Best Management Practices for Sustaining Agricultural Production at Choctawhatchee Watershed in Alabama, USA, in Response to Climate Change

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ABSTRACT: Climate change will ultimately result in higher surface temperature and more variable precipitation, negatively affecting agricultural productivity. To sustain the agricultural production in the face of climate change, adaptive agricultural management or best management practices (BMPs) are needed. The currently practiced BMPs include crop rotation, early planting, conservation tillage, cover crops, effective fertilizer use, and so on. This research investigated the agricultural production of BMPs in response to climate change for a Hydrologic Unit Code12 sub-watershed of Choctawhatchee Watershed in Alabama, USA. The dominating soil type of this region was sandy loam and loamy sand soil. Agricultural Production Systems sIMulator and Cropping Systems Simulation Model were used to estimate the agricultural production. Representative Concentration Pathway (RCP) 4.5 and RCP8.5 that projected a temperature increase of 2.3℃ and 4.7℃ were used as climate scenarios. The research demonstrated that crop rotation had positive response to climate change. With peanuts in the rotation, a production increase of 105% was observed for cotton. There was no consistent impact on crop yields by early planting. With selected peanut-cotton rotations, 50% reduced nitrogen fertilizer use was observed to achieve comparable crop yields. In response to climate change, crop rotation with legume incorporation is thus suggested, which increased crop production and reduced fertilizer use.

KEYWORDS: Peanuts, cotton, rotation, legumes, crop yields, fertilizer use

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Introduction

Climate change studies have documented clear warming trends globally, ultimately resulting in higher surface temperature.[1,2] This change in temperature would likely lead to increased precipitation, but rainfall patterns are projected to change in different ways in different geographical locations of the United States.[3,4] For example, summertime precipitation in the northwestern United States is predicted to decrease by 15% to 25%, whereas the northern central and eastern United States will see an increase of 5% to 15%. In contrast, winter precipitation is projected to increase by 5% to 15% in the northern and central United States, but decrease by 5% to 10% along the southern US border.[5,6] Higher surface temperature and more variable precipitation in terms of intensity and amount may increase evapotranspiration, reduce soil water storage, and degrade the soil by mechanical weathering and erosion.[7-9] These changes will negatively affect agricultural productivity in most regions of the United States, affecting irrigated and non-irrigated crops, livestock, and forest systems.[10,11] The climate change with associated increased temperature and fluctuating precipitation would decrease water availability and crop yields.[12] To sustain the nation's agricultural production in the face of climate change, adaptive agricultural management or best management practices (BMPs) are needed.[13-15]

Best management practices describe ways to manage agricultural activities to sustain agricultural production while mitigating pollution of surface and groundwater.[16] Best management practices include crop rotation, early planting, conservation tillage, cover crops, effective fertilizer applications, and so on. The effectiveness of these BMPs depends on the soil characteristics, climate, and management factors. Best management practices can affect a wide range of environmental and landscape attributes, including the quality of water, ecosystem processes and services, and the climate itself through greenhouse gas (GHG) fluxes and surface albedo effects.[17] Agricultural activities are a major source of climate change, which are responsible for 25% of total anthropogenic CO_2, 50% of CH_4, and 75% of NO_2 emission.[18] Fertilization is the significant portion of the agricultural activities that are associated with GHG emission.[19] For instance, 48% of N_2O emission was associated with wheat production and 52% was associated with nitrification-denitrification in the soil during nitrogen fertilizer applications.[20]

Climate change adaptation within agricultural systems is achieved by adjustment of agricultural activities to minimize the vulnerability of the existing system.[21] Under certain conditions, reconstruction of the whole system to adapt to the changing climate is required.[22,23] Different agricultural management practices have varying impacts on the agricultural

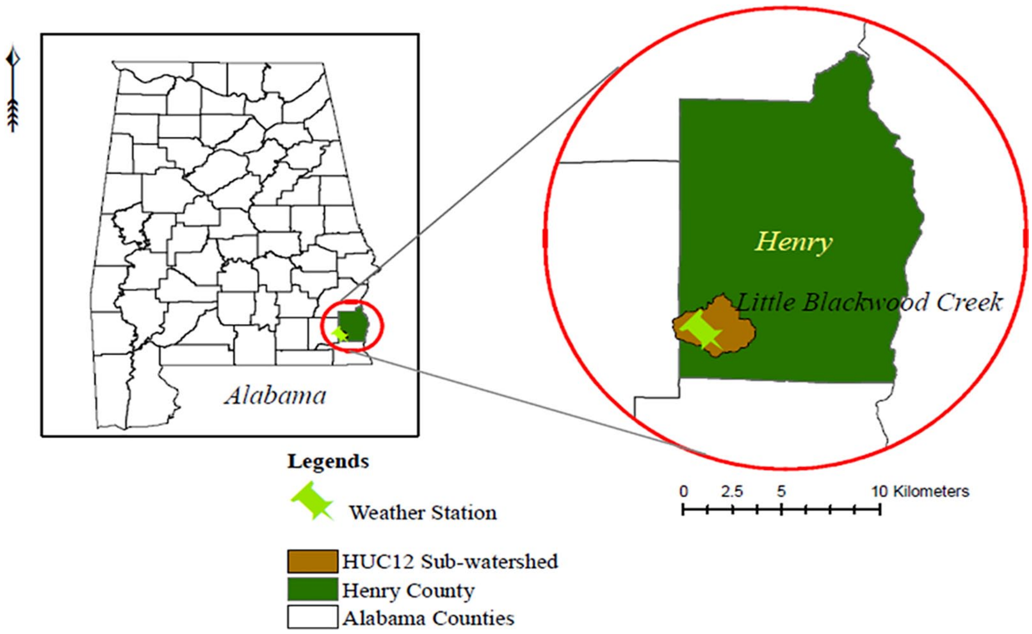

Figure 1. Location of the study region and weather station.
HUC indicates Hydrologic Unit Code.

system, including soil carbon sequestration, GHG emission, soil fertility, and so on.[24] Climate change prediction and adaptation strategies based on local region and cropping system can be more reliable as the response of BMPs is mostly region-specific and cropping system–specific.[18,23,25] For the next 50 years, temperature is projected to increase by 2.5°C to 5°C. Best management practices are needed across a broad range of climate and environmental conditions, and under the pressure of increased food demand.

Best management practices have been widely implemented at regional, national, and international scales for water quality protection and soil conservation.[26-28] However, BMPs are more reliable when arranged based on local or regional scenarios. For instance, in the United State, approximately 20% of the corn is grown in continuous monoculture, whereas most of the remaining 80% is grown in 2-year rotation with soybean.[29] The crop rotations have been economically successful with more and more ripen technologies being incorporated, leading to dramatic growth of output from the US farms.

Best management practices can be evaluated based on predictive models in a spatially explicit, multiscale, and integrated manner. This is important for the quantitative exploration of alternative pathways into the future.[30-32] Using the modeling tools, a correspondingly large array of adaptation options can be tested to improve the resilience of the agricultural system to the impact of climate change. Although the identified BMPs are inherently local, their ecological impact may be extended to regional and global scales.[33,34] In addition, BMPs may have social and economic impact, such as agricultural production and constraints on policy implementation within the agricultural production system.[35-37] With the potential higher temperature and more variable precipitation, there is an urgent need to pre-emptively evaluate the environmental and economic impact of BMPs across multiple services and scales before thorough implementation.

This research evaluated the current agricultural landscape scenarios of a Hydrologic Unit Code (HUC)12 sub-watershed of Choctawhatchee Watershed in Alabama, USA. The agricultural production of BMPs in response to climate change was assessed by Agricultural Production Systems sIMulator (APSIM) and Cropping Systems Simulation (CropSyst) Model under Representative Concentration Pathway (RCP) 4.5 and RCP8.5 scenarios of the study region from 2016 to 2018.

Materials and Methods

Study site

The study region was an HUC12 sub-watershed of Choctawhatchee Watershed in Alabama, USA. This sub-watershed was named "Little Blackwood Creek" with a US Geological Survey (USGS) HUC Code of "031402010205." The area of the study region was 70.9 km^2 (7090 ha). This sub-watershed was an agriculture-intense part of the Choctawhatchee watershed in Alabama, USA. The weather station for the study region was the NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) weather station with 31.4° latitude and −85.4° longitude, located within the HUC12 sub-watershed of this study. The location map of the study region and the weather station is illustrated in Figure 1.

For the Choctawhatchee Watershed, the primary land cover was forest dominated by sand pine (*Pinus clausa*). For the study HUC12 sub-watershed, agriculture was the important land use. The selected sub-watershed was located in the Henry County of Alabama, one of the most agriculture dominant parts of the

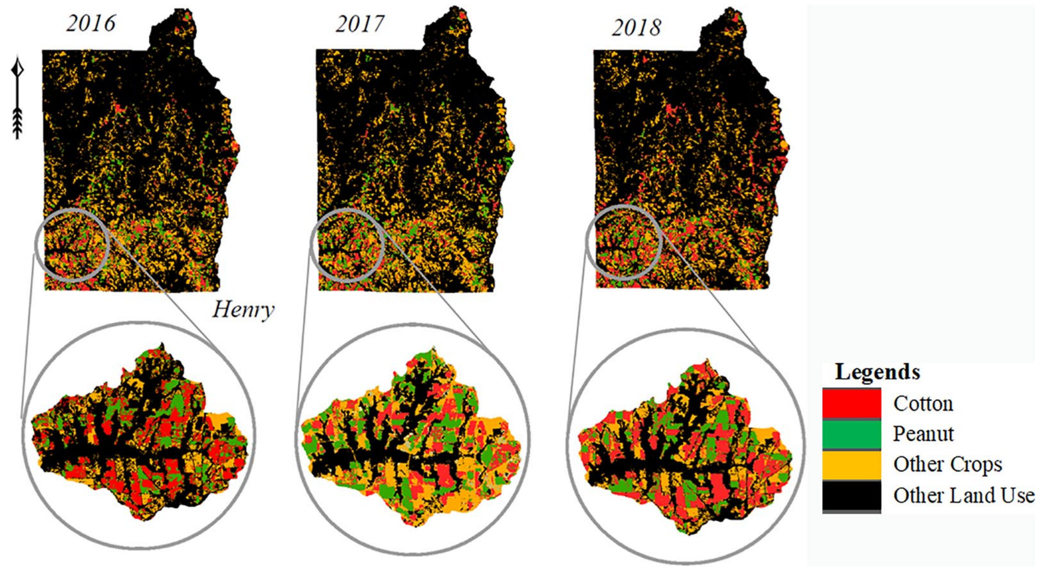

Figure 2. Land use of the study sub-watershed from 2016 to 2018.

Table 1. Soil texture and composition.

SOIL TEXTURE	AREA (HA)	% AREA COVERAGE
Sandy loam	1.8×10^6	44.6
Loamy sand	1.6×10^6	39.5
Sand	1.3×10^5	3.1
Fine sandy loam	1.0×10^4	0.2
Fine sand	1.6×10^5	4.0
Muck	3.5×10^5	8.5

Choctawhatchee Watershed. The land use in the study region was dominated by cotton and peanuts. The land use from 2016 to 2018 of the study region is illustrated in Figure 2.

The soil of the study region mainly comprised sandy loam and loamy sand, occupying 45% and 40% of the soil, respectively (Table 1). The soil type information was obtained from the US Department of Agriculture (USDA) Soil Survey Geographic (SSURGO) database.[38] Like typical soils, the particles aggregated together with soil organic matter, which affected water flow in the soil. The soil collected from the study region was composed of clays (<0.002 mm), silts (0.002-0.02 mm), and sands (0.02-2 mm), which made up the inorganic solid phase of the soil. The soil particle size distribution from the samples collected from the study region was characterized by a sieve analysis. Five sample analysis was conducted and the average was reported. Based on the sieving analysis, around 93.6% of the particles were found to be smaller than 0.4 mm, that is, passing through the 40 sieve. Around 0.6% of the particles were found to be smaller than 0.07 mm, that is, passing through the 200 sieve (Figure 3).

The average soil organic carbon was found to be 1.45% by the Mebius method, which was consistent with the fact that the soil bulk density was below average.[39] Using the permanganate-reduced iron modification of a semimicro-Kjeldahl procedure, the total nitrogen of the soil was found to be in the range of 0.09% to 0.3%.[40] But the pH of the soil was low, that is, <5.5, which was not ideal for microbial activities. Using plate count method with a general substrate or agar, the plate counts showed an average of 1.9×10^6 CFU/g soil.

Projected temperature and precipitation change

Climate change ultimately results in higher surface temperature. Historically, global average surface temperature increased by about 0.74°C during the 20th century. Over the next 50 years, the average US temperature is projected to increase by 1°C to 2°C, with an increase of 2°C to 5°C in the interior.[41] This change in temperature will likely lead to increased precipitation. However, rainfall patterns are projected to change in different ways compared with those of temperature. The future climate scenarios were analyzed using NEX-GDDP data set for the timeline (2006-2100) (Figure 4). For this research, 3 climate scenarios were studied, that is, historic (1950-2005), RCP4.5 (2006-2099), and RCP8.5 (2006-2099). Representative Concentration Pathway, a GHG concentration trajectory adopted by Intergovernmental Panel on Climate Change, was used as a climate change indicator in this research. RCP4.5 and RCP8.5 are scenarios with possible radiative forcing values of 4.5 and 8.5 W/m^2, which are medium and high emission scenarios. There is an obvious trend in temperature increase for all the 3 scenarios, that is, the slopes of increase are 0.01, 0.02, and 0.05 for historical, RCP4.5, and RCP8.5, respectively (Figure 4). This implies that the temperature is projected to increase about 2.3℃ and 4.7℃ for RCP4.5 and RCP8.5 scenarios, respectively. Similarly, there is an obvious trend in precipitation increase. The analysis of Standardized Precipitation Index (SPI) index shows that more than 60% of the precipitation years are near normal zones under

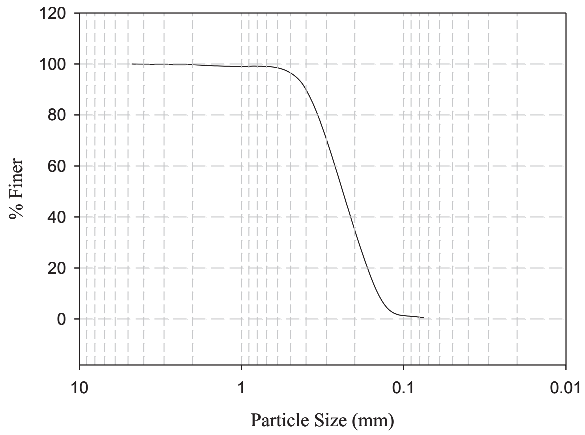

Figure 3. Soil particle size distribution from sieving analysis.

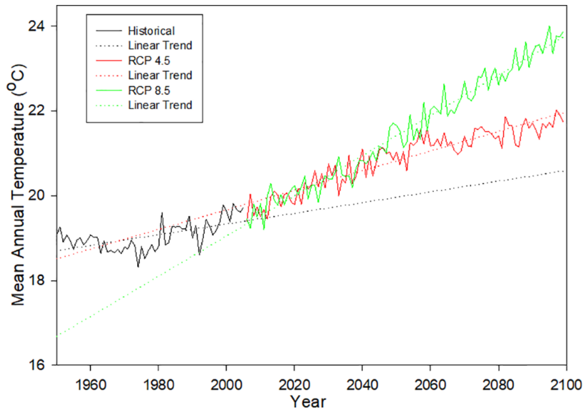

Figure 4. Annual temperature trend analysis with averaged model data. Historical timeline: 1950-2005 and future timeline: 2006-2099 for both RCP8.5 and RCP4.5 scenarios.
RCP indicates Representative Concentration Pathway.

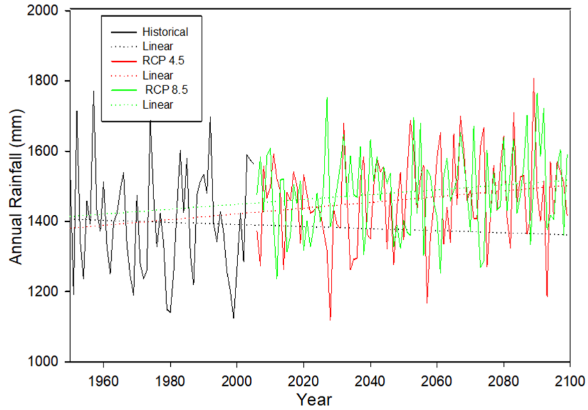

Figure 5. Annual precipitation trend analysis with averaged model data. Historical timeline: 1950-2005 and future timeline: 2006-2099 for both RCP8.5 and RCP4.5 scenarios.
RCP indicates Representative Concentration Pathway.

all 3 scenarios (Figure 5). The percent occurrences of various categories of droughts or flood events are almost similar for both the historical and future timelines. Mann-Kendall test (nonparametric) was conducted on the annual mean temperature and precipitation, and significant increasing trends ($P < .05$) were noticed (Tables 2 and 3 and Figure 6). For this research, the crop yields were focused on the time range from 2016 to 2018, with assumptions that RCP4.5 and RCP8.5 scenarios were happening in these years.

Model calibration and performance

Process-based simulation models have been widely used in agricultural research for developing cropping technologies. This process explores management practices and assesses policy decisions. For this research, the APSIM and CropSyst Model were used to assess the biophysical, biogeochemical, and economic consequences of management decisions and farming practices.[42-44] The APSIM was developed by the Commonwealth Scientific and Industrial Research Organization, State of Queensland and University of Queensland, Australia. The APSIM contains a suite of modules that enable the simulation of system management interactions.[45] This model simulates variables in crop yields based on soil functions in response to weather and management.[46-48] Plant growth modules are interchangeable, and more than one can be connected simultaneously. The APSIM consists of a number of biophysical modules to simulate the different biological and physical processes occurring in farming systems. The APSIM operates on a daily time step with weather and management data as the main inputs. The CropSyst Model was developed by Dr Stockle at Washington State University. It simulates crop yields with interactions with soil water budget, soil-plant nitrogen budget, crop phenology, crop canopy and root growth, biomass production, residue production and decomposition, water erosion, and pesticide fate.[49] The CropSyst Model is sensitive to temperature and precipitation.

For the selected study region of this research, peanuts and cotton are the major economic crops. For each crop, specific management practice data including cultivar selection, planting time, fertilizer applications, tillage, and so on were used as input data. In addition, daily weather variables (maximum and minimum temperature, precipitation, and radiation) were used as inputs to simulate crop growth. These modules were linked with soil modules that simulated soil processes including soil water and nitrogen cycles and surface residue decomposition in response to weather and management. The APSIM and CropSyst Model were developed with the assumption that the daily biomass production was directly proportional to intercepted photosynthetically active radiation. Besides crop growth rate, crop growth duration is also very important in determining the potential crop yields. The principal functional approach used to estimate the duration of crop growth is based on thermal time, t_d, which is the accumulation of degree-days (ie, °C d) above a base temperature:[50]

$$t_d = \sum_{i=1}^{n} \left(T_a - T_b\right)$$

Table 2. Man-Kendall trend test (nonparametric) on annual average modeled precipitation and temperature on historical (1950-2005) and future (2006-2099) timelines.

DATA SET FOR TEST	TEMPERATURE (HISTORICAL)	TEMPERATURE (RCP8.5)	TEMPERATURE (RCP4.5)	PRECIPITATION (HISTORICAL)	PRECIPITATION (RCP8.5)	PRECIPITATION (RCP4.5
H value	1	1	1	0	0	0
P value	0.000087	0	0	0.9831	0.1563	0.1681
Significance	Significant	Significant	Significant	Not significant	Not significant	Not significant
Trend	Increasing	Increasing	Increasing	No trend	Increasing	Increasing

Abbreviation: RCP, Representative Concentration Pathway.

Table 3. Quantification of dry, wet, and normal years with Standardized Precipitation Index (SPI) values for historical (1950-2005) and 2 future scenarios (2006-2099) for both RCP8.5 and RCP4.5.

SPI VALUE	CATEGORY	1960-2005 HISTORICAL	2006-2099 RCP8.5	2006-2099 RCP4.5	OCCURRENCE (HISTORICAL), %	OCCURRENCE (RCP8.5), %	OCCURRENCE (RCP4.5), %
⩾2.00	Extremely wet	0	1	3	0.0	1.1	3.2
1.5 to 1.99	Severely wet	3	5	4	5.4	5.3	4.3
1.00 to 1.49	Moderately wet	7	9	8	12.5	9.6	8.5
0.99 to −0.99	Near Normal	37	64	66	66.1	68.1	70.2
−1.0 to 1.0	Moderately dry	5	8	7	8.9	8.5	7.4
−1.5 to −1.99	Severely dry	2	4	5	3.6	4.3	5.3
⩽−2.00	Extremely dry	2	3	1	3.6	3.2	1.1

Abbreviations: RCP, Representative Concentration Pathway; SPI, Standardized Precipitation Index.

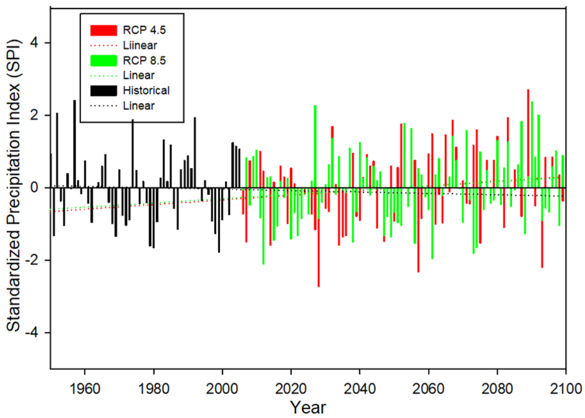

Figure 6. Rainfall anomalies (SPI as an indicator) for a representative site of Choctawhatchee Watershed with simulated averaged data (historical timeline: 1950-2005 and future timeline: 2006-2099 for both RCP8.5 and RCP4.5 scenarios).
RCP indicates Representative Concentration Pathway; SPI, Standardized Precipitation Index.

where T_a is the 24-hour daily mean temperature, is the base temperature below which the crop growth ceases, and n is the number of days. T_a is usually approximated by taking the mean of daily maximum and minimum temperature. The economic crop species in the study region are sensitive to photoperiod, that is, peanuts and cotton adapt to grow in shorter day-lengths; they thus develop more quickly when exposed to shorter days. In the APSIM, the photoperiod is assumed to affect phenology between emergence and floral initiation, during which thermal time is a function of photoperiod. Therefore, the APSIM gives a more reasonable simulation result. The APSIM and CropSyst Model were calibrated against the harvest time of USDA Field Crops Usual Planting and Harvesting Dates for Alabama, where the simulation site was located.

The evaluation was conducted by the APSIM and CropSyst Model that were calibrated based on the existing production data of 2016-2018 of the study region. The impact of BMPs of crop rotation, early planting, conservative tillage, cover crops, and effective nitrogen fertilizer use on crop yields was evaluated using the APSIM and CropSyst Model for 2026-2018 under RCP4.5 and RCP8.5 scenario conditions for the study region. These BMPs are currently the most commonly practiced ones in the study region.

Results

Crop yields in response to climate change

There is a linear increased trend for both historic data and RCP4.5 and RCP8.5 data. Compared with the historic temperature data, there will be around 2.5°C increase for both RCP4.5 and RCP8.5 until 2050. After 2050, the temperature increase will

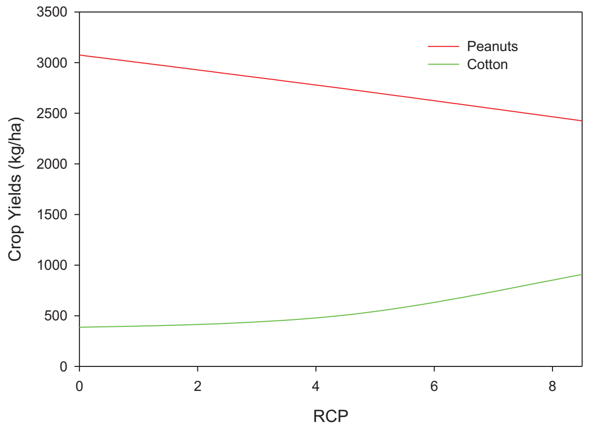

Figure 7. Peanut and cotton yields in response to RCP4.5 and RCP8.5. RCP indicates Representative Concentration Pathway.

be much more pronounced for RCP8.5 than that of RCP4.5 (Figure 4). On the contrary, the precipitation patterns are similar for both RCP4.5 and RCP8.5 (Figure 5). The *H* value of temperature was 1 for historic, RCP4.5, and RCP8.5, and the *H* value of precipitation was 0 for all the 3 scenarios (Table 2).

The APSIM simulated crop growth, soil water balance, and nutrient cycling in daily time steps. Peanuts and cotton were sensitive to temperature but responded differently to temperature variation. Projected temperature changes significantly decreased peanut yields, while they increased cotton yields (Figure 7). For RCP4.5 and RCP8.5, peanut yields decreased by 10% and 21% and cotton yields increased by 31% and 135%. Cotton yield increase was much more pronounced than those of peanut yield decrease. Temperature plays an important role in peanut growth and production. While peanuts prefer warm weather, they are frost-tolerant and able to grow in areas with an average low winter temperature of −10°C. Peanuts reach their peak growing performance in soil temperatures between 21°C and 26°C. The temperature changes of RCP4.5 and RCP8.5 are out of the ideal range for peanut growth. Subsequently, peanut yields decrease accordingly. Cotton prefers warm and humid climate. During active growth, the ideal air temperature for cotton is 21°C to 37°C. Cotton can also survive in temperatures up to 43°C for short periods without great damage. The temperature changes within RCP4.5 and RCP8.5 are still within the ideal temperature range of cotton growth. Thus, cotton yields increase.

Crop rotation

The existing crop rotation scenarios of the study region were extracted by QGIS operations. This was conducted in the HUC12 watershed covering Henry County in 3 consecutive years of 2016-2018. In the study region, the top 3 unique rotations were 2 years of cotton with 1 year of peanuts (peanut-cotton-cotton [17.3%] or cotton-cotton-peanut [6.9%]), monoculture (cotton-cotton-cotton) (10.8%), and peanut-cotton rotation in alternate years (cotton-peanut-cotton [9.9%] or peanut-cotton-peanut [5.1%]). The peanut-cotton–based rotations cover approximately 40% area of the HUC12 region.

Crop yields with rotations are typically 10% higher than those of crops grown in monoculture in normal growing seasons. Involving legumes (ie, peanuts) into cotton rotation introduced significant amounts of nitrogen to the succeeding cotton. Peanuts promoted a symbiotic relationship with specific *Rhizobia* bacteria that made an important contribution to plant nutrition for the study region. There was a steady increase in cotton production in monoculture from 2016 to 2018, with cotton production of 386.6, 455.5, and 614.2 kg/ha for 2016, 2017, and 2018, respectively (Figure 8). From 2016 to 2018, an increase of 59% was observed. With the introduction of peanuts in rotation, the increase in cotton production was more pronounced. For instance, for cotton-peanut-cotton rotation, cotton production was 386.6 kg/ha for 2016 and 790.7 kg/ha for 2018, an increase of 105% from 2016 to 2018. Currently, more attention is focused on rotations of legumes, which supply significant amounts of nitrogen to succeeding crops and increase soil organic matter. With the nitrogen fixation by legumes, reduced nitrogen fertilizer use is required. Thus, using legumes in crop rotations can dramatically reduce nutrient loading at the watershed, which can help sustain the agroecosystem.

Early planting

Photoperiod and other factors significantly affect the harvest index. To account for effects of photoperiod on harvest index, Peanut, Cotton, and Maize modules were calibrated against the historic data for the APSIM and CropSyst Model. Crop phenology was also calibrated by varying the crop phenology parameters until the modeled phenology dates matched the observed dates. With an increase in temperature such as in RCP4.5 scenarios, peanut production decreased by 7%, but there was increase in cotton production by 23%, indicating that cotton was more heat-resistant (Figure 9).

Early planting is important to maximize yields in face of climate change. Over the last 3 years, crop planting has started earlier, which contributed to increased crop yields. For the study region, cotton and peanuts were planted between April 24 and May 24 and April 25 and May 25, with the average planting dates of May 9 and May 10 for cotton and peanut. The harvest dates were between September 20 and October 20 and September 22 and October 22, with the average harvesting dates of October 5 and October 7 for cotton and peanuts. With a 10-day earlier planting, there was no consistent impact on crop yields with a second year decrease in cotton but increase in peanuts, and minimal impact for both cotton and peanuts in the third year for all the rotation types. However, with a 10-day later planting, there was obvious decrease in both cotton and peanuts for 3 years for all the rotation types (Figure 9). For cotton grown in monoculture or in the first 2 years of cotton-cotton-peanut rotation, there was no impact on cotton yields.

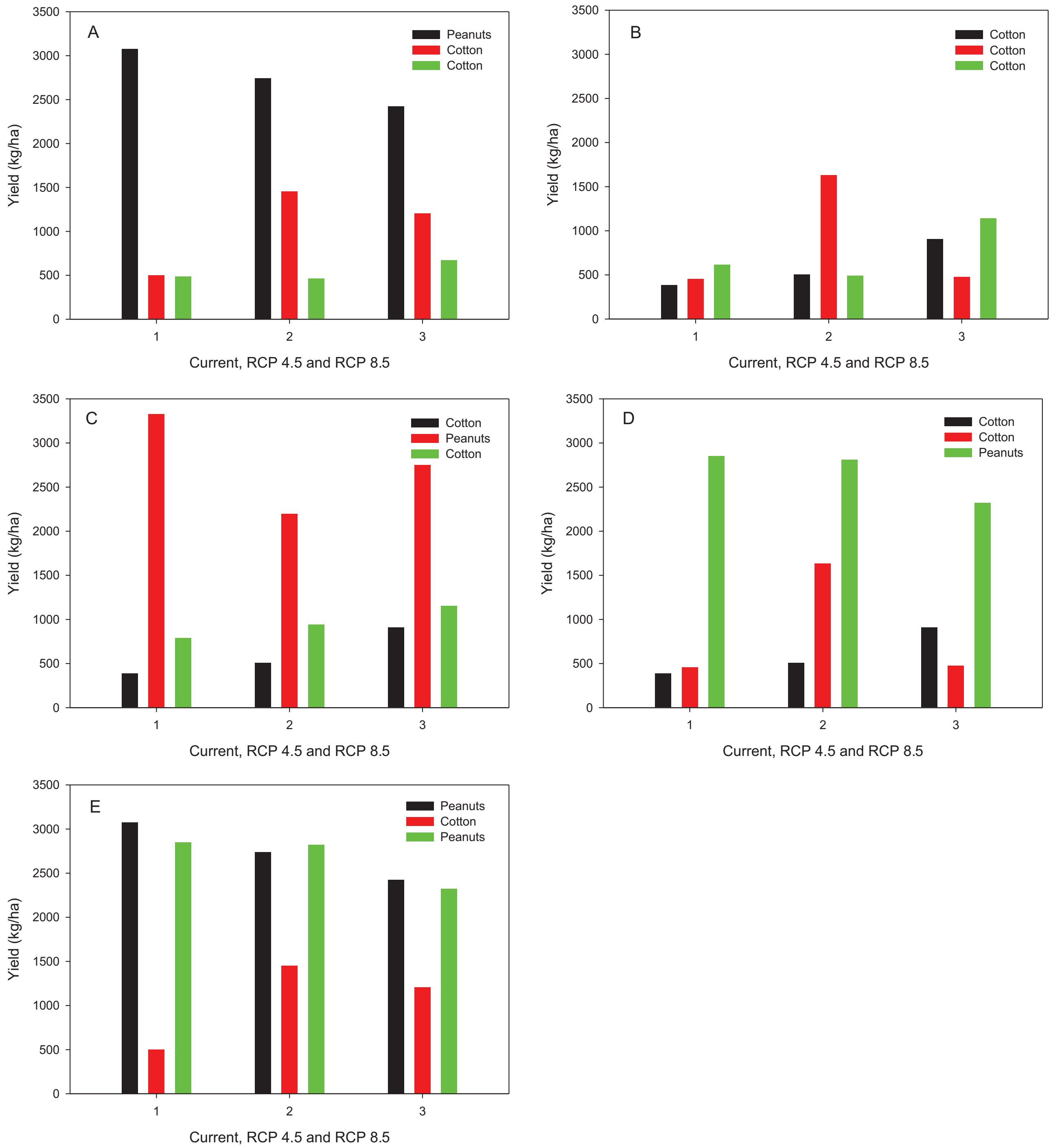

Figure 8. Peanut and cotton yields under various rotation conditions in response to RCP4.5 and RCP8.5. (A) Peanut-cotton-cotton rotation, (B) cotton-cotton-cotton rotation, (C) cotton-peanut-cotton rotation, (D) cotton-cotton-peanut rotation, and (E) peanut-cotton-peanut rotation.

Fertilization

The nitrogen fertilizer use rate is based on nitrogen requirements that are suggested to produce the expected yields while minimizing adverse environmental effects. Besides fertilizers, agronomic rate is also often factored in nitrogen available to the crops throughout the growing season from all sources such as mineralization of organic residues and soil organic matter as well as residual inorganic nitrogen in the rooting zone. The introduced nitrogen with fertilizer applications are thus based on the crop type, soil characteristics, and the application methods. The nitrogen fertilizer use rates for this research were 80 kg/ha for cotton and 30 kg/ha for peanuts during sowing as suggested by extension services.

In this research, urea was used as the nitrogen fertilizer. With an increase in temperature such as in RCP4.5 and RCP8.5 scenarios, reduced fertilizer use was considered because peanuts were not sensitive to further fertilization and cotton yields increased with increased temperature. Urea fertilizer use was reduced to 40 kg/ha for cotton and 15 kg/ha for

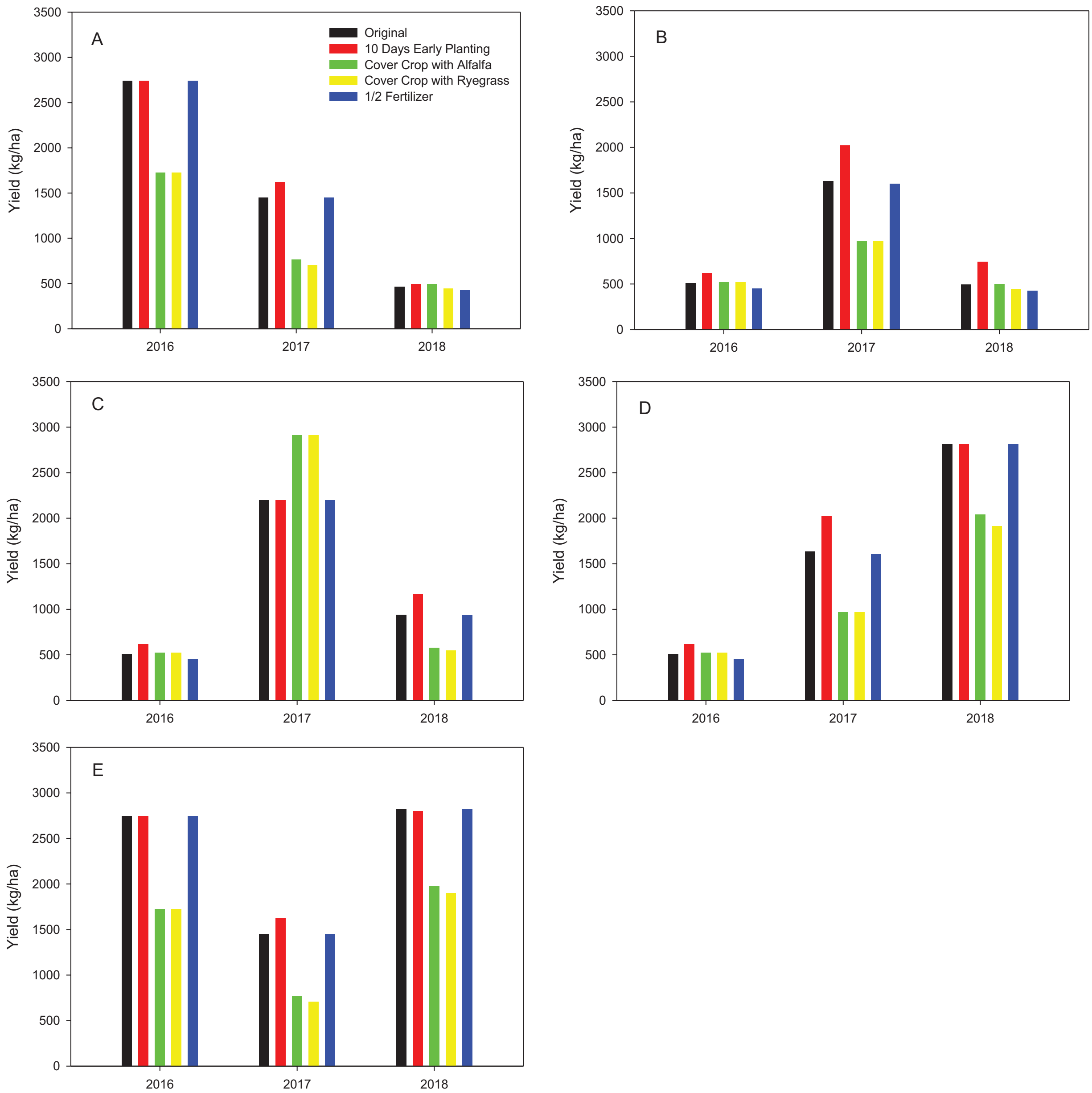

Figure 9. Peanut and cotton yields under various best management practices in response to RCP4.5. (A) Peanut-cotton-cotton rotation, (B) cotton-cotton-cotton rotation, (C) cotton-peanut-cotton rotation, (D) cotton-cotton-peanut rotation, and (E) peanut-cotton-peanut rotation. Black bar refers to original management conditions, red bar refers to 10 days of early planting, green bar refers to using cover crop of alfalfa, yellow bar refers to using cover crop of ryegrass, and blue bar refers to one-half of fertilizer use compared with original management.

peanuts during sowing for this research in response to RCP4.5 and RCP8.5 scenarios. With 50% decrease in fertilizer use, peanut yields only experienced 6% decrease in the first year. For the second and third year of rotations, peanut yields were comparable with those of 2017 and 2018 (Figure 10). With 50% reduced fertilizer use, cotton yields were comparable to those of 2016. For the following 2 years of rotation, cotton yields were much higher than those of 2017 and 2018.

Cover crop

For this research, cover crops of alfalfa and ryegrass were used in the cotton-peanut rotation. However, for all the rotation scenarios of this study, there was no obvious positive impact. There was a slight increase observed in peanut yields in the second year of cotton-peanut-cotton rotation for RCP4.5 and RCP8.5 and in cotton yields in the second year of cotton-cotton-cotton and cotton-cotton-peanut rotations for RCP8.5.

Tillage

Conservation tillage achieves the production goals by keeping agricultural residues in the fields to improve soil properties including infiltration rate, water-holding capacity, cation exchange capacity, soil organic content, and soil biota diversity, thus ensuring optimum crop production. Nitrogen existing in

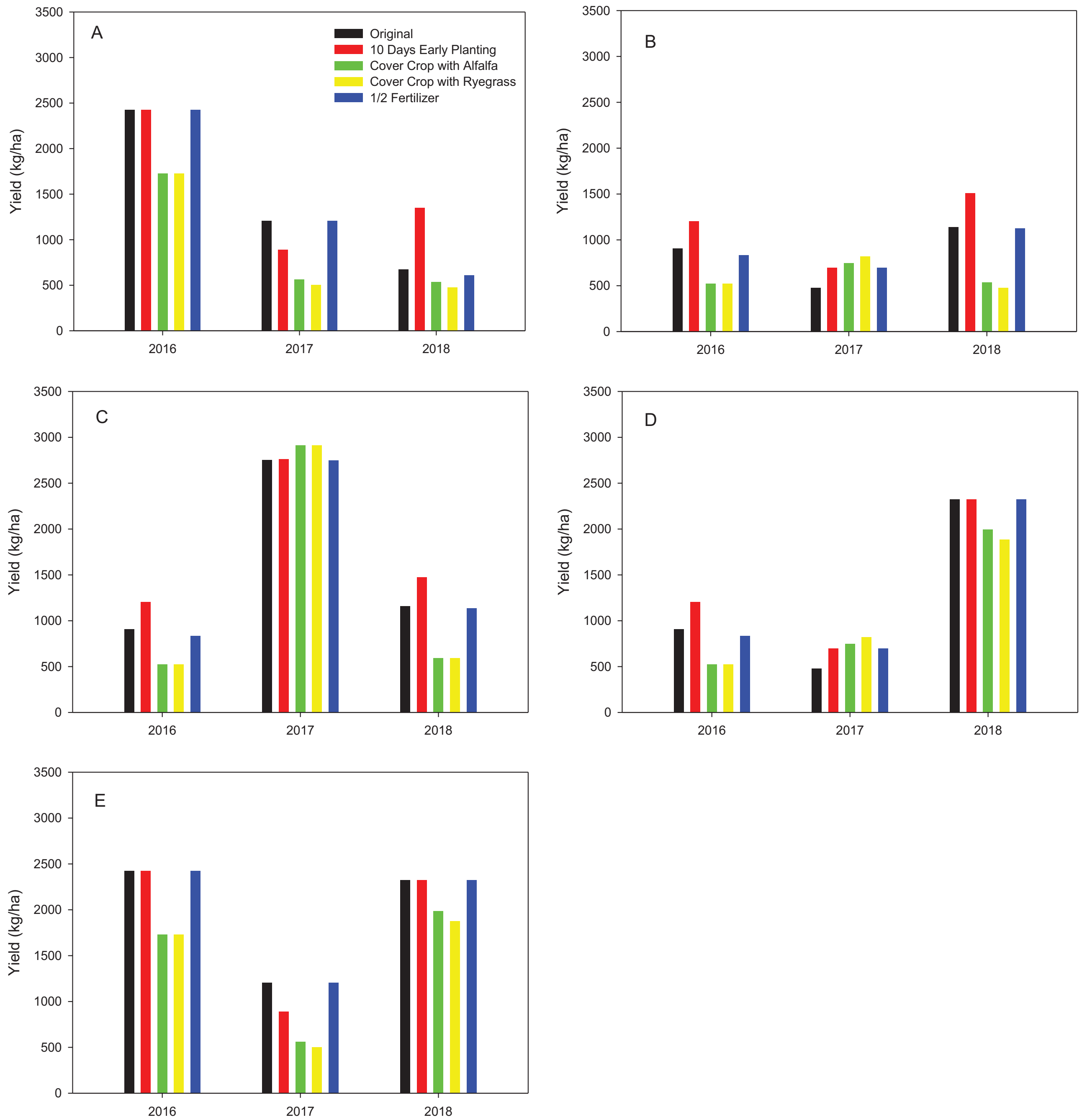

Figure 10. Peanut and cotton yields under various best management practices in response to RCP8.5. (A) Peanut-cotton-cotton rotation, (B) cotton-cotton-cotton rotation, (C) cotton-peanut-cotton rotation, (D) cotton-cotton-peanut rotation, and (E) peanut-cotton-peanut rotation. Black bar refers to original management conditions, red bar refers to 10 days of early planting, green bar refers to using cover crop of Aafalfa, yellow bar refers to using cover crop of ryegrass, and blue bar refers to one-half of fertilizer use compared with original management.

crop residues by no-till practices can provide potential nitrogen for plant use. However, no obvious positive or negative effects on crop yields were observed in this study.

Discussion

Temperature and precipitation stress reduced plant activity and their subsequent yields. This was especially the case of nitrogen fixation. In this research, increase in temperature was found to have a negative effect on peanut yields. However, it had a positive effect on cotton yields, which might be offset by the increasing CO_2. In this research, crop yields were simulated by the APSIM and CropSyst Model, in which the rate of crop development was governed by thermal time and was computed based on the daily maximum and minimum temperatures as well as the base temperature for root growth. Photosynthesis of plant leaves was computed hourly using the asymptotic exponential response equation, where quantum efficiency and light-saturated photosynthesis rate variables were dependent on CO_2 and temperature.[51] Peanuts were more sensitive to photoperiod than cotton, that is, peanuts adapted to grow in shorter day-lengths. They thus developed more quickly when exposed to shorter days. During the simulation, the photoperiod was assumed to affect phenology between emergence and floral initiation, during which thermal time was a function of photoperiod.

Rotations are an important part of any sustainable agricultural system. Crop rotation was originally developed to battle problems with insects, parasitic nematodes, weeds, and diseases caused by plant pathogens. Three-year rotation of peanut-cotton-peanut showed the obvious yield benefits for RCP4.5. For RCP8.5, both peanut-cotton-peanut rotation and cotton-peanut-cotton rotation showed advantages for crop yields. These benefits resulted from the nitrogen fixation by peanuts and increased cotton yields in response to increased temperature and CO_2. Peanuts are good nitrogen fixers and may fix up to 250 lb of nitrogen per acre theoretically. Most importantly, peanuts were not fertilized except for sowing.

Early planting is extremely important to maximize yields in the face of increased temperature. In this study, the positive effect of early planting was more obvious for RCP8.5 scenarios. For most cases, the positive effect was observed for cotton. Research has demonstrated that an "ideal" planting window exists, with a decline in yield with each additional day as less light and growing degree-days are available to the plant. It should be noted that "ideal" time each year may vary due to the specific weather conditions of the given year. Under ideal conditions, optimum planting date was from April 24 to May 24 for cotton and from April 25 to May 25 for peanuts.

Perennial and forage legumes, such as alfalfa, sweet clover, true clovers, and vetches, may fix 250 to 500 lb of nitrogen per acre. Like the grain legumes, they are not normally fertilized with nitrogen. They occasionally respond to nitrogen fertilizer at planting or immediately after a cutting when the photosynthate supply is too low for adequate nitrogen fixation. It is important that N_2-fixing alfalfa is much more capable of fixing N_2. A perennial or forage legume crop only adds significant nitrogen for the following crop if the entire biomass (stems, leaves, roots) is incorporated into the soil.[52,53] If a forage is cut and removed from the field, most of the nitrogen fixed by the forage is removed. Roots and crowns add little soil nitrogen compared with the aboveground biomass. Again, it also needs time for the benefits to be observed. For this research, only 3-year rotations were investigated. Thus, the benefits of crop cover by alfalfa were not observed.

Optimized fertilizer applications also mitigate the adverse impacts of increased temperature on agricultural production.[54] As peanuts did not respond sensitively to nitrogen fertilizer and cotton yields increased for RCP4.5 and RCP8.5 scenarios, 50% reduced nitrogen fertilizer use was possible to achieve comparable crop yields. That legumes such as peanuts responded insensitively to the nutrient may result from their enhanced nitrogen fixation activities with increased temperature. Although most of the fixed nitrogen went to peanuts, some nitrogen (around 30-50 lb N/acre) was "leaked" or "transferred" into the soil for succeeding nonlegume plants. Sustained crop productivity relied on continuous supply of nutrients. Therefore, legumes should always be kept in rotations to avoid the constraint to plant growth and development. Although application of chemical fertilizers is necessary for enhancing crop yields and sustaining soil fertility, inappropriate or excessive fertilizer application does not guarantee constantly increasing yields and might result in low nutrient use efficiency and lead to environmental contamination in agroecosystems. For the climate change scenarios, 50% reduced fertilizer use combined with the selected rotations achieved comparable crop yields. This indicated that crop rotations with legumes had the capacity to battle temperature increase.

Cover crop can be useful to promote crop yields by retaining fertilizer in the soil.[55] Introduction of cover crop into crop rotation is a potential way for long-term conservation of soil carbon sequestration and yield maintenance.[56] Legumes and grasses are the most extensive cover crops in north Florida and south Alabama. Especially, a multiyear legume sod such as alfalfa can well supply all the nitrogen needed by the following crop.[53,57] Growing sod-type forage grasses, legumes, and grass-legume mixes as part of the rotation also increases soil organic matter. Cover crop thus plays a vital role in climate change adaptation with potential to reduce soil erosion, fix atmospheric nitrogen, reduce nitrogen leaching, and improve crop yields.[58] However, for all the rotation scenarios of this study, there was no obvious positive impact.

Adaptation of conservation tillage and higher residue incorporation is a way to sequester carbon and reduce net global warming potential.[59,60] Conservation tillage, in its various forms, is often practiced to offset both soil degradation and increased temperature effects.[61,62] Conservation tillage improves soil and water quality by adding organic matter as crop residue decomposes, reducing runoff, conserving water by reducing evaporation at the soil surface, conserving energy by reducing machinery operation, and reducing potential air pollution from dust and diesel emission.[63] As a conservation practice, no-till is currently practiced on over 62 million acres in the United States.[64] No-till leaves the crop residue undisturbed from harvest through planting. However, it takes time before benefits can be observed for no-till practice. The organics introduced to the soil need time to be decomposed and used in crop production. Subsequently, no obvious positive or negative impacts on crop yields were observed in this study.

Conclusions

With an increase in temperature corresponding to RCP4.5 and RCP8.5 scenarios, significantly decreased yields were observed for peanuts, while they increased for cotton. When peanuts were introduced in the rotation, the increase in cotton production was more pronounced. With a 10-day earlier planting, there was no consistent impact on crop yields with a second year decrease in cotton but increase in peanuts, and minimal impact for both cotton and peanuts in the third year. However, with a 10-day later planting, there was obvious decrease in both cotton and peanuts. With 50% decrease in fertilizer use, peanut and cotton yields were comparable with those of regular fertilizer applications because peanuts did not respond sensitively to nitrogen fertilizer and cotton yields increased for RCP4.5 and RCP8.5 scenarios. Three-year rotation of peanut-cotton-peanut showed the obvious yield benefits for RCP4.5. For RCP8.5, both peanut-cotton-peanut rotation and cotton-peanut-cotton rotation showed advantages for crop yields, which resulted from the nitrogen fixation by peanuts and increased cotton yields in response to increased temperature.

Author Contributions

Mahnaz Dil Afroz was the primary author of this manuscript. She conducted the analysis and drafted the manuscript. Runwei Li worked on portions of the analysis and edited the manuscript. Khaleel Muhammed helped with the analysis. Aavudai Anandhi and Gang Chen are PIs of the projects. They oversaw the analysis progress and edited the manuscript.

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