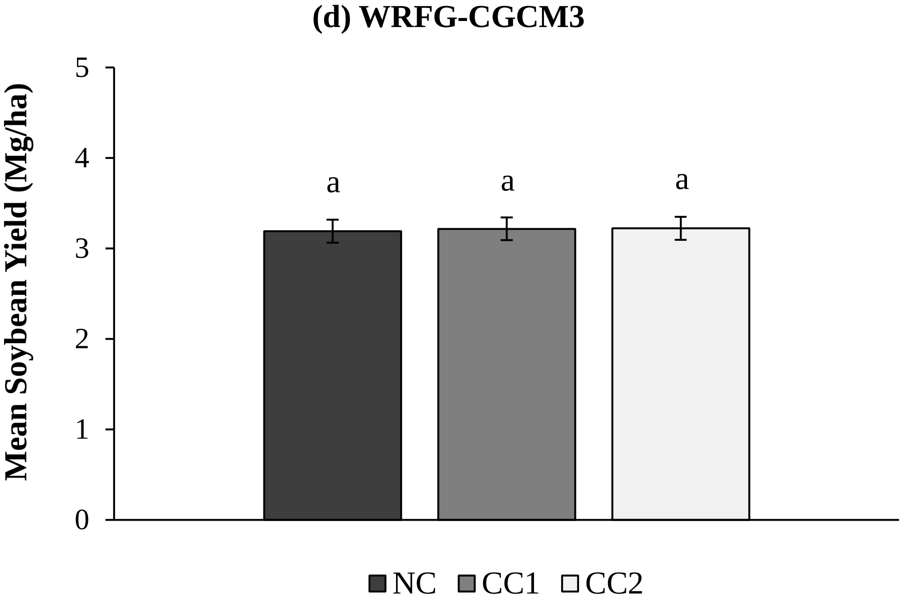


Figure 4.18. Mean soybean yields (dry weight basis) in a rainfed corn-soybean rotation under future (2041–2070) climate change in the Eastern US, with no cover crop (NC), with a rye cover crop after corn (CC1), and with a rye cover crop after both corn and soybeans (CC2), as simulated by APEX under four different climate models. Error bars indicate standard errors. Different letters above the bars indicate significant differences between the three means at α=0.05.

Discussion

Climate Change Effects

The simulated effects of climate change on corn and soybean yields differed between the four climate models used, ranging from decreases to increases. Mean corn yields experienced decreases of 15–51% and increases of 14–85% while mean soybean yields experienced decreases of 7.6–13% and increases of 22–170%. The fact that the effects of climate change on yields varied greatly between the four climate models highlights the fact that climate change impact studies cannot rely on the weather predictions of only one climate model; rather, they must use a variety of climate model predictions. In this study, yield decreases were greatest and most common under WRFG-CCSM, the only climate model that predicted a decrease in precipitation and the highest increase in temperature out of the four models. In the case of corn, the only climate models that led to yield increases were WRFG-CGCM3 and RCM3-GFDL. The first predicts the smallest increase in temperature out of all four climate models and an intermediate increase in precipitation, while the second predicts an intermediate increase in temperature and a relatively large increase in precipitation. In the case of soybeans, yield increases occurred most commonly under the RCM3-GFDL and RCM3-CGCM3 climate models, the second predicting slightly greater increases in temperature and precipitation than the first. These results suggest that an increase in temperature may not lead to reductions in corn and soybean yields—in fact it could lead to increases in some areas—as long as precipitation increases sufficiently. However, an increase in temperature without a sufficient increase or with a decrease in precipitation would likely reduce yields.

This phenomenon was observed by Phillips et al. (1996), who used EPIC to analyze the effects of changes in temperature, precipitation, and CO_2 on mean corn and soybean yields in the US Corn Belt. They found that increasing the baseline temperature by 2°C without increasing precipitation reduced corn and soybean yields, but increasing precipitation by 10% roughly compensated for the temperature-induced reductions.

In a recent study that modeled climate change impacts on rainfed yields in the Eastern US corn-soybean belt, Jin et al. (2017) used the Agricultural Production Systems Simulator (APSIM) model to compare mean corn and soybeans yields in 1995–2004 with those in 2085–2094 under the Weather Research & Forecasting (WRF) climate model. The WRF model was driven with two of the Intergovernmental Panel on Climate Change (IPCC)'s Relative Concentration Pathways (RCPs)—future greenhouse gas concentration pathways—a medium-low emissions pathway (RCP4.5) and a high emissions pathway (RCP8.5). The CO_2 concentrations used were 370 ppm for the baseline period, 534 ppm for the future period under RCP4.5, and 845 ppm for the future period under RCP8.5. The results showed that under the RCP4.5-driven climate, which projects an increase in mean maximum growing season temperature of 0–1.5°C and an increase in cumulative growing season precipitation of 0–150 mm in almost the entire Eastern US, mean corn yields increased in some areas by up to 10% and decreased in other areas by up to 30%. However, under the RCP8.5-driven climate, which predicts an increase in mean maximum growing season temperature of 2.5–3.5°C and an increase in cumulative growing season precipitation of 50–250 mm in almost the entire Eastern US, mean yields decreased in the entire region by up to 40%. This suggests that the increase in precipitation under RCP8.5 was insufficient to compensate for the increase in temperature. In the case of soybeans, however, under the RCP4.5-driven climate, mean yields increased in some areas by up to 30% and decreased in others by up to 30%, while under the RCP8.5-driven climate, mean yields increased over a greater area and where they decreased they did so by up to only 10%. However, this was due to CO_2 fertilization, given that when the future simulations were carried out at the same CO_2 concentration as the baseline simulations, mean soybean yields were lower under RCP8.5 than under RCP4.5 in most areas. This again suggests that the increase in precipitation under RCP8.5 was insufficient to compensate for the increase in temperature.

In this study, the effects of climate change on corn and soybean yields often worsened over time within the 30-year period. In some cases, climate change increased yields at first and then decreased them or had no effect, and in others cases climate change had no effect at first and then decreased yields. We believe this was due to temperatures increasing over the 30-year period without increases in precipitation or CO_2 to compensate.

Bhattarai et al. (2017) also observed yield declines over time when modeling climate change impacts in the US Corn Belt. Using EPIC, they simulated corn and soybean production between 2015 and 2099 under eight different GCMs and three different RCPs: RCP2.6 (low emissions), RCP4.5, and RCP8.5. Under RCP8.5, which is broadly comparable to the A2 family of emissions scenarios (IPCC, 2014a), mean corn and soybean yields declined over time. Between 2015–2034 and 2080–2099, mean corn yields decreased by 6.4% and mean soybean yields decreased by 3.6%, even though the CO_2 concentration increased throughout the entire 85-year period.

In this study, the effects of climate change on corn and soybean yields varied by region within the Eastern US, generally improving with latitude. For both corn and soybeans, yield increases were greater and more common in the northern region, followed by the central region and lastly the southern region. In the southern region, corn yields did not increase under any of the four climate models and soybean yields increased only in 2051–2055 under the RCM3-CGCM3 climate model. We believe this is attributable to corn and soybean growth under the baseline climate being most limited by low temperatures in the northern region and most limited by high temperatures in the southern region. Although in all three regions higher temperatures likely increased yields during spring and fall and decreased them in summer, we speculate that the spring and fall increases were greatest in the northern region and lowest in the southern, while the summer decreases were greatest in the southern region and lowest in the northern.

Jin et al. (2017) also found the effects of climate change to generally improve with latitude within the Eastern US corn-soybean belt. For both corn and soybeans under both RCP4.5 and RCP8.5, the northern region generally experienced the smallest decreases or largest increases in yields, followed by the central region and lastly the southern region. An exception to this general observation occurred in New Jersey, which often exhibited yield responses similar to those of the central or even the southern states.

In this study, climate change generally affected corn yields more negatively or less positively than it did soybean yields. Although the effects on both corn and soybean yields ranged from decreases to increases, decreases were greater and more common for corn and increases were greater and more common for soybeans. Corn yields experienced decreases under three of the four climate models and did not experience any increases in two of those models. In contrast, soybean yields underwent increases without any decreases under three of the four climate models. We believe this was due to the difference in the effects of increased CO_2 on corn, a C4 plant, and soybeans, a C3 plant. Although an increase in CO_2 decreases stomatal conductance and therefore increases water use efficiency (WUE) in both C3 and C4 plants, C4 plants do not benefit from an increase in photosynthesis comparable to that experienced by C3 plants (USDA, 2013).

Phillips et al. (1996) observed that an increase in CO_2 concentration from 350 ppm to 625 ppm had a greater effect on mean corn and soybean yields than any of the other changes studied (temperature increase of 2°C, precipitation changes of -20%, -10%, +10%, and +20%, and wind speed changes of -20%, -10%, +10%, and +20%). The increase in CO_2 increased soybean yields more than it did corn yields. In addition, while the CO_2-induced increase in soybean yields remained nearly constant at all levels of precipitation, the increase in corn yields decreased as precipitation increased. This was due to the fact that the WUE of corn increased with CO_2 more at lower precipitation levels than at higher ones.

Other modeling studies have also observed climate change to have less negative and/or more positive effects on soybean yields than on corn yields in the US. For example, Bhattarai et al. (2017) found that between 2015–2034 and 2080–2099, mean corn yields increased by 4.2% under RCP2.6 and by 5.5% under RCP4.5, while mean soybean yields increased by 8.9% and 11.1%, respectively, over twice the percent increases in corn yields. Under RCP8.5, mean corn yields decreased by 6.4% while mean soybean yields decreased by 3.6%, approximately half the percent decrease in corn yields. In order to evaluate the effect of increased CO_2 on corn and soybean yields, Bhattarai et al. ran the 85-year future simulations with and without an increase in CO_2 concentration. They found that increased CO_2 had little effect on mean corn yields but increased soybeans yields by up to 20%.

Another modeling study that investigated climate change impacts on corn and soybean yields in the US Corn Belt was Wang et al. (2015). Using the Root Zone Water Quality Model 2 (RZWQM2), coupled with two crop growth models (CERES-Maize and CROPGRO in DSSAT), Wang et al. simulated a corn-soybean rotation system in Iowa under historic (1990–2009) weather and under the future (2045–2064) weather projections produced by six of NARCCAP's RCM-GCM pairs. The CO_2 concentrations used were 369 ppm for the historic period and 548 ppm for the future period. In addition, the predicted changes in the seven atmospheric variables (maximum and minimum temperature, precipitation, solar radiation, relative humidity, wind speed, and CO_2 concentration) were simulated one at a time (while keeping the other six variables at the baseline levels) in order to study the effects of each variable on corn and soybean yields. The results showed that mean soybean yields increased by 28% with climate change, mainly due to the increase in CO_2, while corn yields decreased by 14.7%, mainly due to the increase in temperature. The rise in CO_2 alone increased yields of both crops, soybeans by 26.8% and corn by 5.7%. However, while the increase in temperature had almost no effect on soybean yields, it decreased corn yields by 9.4%.

Climate Change Adaptations

No Tillage

No tillage did not have any effect of practical significance on simulated corn or soybean yields; therefore, it did not act as an effective climate change adaptation in regards to yields. Although no tillage increased soybean yields relative to reduced tillage under one of the four climate models used (WRFG-CCSM), this increase was so small (2.7%) that it was practically insignificant.

Despite the fact that no tillage and conservation tillage have often been proposed as climate change adaptations in crop production, few modeling studies have examined the effects of tillage on crop yields under climate change. In one such study, Parajuli et al. (2016) used the Soil and Water Assessment Tool (SWAT) model to simulate corn and soybean yields in Mississippi, US during the mid-21st century (2046–2065) and late 21st century (2080–2099) under the CCSM climate model. They compared yields under three tillage treatments: 1) conventional tillage, consisting of five tillage operations that cumulatively left less than 1% ground cover; 2) reduced tillage 1, consisting of three tillage operations that cumulatively left 21% ground cover (similar to the reduced tillage treatment used in this study); and 3) reduced tillage 2, consisting of two tillage operations that cumulatively left 55% ground cover. Their results showed no significant differences in yields between the three tillage treatments. Mean corn yields were 8.38 Mg/ha under conventional tillage, 8.35 Mg/ha under reduced tillage 1, and 8.38 Mg/ha under reduced tillage 2. Mean soybean yields were 2.77 Mg/ha under all three treatments. Thus, their results appear to agree with those of this study.

However, one study that was carried out in a dry climate obtained different results. Using the EPIC model, Farina et al. (2011) simulated corn yields in Italy during three periods: 2010–2039, 2040–2069, and 2070–2099. They used two different climate models—the National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies (GISS) model and the Hadley Centre Coupled Model version 3 (HadCM3)—and two different SRES emissions scenarios—A2 and B2. They had two tillage treatments: conventional tillage (consisting of a moldboard plow operation and two harrowing operations) and no tillage. The results were mixed; in some cases corn yields were lower under no tillage than under conventional tillage, while in other cases the opposite occurred. Under the A2 emissions scenario in 2040–2069 (the same emissions scenario and time period as those used in this study), no tillage increased yields under HadCM3 but decreased them under GISS. An interesting finding was that under both climate models and emissions scenarios, yields were higher under no tillage than conventional tillage in 2070–2099. Under HadCM3, employing no tillage instead of conventional tillage reversed the negative effect of climate change on yields, turning decreases of over 15% into increases of over 30%. This suggests that even if no tillage does not have a positive effect on yields in the early or mid-21st century, it could have one in the late 21st century.

It is possible that in this study we did not observe a difference in yields between no tillage and reduced tillage because we only focused on the mid-21st century and not the late 21st century. Another possible explanation is that no tillage will only increase yields in dry regions, where increased surface cover has a large effect on soil moisture, and not in humid regions like the Eastern US. However, even if no tillage does not increase yields under climate change in the Eastern US, it could still provide other ecological and economic benefits that would be of interest to producers and society at large, such as reduced soil erosion, increased soil quality, greater weed suppression, reduced fuel costs, and earlier planting. Future research on the effects of no tillage or conservation tillage on soil erosion, soil quality, nutrient losses, and other such variables under climate change would help guide efforts to prevent soil and water degradation in the future.

Rye Cover Cropping

Like with no tillage, rye cover cropping did not act as an effective climate change adaptation in regards to corn or soybean yields. Planting a rye cover crop did not have any effect of practical significance on simulated soybean yields. Although planting rye after corn reduced the mean soybean yield in the southern region under the WRFG-CCSM climate model, this decrease was of only 3.2%, making it practically insignificant. However, rye cover cropping did have a statistically and practically significant effect on corn yields, albeit not the one expected. Under all four climate models, planting rye after corn had no effect on corn yields, but planting rye after both corn and soybeans reduced mean corn yields in part or all of the Eastern US by 3.1–28%. Given that the only difference between the two cover crop treatments was the rye cover crop following soybeans, this indicates that the decrease in corn yields was due to the presence of the rye before corn. This reduction in corn yields was not due to the rye cover crop reducing the amount of nitrogen or phosphorus available to the following corn crop because APEX was set to automatically fertilize so as to prevent any nitrogen or phosphorus stress in the simulated corn and soybeans. We speculate that the reduction in corn yields occurred because of the rye reducing the amount of soil water available to the following corn crop, which has greater water requirements than soybeans.

This hypotheses is consistent with the modeling results obtained by Baker and Griffis (2009). Using a model they developed, Baker and Griffis simulated the potential biomass production and water use of rye grown after corn in continuous corn and corn-soybean rotations at eight locations in the Midwestern US between 2002 and 2007. The results showed that soil moisture depletion was highest in years and locations with the highest rye production.

Few modeling studies have examined the effects of rye cover cropping on corn or soybean yields under climate change. One study that did (Basche et al. 2016), obtained results similar to those of this study. Basche et al. used the APSIM model to study the effect of planting rye after both corn and soybeans in corn-soybean rotation systems in Iowa between 2015 and 2060. They used 20 different GCMs from the Coupled Model Intercomparison Project 5 (CMIP5), all of them driven with the greenhouse gas emissions projected by RCP4.5. The results showed that rye cover cropping did not have a significant effect on mean corn or soybean yields. However, the years during which rye reduced corn and soybean yields were dry years. Although rye cover cropping did not increase corn or soybean yields, it did have positive effects on the soil. The soil carbon content declined less with the rye cover crop (3%) than without it (6%). In addition, rye cover cropping reduced the amount of soil erosion by 11–29%.

Given the multiple benefits of cover crops, even if rye cover cropping does not increase corn or soybean yields under climate change in the Eastern US, it may still be advantageous for producers to employ this practice. Relative to other crops, rye quickly produces abundant biomass and is therefore effective at suppressing weeds (SARE, 2007). Given its vigorous growth, rye is also exceptionally efficient at taking up nutrients remaining in the soil at the end of the main crop season, thereby increasing their availability to subsequent crops once the rye tissues decompose (SARE, 2007). Thus, even without an increase in corn or soybean yields, a rye cover crop could increase farm profits by reducing the cost of inputs, such as fertilizer and pesticides. In addition to decreasing farm inputs, rye cover cropping increases soil organic matter levels, reduces soil erosion, decreases nutrient pollution to water bodies, and reduces soil compaction, providing benefits at the farm, regional, and global scales (SARE, 2007). In order to aid in climate change adaptation and mitigation in crop production, further studies are necessary to evaluate the effects of cover cropping on soil erosion, soil organic matter, and nutrient losses under climate change.

Conclusions

The simulated effects of climate change on yields in rainfed corn-soybean rotation systems in the Eastern US varied depending on the climate model used, ranging from decreases to increases. Mean corn yields experienced decreases of 15–51% and increases of 14–85% while mean soybean yields experienced decreases of 7.6–13% and increases of 22–170%. Yield decreases were most common under the climate model predicting the highest increase in temperature and a reduction in precipitation, whereas yield increases were most common in the climate models predicting either a relatively small increase in temperature or a relatively large increase in precipitation. The effects of climate change on yields were often not constant throughout the 30-year future period (2041–2070), but worsened with time. In some cases, climate change increased yields at first and then decreased them or had no effect, and in others cases climate change had no effect at first and then decreased yields. The effects of climate change differed between the northern, central, and southern regions of the Eastern US, generally improving with latitude. While yields often increased in the northern region, especially in the case of soybeans, the southern region experienced mostly decreases or no changes. Lastly, climate change generally affected corn yields more negatively or less positively than it did soybean yields, as expected given that corn is a C4 crop and soybeans are a C3 crop. While soybean yields often increased, especially in the northern and central regions, corn yields experienced increases and decreases in approximately equal measure.

Neither no tillage nor rye cover cropping acted as effective climate change adaptations in regards to corn or soybean yields. The only effect of practical significance observed was that of rye cover cropping on corn yields. Under all four climate models, planting rye after corn had no effect on corn yields relative to the control (no cover crop), but planting rye after both corn and soybeans reduced mean corn yields in part or all of the Eastern US by 3.1–28%. We speculate that this reduction in corn yield occurred because the rye cover crop reduced the amount of soil water available to the following corn crop.

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Chapter 5: General Summary

In the first study, we conducted surveys and interviews in order to identify the main weather-related conditions affecting crop production and the management practices that producers are using as climate change adaptations in the Mid-Atlantic United States (US). We surveyed 193 producers at nine conferences held in Maryland, Delaware, New Jersey, and Pennsylvania and interviewed nine University of Maryland Extension agents between January and February, 2015. The results of this study suggest the following:

- The most important weather-related challenges to crop production are those related to precipitation—unpredictability in precipitation, low summer moisture, high spring moisture, and strong rainfall events—followed by those related to temperature—unpredictability in temperature, high summer temperatures, and low spring temperatures.
- Although crop production is being affected by both short and long growing seasons, long seasons are more prevalent, which is providing an opportunity to crop production.
- In response to low moisture, mainly a challenge in summer, producers are using increased irrigation, high-efficiency irrigation, conservation tillage, cover cropping, and drought-tolerant crops.
- In response to high moisture, mainly a challenge in spring, producers are using drainage.
- In response to intense rainfall events, producers are using conservation tillage and cover cropping.

- In response to high temperatures, mainly a challenge in summer, producers are planting heat-tolerant crops and/or cultivars.
- In response to long growing seasons, producers are planting earlier and using longer-season cultivars.
- In response to unpredictability in precipitation and temperature, producers are using crop rotations and an increased diversity of crops and/or cultivars.

In the second study, we used the Agricultural Policy/Environmental eXtender (APEX) model to evaluate the effects of climate change on yields and the effectiveness of no tillage and rye cover cropping as adaptations in rainfed corn-soybean rotation systems in the Eastern US. We simulated corn-soybean production in the future (2041–2070) at nine land grant university research farms located throughout the Eastern US corn-soybean belt from New York to Georgia. The results of this study were the following:

- The effects of climate change on yields ranged from decreases to increases, depending on the climate model used. Mean corn yields experienced decreases of 15–51% and increases of 14–85% while mean soybean yields experienced decreases of 7.6–13% and increases of 22–170%.
- In many cases, the effects of climate change on yields worsened with time within the 30-year future period.
- The effects of climate change differed between the northern, central, and southern regions of the Eastern US, generally improving with latitude.
- Climate change generally affected corn yields more negatively or less positively than it did soybean yields.

- No tillage and rye cover cropping did not serve as effective climate change adaptations in regards to corn or soybean yields. In fact, planting rye after corn and soybeans reduced mean corn yields by 3.1–28% relative to the control (no cover crop).

Appendices

Appendix A. Questionnaire used when surveying crop producers at nine agricultural conferences in Maryland, Delaware, Pennsylvania, and New Jersey in January and February 2015.

Survey for Crop Producers: How Do You Manage for Weather?

(Please do not indicate your name, address, or any other identifying information on this survey)

1. Approximately how many years have you been managing crops? __________
How many years have you been managing crops at your current location? __________

2. Approximately how many average acres of crop production at your current location have you managed? __________

3. Please indicate the main crops that you have managed at your current location. You may specify what hay, vegetable, and fruit crops you have managed.

☐ Field corn
☐ Small grains: ☐ Wheat ☐ Rye ☐ Barley ☐ Oats ☐ Other: ________________
☐ Soybeans
☐ Hay: ☐ Grass ☐ Legume
____
☐ Vegetables: ☐ Market vegetables ☐ Legumes ☐ Potatoes ☐ Sugar beets ☐ Oilseeds
____
☐ Fruits (including nuts): ☐ Tree fruits ☐ Non-tree fruits
____
☐ Other: ____

4. Where are the lands you currently manage located?
State: _________________
County: _________________

5. Please select the weather conditions that have affected your crop production the most at your current location and indicate whether the effect has been positive, negative, or both.

☐ **a.** Unpredictability in temperature: ☐ Positive effect ☐ Negative effect
☐ **b.** Low temperatures: ☐ Positive effect ☐ Negative effect
☐ **c.** High temperatures: ☐ Positive effect ☐ Negative effect
☐ **d.** Unpredictability in precipitation: ☐ Positive effect ☐ Negative effect
☐ **e.** Low moisture: ☐ Positive effect ☐ Negative effect
☐ **f.** High moisture: ☐ Positive effect ☐ Negative effect
☐ **g.** Strong rainfall events: ☐ Positive effect ☐ Negative effect

☐ **h.** Long growing season: ☐ Positive effect ☐ Negative effect
☐ **i.** Short growing season: ☐ Positive effect ☐ Negative effect
☐ **j.** Other: ______________________________ ☐ Positive effect ☐ Negative effect
☐ **k.** Other: ______________________________ ☐ Positive effect ☐ Negative effect

6. If you selected any weather conditions in questions 5 and 6, what practices have you used at your current location to manage for them? For those practices you select, indicate the weather conditions that caused changes in management by writing the corresponding letters from question 5 (letters a-j).

Used to
manage for…
(write letters a-j

Water management practices
from Q.5)

☐ Increased irrigation inputs ___________
☐ High efficiency irrigation: ___________
  ☐ Center pivot ☐ Movable sprinkler pipes ☐ Drip
☐ Drainage (open ditch, tile, or other) ___________
☐ Other: ______________________________________ ___________

Soil management practices

☐ Conservation tillage (tillage that maintains at least 30% residue cover): ___________
  ☐ Mulch tillage (full-width conservation tillage)
  ☐ Strip tillage (only the seed row is tilled)
  ☐ No tillage (soil is disturbed only by seeding operation)
  ☐ Minimum tillage (any other conservation tillage method)
☐ Partial/total use of plant/animal wastes instead of inorganic fertilizers ___________
☐ Crop rotations ___________
  Rotations used: ____
☐ Cover crops: ___________
  Cover crops used: ____
☐ Other: ____ __________

Changes in crop selection and planting

☐ Longer-season crops or crop varieties ___________
☐ Shorter-season crops or crop varieties ___________
☐ Higher-temperature crops or crop varieties ___________
☐ Lower-temperature crops or crop varieties ___________
☐ Higher-moisture crops or crop varieties ___________
☐ Lower-moisture crops or crop varieties ___________
☐ Increased diversity in crops or crop varieties ___________
☐ Other: ____ ___________

Changes in planting dates

☐ Earlier planting ____________

☐ Later planting ____________

☐ Other: ____ ___________

Appendix B. SAS code used to analyze the simulated effects of climate change on corn and soybean yields for each of the four climate models used
CC: Climate Change

```
PROC MIXED DATA=<Data name>;
CLASS Region Farm CC Period;
MODEL Yield=Region|CC|Period / DDFM=KR;
RANDOM Farm*Region;
REPEATED Period / subject=Farm*CC type=CS;
RUN;

PROC SORT DATA=<Data name>;
BY Region Period;
RUN;

PROC MIXED DATA=<Data name>;
CLASS Region Farm CC Period;
MODEL Yield=CC|Period / DDFM=KR;
RANDOM Farm;
REPEATED Period / subject=Farm*CC type=CS;
BY Region;
RUN;

PROC MIXED DATA=<Data name>;
CLASS Region Farm CC Period;
MODEL Yield=CC;
RANDOM Farm;
BY Region Period;
RUN;
```

Appendix C. SAS code used to analyze the simulated effects of no tillage and rye cover cropping on corn and soybean yields under climate change for each of the four climate models used
Cover: Cover cropping factor

```
PROC MIXED DATA=<data name>;
CLASS Region Farm Tillage Cover Period;
MODEL Yield=Region|Tillage|Cover|Period;
RANDOM Farm*Region;
REPEATED Period / subject=Farm*Tillage*Cover type=<CS, CSH, or AR(1)>;
RUN;

PROC SORT DATA=<data name>;
BY Region Period;
RUN;

PROC MIXED DATA=<data name>;
CLASS Region Farm Tillage Cover Period;
MODEL Yield=Cover|Period;
RANDOM Farm;
REPEATED Period / subject=Farm*Tillage*Cover type=<CS, CSH, or AR(1)>;
BY Region;
LSMEANS Cover / PDIFF ADJUST=TUKEY;
RUN;

PROC MIXED DATA=<data name>;
CLASS Region Farm Tillage Cover Period;
MODEL Yield=Cover;
RANDOM Farm;
BY Region Period;
LSMEANS Cover / PDIFF ADJUST=TUKEY;
RUN;
```

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