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Impact of recent climate change on cotton and soybean yields in the southeastern United States

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ABSTRACT

The Southeastern region of the United States (SE-US) is agroecologically diverse, economically agriculture reliant, and distinct from the twentieth-century warming trend. Considering the inextricable link between climate and agricultural production, it is necessary to quantify future environmental implications on economically important crops of cotton (*Gossypium hirsutum* L.) and soybean [*Glycine max* (L.) Merr.] in the SE-US. The current study used the fixed-effect model (panel data approach) for climate and yield studies, to assess the impact of climatic variables from 1980 to 2020 such as daily maximum temperature (T_{max}), minimum temperatures (T_{min}), and rainfall on cotton and soybean yields. The data from 11 states were averaged per growing season and results revealed significant variability in temperature and rainfall during the last four decades. The T_{max}, T_{min}, and rainfall shifted in the range of 0.46–0.50 °C, 1.30–1.45 °C, and 3.74–3.95 cm, respectively, during the cotton growing season (CGS) and soybean growing seasons (SGS). However, the annual rate of change in T_{max}, T_{min}, and rainfall from 1980 to 2020 was in the range of 0.011–0.012 °C, 0.031–0.034 °C, and 0.089–0.094 cm, respectively, during the CGS and SGS. Rainfall had no significant effect on cotton and soybean yields. A 1 °C rise in T_{min} increased cotton yield by 20.8% while decreasing soybean yield by 31.6%. Alternatively, a 1 °C rise in T_{max} decreased cotton and soybean yield by 10.3% and 25.6%, respectively.

1. Introduction

Climate change refers to the shifting of the mean meteorological indices – rainfall and temperature across a longer time span [1]. It is currently the most pressing issue, especially in the context of agriculture [2]. By 2100, the rate of global climate change is anticipated to be swift compared to the previous 1000 years [3]. Global climate change is expected to have a substantial, direct, and socioeconomic impact on agricultural production [4]. These climatic shifts cause abiotic and biotic stresses and alter micro-climates around plants number of hosting micro-organisms, and the microbe-plant relationship [5]; these stresses also control plant vegetation and numerous phenological processes further affecting crop production [6,7]at different scales (local, regional, and global) [8]. While evaluating the influence of climate change on agricultural production, a common assumption is that yield elasticity regarding climatic variables is constant, which is not the case [9]. The precise, and reliable determination of the climatic variables that impact agricultural production is pivotal to mitigating climate change's impact on crop output [10]. The first step to creating and implementing successful management solutions is to quantify the direction, and amplitude of these impacts [11].

Climate models normally estimate potential agro-climatic possibilities on a global or national scale; therefore, the regional implications remain largely unknown [12,13]. On a regional scale, the SE-US is often the most neglected region for agroclimatic researchers [14], despite its heterogeneous cropping system and economic reliance on agriculture [15]. In addition, the SE-US has the highest increasing trend in 20-year daily Tmax values in the US [16]. Drought is already posing a significant challenge to rain-fed crops in the SE-US [17]. As a result, there is uncertainty regarding environmental obstacles and benefits for the growers of the SE-US [14].

Cotton is an economically crucial crop and it is among the most widely grown crops for global fiber production in more than 60 different countries under temperate and tropical climatic regions [18]. The SE-US

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contributes 84.36% of the nation's cottonseed production [19]. Among the two US-grown cotton varieties, Pima cotton (*Gossypium barbadense* L.) has been cultivated in the early twentieth century close to the coastal areas of South Carolina and Georgia, as well as in northern Florida. However, upland cotton (*Gossypium hirsutum* L.) is currently grown on a commercialized scale throughout the SE-US, with over 1.2 million hectares grown in Alabama, Florida, Georgia, North Carolina, South Carolina, and Virginia [20]. The cotton acres harvested for SE-US is 88.72% of the national cotton acres harvested [21]. Moreover, cotton is an important crop to study from a climate perspective because of its limited affinity to alterations in the environment [22]. Previous studies has documented that the cotton yield benefited from elevated temperatures [23–26] and changing rainfall patterns [18,26,27]. [28] noted that elevated temperatures during the start and end of the CGS increased cotton yield. However, increase in temperatures during the middle of the CGS negatively affected yield [29]. Additionally, an increased number of days with extreme temperature could be detrimental to cotton yield [18, 26].

Soybean [*Glycine max* (L.) Merr.] is the legume with the greatest acreage worldwide [30]. The area (acres harvested) under soybeans for SE-US is 15.35% of the national area for soybeans production [21]. Soybean is a vital determinant of ensuring food security, human, and animal edible protein as well as biofuels [31]. Soybean has also been designated a "miracle crop" throughout North, and South America for the last 60 years because of its large economic success [32]. Soybean is important crop to study from a climate change perspective because of its photoperiod responsiveness [33]. Previous studies investigating effects of climate change on soybean yield has mixed results, *i.e.*, positive [34, 35] and negative [36,37] implications of elevated temperatures and changing rainfall patterns on soybean yields. These contradictions could possibly be due to the varying degrees and directions of changing climate parameters linked with distinct geographical regions studied [38].

While there has been substantial research documenting the influence of climate change on agricultural productivity [39–41], most research was restricted to key staple crops *i.e.,* rice, wheat, and corn [42]. This is mainly due to our reliance on the contribution of calories or nutrients from these cereal crops [43]. In comparison, very few studies specific to the SE-US (combinedly as a whole) on cotton [44–47] and few studies on soybean [37,48–54] reported climate change effects on yields. Thus, a considerable gap exists in studying the cotton and soybean crops' yield response to climate change in the SE-US. Understanding the effects of climate change on crop production will allow cotton and soybean growers to adapt to the changing climate and develop mitigation strategies to boost future production [26]. As such the objective of this study is to quantify the effect of climate change (rainfall, T_{max}, and T_{min}) from 1980 to 2020 on cotton and soybean yields in the SE-US.

2. Material and methods

2.1. The region and time period of study

The SE-US is the 3rd most leading agricultural commodity supplier of the US, contributing 47 billion dollars per year to the national agriculture export [55]. It covers 19.08% of the total land area of the country [17,56]. A map of 11 states considered in this study is shown in Fig. 1. The climate in the SE-US is warm and humid, with low seasonal variation in rainfall and a higher evapotranspiration rates [57]. The SE-US has registered warming at the rate of 0.22 °C per decade over the last five decades [58]. The SE-US states except Texas and Virginia, receive ample annual average rainfall (50–60 inches) [59]. Excess rainfall has been considered as one of the top two contributors to crop yield losses in the SE-US [60].

The recent 41-year time period is taken since it is adequate to reflect the most current and fairly representative climatic change [61]. The starting year of 1980 was taken because it was the start of the latest phase of sustained climate change in the twentieth century [62]. Moreover, during 1980, the rate of yearly T_{avg} rise was comparable to the rate of extrapolated warming for the remaining portion of the twenty-first century [62]. Since 1980, the SE-US region has had numerous extreme climate occurrences in comparison to the rest of the United States [63]. As such, there were years of drought (1988, 2000, and 2012), hurricanes (1985, 1995, 1998, and 2005), storms (2000, 2001, 2005, 2008, 2009, and 2011), and tornados (2001, 2002, 2007, and 2008) among the SE-US's extreme events [64]. According to the National Weather Service website (https://www.weather.gov/mob/events#80s), the specific events that affected either of the crops (soybean or cotton) in the SE-US were the drought of 2000, hurricane Juan 1985, hurricane Erin 1995, hurricane George 1998, and hurricane Dennis 2005 [64].

2.2. Data

A panel data previously employed for similar studies by Ochieng et al. [65], and Maggio et al. [66], is utilized in this study. We have cross-sectional data of 11 states, T_{min}, T_{max}, T_{avg}, rainfall, cotton, and soybean yields, split continuously over time series of 41 years from 1980 to 2020. This cross-section and time-series combinedly form a panel of 451 rows (41 years × 11 states), and 10 columns (rainfall, T_{min}, T_{max}, T_{avg}, and yields x 2 crops) in the panel data model.

The rainfall, T_{max}, and T_{min}, were the explanatory variables, and the yield of soybean, and cotton were the response variables in the study (Table 1). The source of yield data was the USDA-NASS database [19], and the climate data(the daily rainfall, daily T_{max}, and daily T_{min}) was the National NOAA database [67] (Table 1).

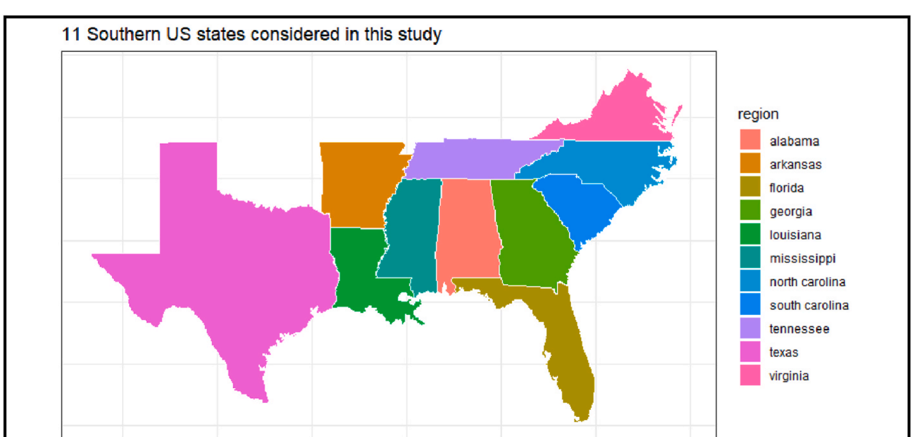

Fig. 1. The map of the SE-US's 11 states considered under study.

Table 1
Description of the explanatory and response variables used in the fixed effect panel model.

Crops	Growing Period	Panel districts	No. of years	Variables considered	Sources of data
Cotton	April to August	• Arkansas • Alabama • Florida • Louisiana • Mississippi	41 years (1980–2020)	• T_{max} (°C) • T_{min} (°C) • T_{avg} (°C) • Rainfall (cm) • Cotton yield (Mg ha^{-1})	• Cotton yield [19] • T_{max}, T_{min}, T_{avg}, and Rainfall [67]
Soybean	May to September	• Georgia • Tennessee • North Carolina • South Carolina • Texas • Virginia		• T_{max} (°C) • T_{min} (°C) • T_{avg} (°C) • Rainfall (cm) • Soybean yield (Mg ha^{-1})	• Soybean yield [21] • T_{max}, T_{min}, T_{avg}, and Rainfall [67]

The data on the NOAA website was essentially the monthly averaged values of daily Tmax, Tmin, and rainfall. The units of rainfall, T_{min}, T_{max}, T_{avg}, and yield in this study are cm (centimeter), °C (degree Celsius), and Mg ha^{-1} (Megagrams per hectare), respectively. The 11 states considered under study were Arkansas, Alabama, Florida, Louisiana, Mississippi, Georgia, Tennessee, North Carolina, South Carolina, Virginia, and Texas. As the fixed effect model is meant to work only for continuous data [68], all the data were consistently continuous for 41 years. The CGS was counted from April to August and the SGS from May to September, in compliance with the USDA's agricultural handbook for field crop planting and harvesting dates [21]. The daily T_{min}, T_{max}, and T_{avg} were averaged over both growing seasons, and the daily rainfall was totaled to represent the cumulative rainfall during both growing seasons. These averages and totaling over the growing seasons were calculated as guided by the similar studies of Fermont et al. [69], and Kumar and Kaur [70], on changing climate and crop yields.

2.3. Panel data approach used in the study

In general, two methodologies, statistical or crop simulation, are used to estimate the influence of climate change on crop yields in the past. Statistical approaches outperform crop simulation methods, especially at the regional scale because crop simulations require massive datasets which are difficult to collect [71,72]. Among statistical methods, the panel data approach is robust and has a low error in terms of validating heterogeneity, addressing farmer adjustability factors over time, and reducing correlations in unobserved variables [73]. Therefore, the panel data approach has been widely used in numerous relevant studies [9,65,73,74]: [66].

A panel data technique comprises a fixed-effect model and a random effect model. The fixed-effect model has the capability to control "omitted variable biases" caused by time-unvarying heterogeneity of unconsidered variables [70,75]. This heterogeneity issue is minimized by applying first differencing (successively subtract cross-sectional data from its previous year's values) all over the data for all years [76]. The above mentioned unconsidered variables can be soil factors, topography, and farm owners' self-regulatory measures, such as switching sowing dates or varieties and changing input levels on yearly basis according to climate [70]. The random effect panel model may be efficient in studies where the unconsidered variables are non-correlated with explanatory variables [76,77]. However, in our study, these unobserved variables influence our study variables and are assumed to be un-variant over time, so we used a fixed-effect model. These time un-variant variables are absorbed by the spatially fixed effects in the panel model [40, 77]. Similar studies by Deschenes and Greenstone [78] and Geng et al. [79], have also recommended a fixed-effect model against a random effect model under a panel data approach. The regression method was used in panel data analysis to build a production function that calculated the effect of climatic changes on crop yields [77]. T_{min}, T_{max}, and rainfall are all-important crop yield variables. As a result, considering climatic impacts, the following model, previously employed by Birthal et al. [80], is utilized in this study:

$$\ln y_{it} = S_i + T_t + \beta X_{it} + \varepsilon_{it} \quad (1)$$

where *i and t* represent place (state) and time, respectively. The response variable *y* is the yield (megagrams per hectare) in the model, and *S* represents the place (State in this study) fixed effects. It is hypothesized that the state fixed effects account for all the unconsidered state-related factors which vary with time, influence crop yield, and decrease noise due to excluded variables in the model. Time fixed effects are represented by *T* in the model which might be yield affecting and originated due to changes in infrastructure, technological factors, human capital, etc [80]. The climate variables are represented by *X*, β is a parameter associated with explanatory variables, and ε is the random error. The effect of temperature and rainfall on agricultural yield is generally not linear [23,81]. To address this non-linearity issue, the squared term of rainfall, T_{min}, T_{max}, is included along with these climatic variables in equation (1).

Equation (1) was evaluated as logarithmic linear ($ln\, y_{it}$) to control the excessive variation in the yield (y) resulting from squaring factor. As a result, the explanation of regression coefficients was not clear in the model. Hence, we also calculated marginal coefficients of T_{max}, T_{min}, and rainfall to measure the exact relationship between cotton and soybean yield and climate variables at their mean values and, accordingly, numerically calculated the exact variation in crop yield due to a 1 mm rise in rainfall and a 1 °C increase in temperatures (T_{max} and T_{min}). The Stata® version-16 statistical software (StataCorp, College Station, TX, USA) was used to analyze the panel data of T_{max}, T_{min}, T_{avg}, rainfall, and crop yields. For calculating the trend in climatic variables over the growing seasons, the natural logarithmic values of T_{max}, T_{min}, and rainfall were regressed against time using state-fixed effects as a control against time unchanging variables [80].

2.4. Diagnostic tests

A series of diagnostic tests were conducted prior to regressing a fixed-effect model to verify assumptions. The assumption was: that the mean, variance, and covariance of stationary data are independent of time, with no auto-correlation within unobserved factors, which means that individual time-invariant characteristics should be clearly different and not correlate with other individual characteristics. As each entity is distinct, its error and the constant term should not be correlated with others. In case, these error terms become correlated, the fixed-effect model is rendered ineffective because the extracted inferences may be incorrect. There are possibilities that y_{it} and explanatory variables are nonstationary, which raises the issue of autocorrelation [82]. However, the autocorrelation issue could be more problematic for the series of explanatory variables (T_{max}, T_{min}, and rainfall). To test for stationarity, panel unit root tests *i.e.,* Levin–Lin–Chu [83]; Im, Pesaran and Shin [84, 85]; and the Fisher-type tests [86] were utilized.. The null hypothesis was that the series contains a unit root, and the alternative hypothesis was that the series is stationary. It can be inferred from Table 2, in which

Table 2
Various tests to check the Stationarity in the data.

Variables	Levin-Lin-Chu			Im-Pesaran-Shin		Fisher-Type	
	unit root test			unit root test		unit root test	
	Unadjusted t	Adjusted T	p-value	z-t-tilde-bar	p-value	Chi-sq (pm)	P-value
CT (min)	−11.37	−7.83	0.001***	−8.82	0.001***	23.46	0.001***
ST (min)	8.73	−4.24	0.001***	−8.87	0.001***	24.27	0.001***
CT (max)	−16.40	−11.75	0.001***	−10.99	0.001***	39.59	0.001***
ST (max)	−15.83	−9.81	0.001***	−12.41	0.001***	54.95	0.001***
CR	−13.85	−8.51	0.001***	−12.08	0.001***	50.56	0.001***
SR	−15.93	−11.01	0.001***	−12.08	0.001***	51.25	0.001***
Ln (yield cotton)	−8.14	−3.99	0.001***	−8.4	0.001***	22.99	0.001***
Ln (yield soybean)	−6.49	−3.58	0.001***	−12.08	0.001***	18.72	0.001***

CT, ST, CR, and SR represent the Cotton temperature, Soybean Temperature, Cotton Rainfall, and Soybean Rainfall, respectively. Notes: *** denote significance at a 1% level.

the hypothesis of the unit root non-stationarity is rejected at a 1% level of significance. It implies that the variables are stationary. In conclusion, the data was stationary for all weather variables and autocorrelation was not a significant issue with the dataset.

3. Results and discussion

3.1. Climatic changes across CGS and SGS

The results (Fig. 2A) revealed that the T_{avg} during the CGS was 23.22 °C with T_{min} and T_{max} values of 17.03 °C and 29.42 °C, respectively, over the past four decades *i.e.,* from the year 1980–2020. However, the T_{avg}, $T_{min,}$ T_{max} were comparatively higher during the SGS valued at 24.51 °C, 18.48 °C, and 30.54 °C, respectively. The T_{avg}, T_{min}, T_{max}, and rainfall followed an increasing trend during CGS (Fig. 2A) and SGS (Fig. 3A) over the past 41 years in SE-US. During the CGS and SGS, the SE-US received an average rainfall of 22.27 cm and 22.40 cm, respectively.

The examination (Table 3) of the annual temperature change from 1980 to 2020 showed a significant rise of 0.88 °C and 0.97 °C in T_{avg} values during the CGS and SGS, respectively. This implies that the SE-US has experienced a 9.98% greater overall warming during SGS in comparison to CGS, which can have comparatively severe negative impacts on soybean yield. Overall, warming could be beneficial or detrimental to crops depending on their growth stage during which T_{avg} increment occurs [28]. For example, increased T_{avg} during the start and end of the CGS enhances biomass production but, prolonged exposure to increased T_{avg} can lead to yield reduction [87]. However, regarding SGS, it is believed that the pollination and seed formation stages are far more temperature-sensitive compared to vegetative stages [88]. From the 1980 to 2020 period (Table 3), the shift in T_{max} (0.50 °C) during the CGS was more than the shift of T_{max} (0.46 °C) during SGS by 0.044 °C but the shift in T_{min} (1.302 °C) during the CGS was less than the shift of T_{min} (1.45 °C) during SGS by 0.148 °C. Furthermore, the changes in T_{max} (0.504 °C and 0.46 °C) and T_{min} (1.302 °C and 1.45 °C) seen in the SE-US during CGS and SGS from 1980 to 2020 are far greater than the changes that occurred globally in T_{max} (0.4 °C) and T_{min} (0.8 °C) [89]. From 1980 to 2020, CGS experienced 9.56% more diurnal warming (T_{max} increments) than SGS, whereas SGS experienced 11.37% more nocturnal warming (T_{min} increments) than CGS (Table 3). Commonly, it is believed that the nocturnal temperatures changes are comparatively more influential than diurnal temperature changes in negatively impacting crop's reproductive stages [90] as well as photosynthesis [91]; however, high diurnal temperatures usually coincide with the events of intense sunshine and less rainfall which further aggravate its negative effect on the crop [92]. The shifts in T_{min} values (1.30 °C and 1.45 °C for CGS and SGS, respectively) contributed more to the increase in T_{avg} than T_{max} values (0.504 °C and 0.46 °C for CGS and SGS, respectively), which means the contribution of nocturnal and diurnal temperatures in the overall warming is 72.09% and 27.01% during CGS and 75.92% and 24.08% during SGS. Therefore, the nocturnal temperature majorly explains the heating trend over the 41-year study period for both growing seasons, similar to the findings of Screen [93], who noted that nocturnal temperature normally increases more than the diurnal temperature following unsymmetrical warming trends across the globe.

This paragraph will discuss the region's yearly rate or pace of change of the climatic variables throughout the past 41 years. The yearly rate of change is crucial, as a higher rate gives lesser adapting time for

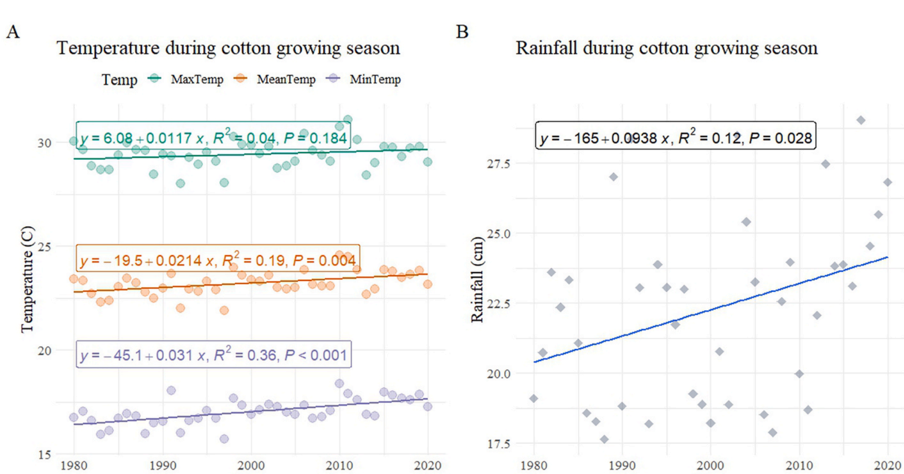

Fig. 2. A. The slope of T_{max} was non-significant, whereas T_{min}, and T_{avg}, were found to be significant during the CGS in the SE-US from 1980 to 2020. **B.** The trend in rainfall during the CGS in the SE-US from 1980 to 2020 was noted to be significant.

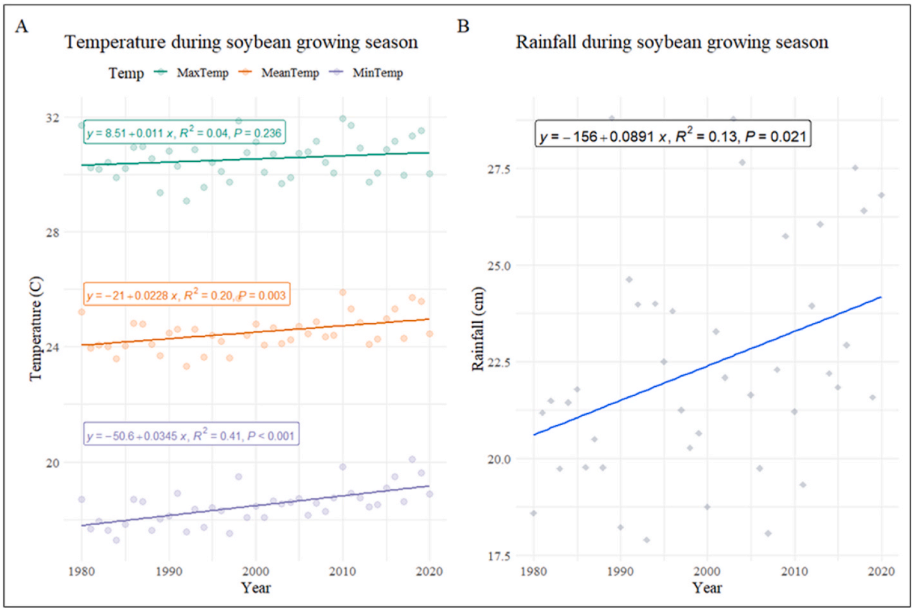

Fig. 3. A. The trend in T_{max} was non-significant, whereas T_{min}, and T_{avg} were significant during the SGS in the SE-US from 1980 to 2020. **B**. The trend in rainfall during the SGS in the SE-US from 1980 to 2020 was significant.

Table 3
The overall change and the annual rate of change occurred in temperature and rainfall from 1980 to 2020 during CGS and SGS in the SE-US.

Particulars	Mean	Change in climatic variables (1980–2020)	The annual rate of change in climatic variables (1980–2020)
Cotton growing period			
T_{max} (°C)	29.42 (0.003)	0.50	0.012***
T_{min} (°C)	17.03 (0.002)	1.30	0.031***
T_{avg} (°C)	23.22 (0.002)	0.88	0.021***
Rainfall (cm)	22.27 (0.02)	3.95	0.094***
Soybean growing period			
T_{max} (°C)	30.54 (0.003)	0.46	0.011***
T_{min} (°C)	18.48 (0.002)	1.45	0.034***
T_{avg} (°C)	24.51 (0.002)	0.97	0.023***
Rainfall (cm)	22.40 (0.02)	3.74	0.089***

Notes: *** denote significance at 1% level, Figures in parentheses are standard errors.

ecosystems to readjust themselves [94]. During the CGS (Table 3), the values of T_{max}, T_{min}, T_{avg}, and rainfall shifted by 0.012 °C, 0.031 °C, 0.021 °C (Figs. 2A), and 0.094 cm (Fig. 2B) per year throughout 41 years, however during the SGS, they changed by 0.011 °C, 0.034 °C, 0.023 °C (Figs. 3A), and 0.089 cm (Fig. 3B) per year. It indicates that the ratio of the yearly rate of change of diurnal temperature during CGS and SGS is 1.09:1, whereas the ratio of the yearly rate of change of nocturnal temperature during CGS and SGS is 0.91:1. The ratio of the yearly rate of change of nocturnal and diurnal temperature, on the other hand, is 2.58:1 during CGS and 3.09:1 during SGS. According to Schlenker and Roberts [23], the rate of the annual increase in temperatures is fine up to a level until the resulted temperature will not surpass the yield damaging thresholds. These thresholds vary with different crops *i.e.,* 32 °C for cotton and 30 °C for soybean, while temperatures above these levels are quite damaging [23]. A look around the CGS and SGS, Figs. 2B and 3B showed a considerable increase in rainfall. The ramifications of climate change in the region were mostly driven by temperature rather than changes in rainfall. Based on these long-term trends in weather variables, T_{max} and T_{min} change influenced agricultural yields by changing crop water needs throughout the growing season [95].

3.2. Impact of climate change on cotton and soybean yield

Estimates of the influence of temperature and rainfall on cotton and soybean yields are presented in Table 4.

During the CGS, the regression coefficient of T_{max} was shown to be negative and significant (Table 4), signifying the reduction in cotton yield, which agrees with the recent similar cotton study by Eck et al. [37] in SE-US. The T_{max} aggravates the plant's water needs (up to 60%) which can prove yield-limiting [96]. Our study results documented that T_{min} had a considerable beneficial influence on cotton yield since the regression coefficient (Table 4) of T_{min} for cotton was positive and significant, and the same has been realized by the recent cotton study by Eck et al. [37] in SE-US. However, according to the research, there is no consensus yet, on T_{min}'s physiological influence on plants [97,98]. The net impact of incremental shifts in T_{max} and T_{min} was still found to be advantageous to cotton yield, which can be interpreted statistically as every 1 °C temperature increment improved cotton yield (Table 4). These results agree with other findings [23,24]. It is notable here to mention that according to Loka and Oosterhuis [92], and Sharwood [99], the threshold of CGS T_{avg} is 35 °C above which it starts decreasing the Rubisco activities by deactivating or increasing respiratory rates, which further lowers the photosynthetic efficiency ultimately reducing yield. The Rubisco enzyme helps in transforming atmospheric CO_2 into glucose or other useful molecules for plants [100]. However, in the SE-US (1A) CGS T_{avg} has never exceeded this threshold in the last 41 years. Moreover, the overall 41-year averaged T_{avg} (23.23) was falling under the range of 20–30 °C which is considered as best for maximum cotton growth [101]. The positive effect of T_{min} on cotton yield in our study had entirely compensated for the damages caused by an increase in T_{max} and these findings are corroborated by Xia et al. [102] and Li et al. [26]. Xia et al. [102] concluded the beneficial effects of increasing nocturnal temperature on crops by enhancing soil respiration, carbon uptake, and overcompensating the photosynthesis in plants.

In contrast, the calculated regression coefficient of both T_{min} and

Table 4
Regression estimates of the impact of temperature and rainfall on the yield of cotton and soybean crops in the SE-US, 1980–2020.

Particulars	Regression coefficient	SE (standard error)	t-value	p-value	Regression coefficient	SE (standard error)	t-value	p-value
	Cotton growing period				Soybean growing period			
T_{min} °C	0.672***	0.193	3.480	0.001	−0.018**	0.178	−0.100	0.05
T_{min} (Square)	−0.014***	0.006	−2.430	0.01	−0.009*	0.005	−1.890	0.06
T_{max} °C	−0.721***	0.290	−2.490	0.001	−0.091**	0.258	0.350	0.05
T_{max} (Square)	0.011**	0.005	2.130	0.03	−0.006	0.004	−1.340	0.18
Rainfall (cm)	0.033**	0.017	1.930	0.05	−0.004	0.015	0.240	0.81
Rainfall (Square)	0.001*	0.000	−1.870	0.06	−0.000	0.000	−0.600	0.55
Constant	10.733***	3.697	2.900	0.00	3.133	3.444	0.910	0.36
District	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
No of Observations	451	451	451	451	451	451	451	451

Note: ***, **, and * denote significance at 1, 5, and 10% levels, respectively.

T_{max} was negative in the case of soybean, indicating the detrimental impact of both T_{min} and T_{max} on soybean yield. These results are in agreement with the findings of Chen et al. [36], and Eck et al. [37]. According to Ramirez-Villegas et al. [103], 30 °C is the critical temperature extreme over which soybean reproductive development begins to suffer from temperature, and the SE-US's SGS (Table 3) has experienced averaged T_{max} of 30.54 °C (>30 °C) for the last 41 years. Eck et al. [37] deduced that soybean daytime temperatures normally surpass the ideal growing range in SE-US. This threshold breaching lowers the net carbon accumulation owing to fastening the plant respiratory systems, which further negatively impacts crop yields [104]. Contrarily, Araji et al. [34] predicted a positive impact of rising temperatures on soybean yields by 2030. Furthermore, Satari and Khalilian [35] also noted an increase in the soybean yield due to increasing temperature. Baker and Allen [105] opined that if the prevailing temperature during the season is below the photosynthetic optimum, a slight temperature rise can considerably improve yield; however, if the prevailing temperature is already near the maximum, a modest rise in temperature can substantially decrease yield. Moreover, our T_{avg} results were also in agreement with Boote et al. [106] according to them, T_{avg} above 23 °C–27 °C decreases soybean yield, and our T_{avg} (Table 3) values of the SE-US on an average was 24.51 °C greater than (>) 23 °C. The regression coefficient of rainfall has been observed to be positively significant throughout the CGS, implying that rainfall would increase cotton yield. Rainfall has been noted to be unfavorable throughout the SGS, although this is not statistically significant because most soybeans in the SE-US are grown under controlled irrigation systems. However, rainfall was significantly favorable across CGS, and the same was realized by Guntukula [107]. According to Cetin and Basbag [108], and [109]; normally, the yields get detrimentally affected either when the rainfall trend is decreasing or variability in rainfall has increased, but our study period had not faced either of the circumstances.

3.3. Marginal effects

The marginal effects were calculated using different variable mean values, which are changes in crop yield caused by a 1 °C rise in temperature or a 1 cm increase in rainfall (Table 5).

During the CGS, the regression coefficient of T_{max} was shown to be negative (−0.103) and substantial (Table 5), implying a 10.30% decline in yield with every 1 °C rise in its value, and these results are similar to the results found in Refs. [91,110]. However, the T_{min} had a considerable beneficial influence with its regression coefficient of 0.208, indicating a boost to the cotton yield by 20.80% with every 1 °C increment in its value. On scrutinizing further, it can be clearly observed that the net impact of incremental shifts in T_{max} and T_{min} was still advantageous to cotton yield which can be interpreted statistically as every 1 °C net temperature increment improved cotton yield by 10.50%. These results are similar as noted by other researchers [23,39]. The positive effect of T_{min} had entirely compensated for the damages caused by an increase in T_{max}. The calculated regression coefficient of both T_{min} and T_{max}, on the other hand, was negative (−0.316 and −0.256) in the case of soybean (Table 5), indicating the only detrimental impact of both T_{min} and T_{max} on soybean yield, causing a drop in yield by 31.60% and 25.60% with every 1 °C rise in T_{max} and T_{min}, respectively. These results are corroborated by Carbone et al. [49], and Bihter et al. [111] findings. The regression coefficient (Table 5) of rainfall has been found to be positive though non-significant throughout the CGS. Rainfall has been found to be unfavorable, but not statistically significant, throughout the SGS, causing a 0.40% (non-significant) decline in yield per 1 cm rainfall increase. Cotton crop benefitted more from the rise in T_{min} as the effect of an increase in T_{min} has been lessened or even minimized due to assured irrigation in the SE-US, which has resulted in an over-utilization of water resources. Soybean crops have incurred more harsh detrimental effects of changing temperatures (T_{min} and T_{max}) than cotton crops since the yield reduction per 1.0 °C rise in T_{max} is 15.30% (25.6–10.3) more in soybean than cotton. It is notable that a 1.0 °C rise in T_{min} dropped soybean yields by 31.60% but increased cotton yields by 20.80%. Therefore, it can be deduced that marginal effects on soybean were more negative than on cotton crops. In comparison to rainfall, shifts in temperature had a more significant influence on crop production due to their correlation with increased solar irradiation intensity, drought, and windy conditions that also influence crop yields [112].

Rainfall marginal coefficients (Table 5) were positive in cotton crop; however, their significance was low, and these results are in agreement with the findings of Ton [45] and Chen et al. [24] on rainfall affecting the SE-US cotton. However, the marginal effect of rainfall on soybean yield has been found to be negative though non-significant (0.004),

Table 5
Marginal Effects of temperature and rainfall on cotton and soybean crop yields in the SE-US from 1980 to 2020.

Variable	Marginal coefficient of regression	SE (standard error)	Z-value	P-value	Marginal coefficient of regression	SE (standard error)	Z-value	P-value
	Cotton growing period				Soybean growing period			
T_{min} (°C)	0.208***	0.033	6.37	0.001	−0.316***	0.027	−11.60	0.001
T_{max} (°C)	−0.103***	0.036	−2.87	0.001	−0.256***	0.029	−8.84	0.001
Rainfall (cm)	0.007**	0.005	1.39	0.05	-0.004^{NS}	0.005	−0.81	0.419

Notes: ***, **, and * denote significance at 1, 5, and 10% levels, respectively, NS: Non-Significant.

implying that a 1 cm increase in rainfall reduced soybean yield by 0.40%. Generally, rainfall has a significantly lower marginal effect than temperature. The analysis of the combined or overall impact of both temperatures and rainfall indicates the damages from temperature were not fully compensated by the rainfall. However, the marginal effect of rainfall on the soybean crop was meagre and insignificant.

3.4. Study limitations

Every study has limitations; therefore, always leaves scope for further improvements. This study has the following limitations:

- The temperatures (T_{max} and T_{min}) data utilized in this study were the daily maximum and daily minimum temperature values averaged over a month which is the most commonly used method in recent relevant studies [70,77,113], but the study might yield a more precise understanding if hourly temperature (T_{max} and T_{min}) data were available consistently for the study period (or at least 30 years). With the availability of data on hourly temperature extremes, the ability to statistically separate out the impact of climate change between the vegetative and reproductive stages of both crops could provide a more detailed understanding of the concept of climate change and yield variability.
- This study utilized only the most commonly used [70,77,113] explanatory variables (T_{min}, T_{max}, and precipitation) because the data pertaining to other salient and yield influential variables (fertilizers, pesticides, sunshine hours, irrigation, wind velocity, and humidity, etc.) was not available consistently for the period of study.
- The county-level yield data of both crops was not available consistently for the study years i.e., not even 30 years which is suggested as a minimum requirement for climate-yield studies as per ANL [61]. Therefore, the study has utilized the state-level yield data of both crops which limits the study findings to understand only the general overview of the SE-US region as a whole in terms of the consequences of changing climate on cotton and soybean yields. Furthermore, for a more detailed understanding of the SE-Us about the aforesaid issue, the county-level yield analysis study is suggested. Consequently, the county-level yield data regressed over hourly temperatures (T_{max} and T_{min}) rainfall, and other salient and yield influential variables can produce more precise and practically useable insights for agriculture stakeholders.

4. Conclusion

The results of the study revealed significant spatial variability in temperature and rainfall across the SE-US coupled with an unsymmetric trend of nocturnal and diurnal warmings throughout CGS and SGS. The major conclusions are: i) The contribution of nocturnal and diurnal temperatures to the overall warming of the SE-US was 72.09% and 27.01% during CGS and 75.92% and 24.08% during SGS, therefore the nocturnal temperature was explaining the overall heating trend for both growing seasons over the 41-years; ii) The ratio of the yearly rate of change of diurnal temperature during CGS and SGS was 1.09:1, whereas the ratio of the yearly rate of change of nocturnal temperature during CGS and SGS was 0.91:1; iii) The ratio of the yearly rate of change of nocturnal and diurnal temperature was 2.58:1 during CGS and 3.09:1 during SGS; iv) From 1980 to 2020, the T_{max}, T_{min}, T_{avg}, and rainfall during the CGS changed by 0.50 °C, 1.30 °C, 0.88 °C, and 3.94 cm, but by 0.46 °C, 1.45 °C, 0.97 °C, and 3.74 cm during the SGS; v) Rainfall had a positive effect on cotton yield but a non-significant negative effect on soybean yield. However, numerically 1 cm of incremental rainfall increased cotton yield by 0.70% and decreased soybean yield by 0.40%; vi) The 1 °C incremental T_{min} boosted the cotton yield by 20.80% while reducing the soybean yield by 31.60%, and vii) The 1 °C rise in the T_{max} decreased the cotton yield by 10.30% and reduced the soybean yield by 25.60%. From the above deliberation, significant policy options from this study include development of climate-resilient soybean and cotton varieties capable of tolerating or escaping abiotic stresses such as droughts, floods, and heat waves. Biotechnology offers numerous opportunities in this direction. Another way to reduce the adverse effects of climate change on agricultural production is through precision irrigation where available to enhance resilience of agriculture to climate change. Further, precise irrigation could improve water-use efficiency by adopting micro-irrigation technologies, such as sprinkler and drip irrigation along with soil moisture sensors.

Declaration of competing interest

The authors declare that there is no conflict of interest.

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