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Crop-climate link in the southeastern USA: A case study on oats and sorghum

Ramandeep Kumar Sharma [a,*], Jagmandeep Dhillon [a,**], Sunny Kumar [b], Kamal Vatta [b], Krishna N. Reddy [c]

[a] Department of Plant and Soil Sciences, Mississippi State University, MS, USA
[b] Punjab Agricultural University, Ludhiana, Punjab, India
[c] Crop Production Systems Research Unit, USDA-ARS, Stoneville, MS, USA

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ABSTRACT

Recognizing the crop and region-specific irreversible effects of climate change on agriculture is unavoidable. The Southeastern United States region (SE-US) contributes significantly to the United States (US) economy through its diverse agricultural productivity. Climatically, this region is more vulnerable than the rest of the country. This study was designed to quantify the effect of changing climate, *i.e.,* daily maximum temperature (Tmax), daily minimum temperature (Tmin), and precipitation, on oats (*Avena sativa* L.) and sorghum (*Sorghum bicolor* L. Moench) in SE-US. The panel data approach with a fixed effects model was applied by creating a production function on a panel dataset (1980–2020) of climate and yield variables. The required diagnostic tests were used to statistically confirm that the dataset was free of multi-collinearity, unit root (non-stationarity), and auto-correlation issues. The results revealed asymmetric warming (Tmin increase > Tmax increase) over the region. Tmax and Tmin significantly increased during the oats growing season (OGS) and sorghum growing season (SGS). Precipitation increased during OGS and decreased during SGS. The growing season average values of Tmax, Tmin, and Tavg (daily average temperature) have shifted by 1.08 °C (0.027 °C/year), 1.32 °C (0.033 °C/year), and 1.20 °C (0.030 °C/year) in OGS and by 0.92 °C (0.023 °C/year), 1.32 °C (0.033 °C/year), and 1.12 °C (0.028 °C/year) in SGS. However, precipitation had shifted by 23.2 mm (0.58 mm/year) in OGS and shifted (decreased) by −5.2 mm (−0.13 mm/year) in SGS. Precipitation had a non-significant effect on oats and sorghum yields. With every 1 °C increase in Tmin and Tmax, oats yield was reduced by (−5%) and (−4%), respectively, whereas sorghum yield was increased by (+13%) and decreased by (−7%), respectively. Taken together, a 1 °C net rise in overall temperature reduced oats yield (−9%) while increased sorghum yield (+6%).

1. Introduction

Long-term shifts in temperature, precipitation, as well as other indices *i.e.,* humidity and pressure are referred to as climate change [1]. Changing climate has become a pressing issue in the last decade [2], as the global temperature has increased by 0.85 °C (degree Celsius) in the previous century, and it is expected to increase in the range of 1.4 °C–5.8 °C by 2100 [3]. Recently, Myhre et al. [4] connected these temperature warmings with the irregularities in intense precipitation events and deduced that these events are doubled for every 1 °C increase in climate warming. Consequently, the irregularities in extreme precipitation events showed an upward trend globally from 1901 to 2000 [5]. A similar increase in irregularities in precipitation has also been confirmed at the country level in the US, Europe, Australia, and Japan [4] and regional levels in the northeast US, and the southeast US [6].

By 2100, extreme precipitation anomalies are expected to intensify by 24–40% [7]. Additionally, these climatic changes are anticipated to be more rapid than witnessed in the previous 1000 years [8,9]. Undoubtedly, this foregoing trend in climate change had already affected and will continue to affect crop developmental stages and productivity [10], at local (domestic), regional, and worldwide scale [11].

Specifically, continuing climatic trend causes abiotic and biotic stresses in plants [12]. Together, these stresses impair plant microclimates, microbial populations, and their interactions with plants, and

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* Corresponding author.
** Corresponding author.
E-mail addresses: rs2564@msstate.edu (R.K. Sharma), jsd369@msstate.edu (J. Dhillon).

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affect their vegetative and phenological mechanisms, and thus, productivity [13]. Furthermore, these effects can be positive [14–16], negative [17,18], or neutral [19,20] depending on the crop, pace, and amplitude of shift of climatic variables, as well as the geographic region [5]. Generally, the impact is negative on C3 crops (wheat, rice, and soybeans) but is less severe on C4 crops (corn, sorghum, and millets) due to their higher photosynthetically optimal temperatures [21].

Nonetheless, approximately 75% of the total cultivated area has shown a negative response to climate-induced scenarios [22]. Tropical areas are typically more vulnerable to climate change because their temperatures are already close to the optimal maximum temperature [23]. However, due to the highly uneven nature of climatic effects on countries with larger landmasses, there are mixed opinions on climate-crop relationships for the US [24–29]. Within the US, the SE-US is more vulnerable climatically [15,30], having previously experienced more billion-dollar disasters [31], rising sea levels, cataclysmic flooding, frequent droughts, intense heat, snow or rainstorms, and hurricanes than any other region in the country, particularly in springs and summers, resulting in crop yield losses [6,30]. Moreover, SE-US agriculture is oversensitive to intense heat as many crops here are produced close to their temperature thresholds [29,32]. The SE-US is producing 17% ($55 billion) of total US agricultural commodities every year and is a key player in the national economy [33,34]. Out of 135 million hectares of gross area in SE-US, twenty-one million hectares, or 13% of US cultivable land, is under cultivation [15]. SE-US is known for its agricultural diversity, and topographical distinctness [29,35]. Thus, the SE-US is one of the most sensitive socio-economic sectors to study from a crop-climate viewpoint [36].

While sizeable research on global or mega-scales has already investigated the climate-crop relationship utilizing crop-simulation models, the regional viewpoint remains unexplored [37]. This may be due to the complexities attached to accumulating massive datasets to apply these models at a regional scale [38]. So far, the climate-crop studies mostly focused on crops *i.e.,* rice, wheat, corn, and soybeans since these crops altogether contribute to 75% of the world's total calorie consumption [22,39]. This is at the exclusion of other minor crops like oats and sorghum, which could be a valuable alternative to combating food security under the current climate change scenario [40].

Sorghum and oats are ranked 5th and 6th in terms of the world's grain production [41,42]. According to USDA-NASS [43], the US produced oats worth 161 million dollars, and sorghum worth two billion dollars. The SE-US has 27.50% (5,63,322 ha) of the national sorghum hectarage. The SE-US accounts for 17.79% (1.82 million tons) of national sorghum production and 20.13% of national sorghum revenue [43]. This region has a sorghum yield of 4.60 Mg ha^{-1} on average and three states, Arkansas, Louisiana, and Mississippi, with yields that are greater than the national average (4.85 Mg ha^{-1}). The SEUS has 30,351 ha of oats cultivation, accounting for 11.54% of total national oats cropland [43]. The SEUS accounts for 11.21% of total US production and 12.74% of oats production income. This region's average oat yield is 4.59 Mg ha^{-1}, which is greater than the national average yield (4.12 Mg ha^{-1}) [43].

Sorghum is a climate-resilient crop, particularly in the face of irregular precipitation and high temperatures, making it valuable for studying the climate-crop link [44]. Furthermore, very few studies on oats have been conducted globally since the 1970s, after horses lost their role in agriculture drastically decreasing the demand for oats as fodder [45]. So far, almost minimal to no crop-climate studies on oats have been conducted, particularly in the SE-US, which is also the case for sorghum. Hence, the goal of this study was to determine the adaptability of the SE-US growers (oats and sorghum) to climate change and provide estimates to crop-climate mitigation policymakers about the vulnerability of the SE-US. This was achieved by: i) Determining the trend, magnitude of change, and annual rate of change in climatic variables (Tmax, Tmin, and precipitation) in SE-US from 1980 to 2020, ii) Determining the impact of changes in the aforesaid climatic variables on oats and sorghum yield, and iii) Determining the marginal effects of change in these climatic variables on oats and sorghum yield. The term "marginal effects" refers to how much yield (in %) is affected (increased or decreased) by a 1 °C or 1 mm change in SE-US temperatures (Tmax and Tmin) and precipitation from 1980 to 2020.

2. Materials and methods

2.1. Data

The present study has used a panel dataset, often called cross-sectional or longitudinal time series data that comprises data of every variable repeating across the time series [46]. The panel dataset has been widely utilized in past crop-climate studies [47–50]. A minimum 30 years timeframe is suggested to adequately depict climatic fluctuations to the finer level [51], and the panel data model requires a continuous dataset [52].

Hence, states meeting this minimum dataset criterion were only considered. Only 7 states in SE-US met the requirements and the state-averaged data from the counties growing respective crops was considered to represent cropland in the SE-US (Table 1). The data included explanatory variables such as Tmin, Tmax, precipitation, and the response variable as yield to form a panel of 287 rows (41 years × 7 states), and 10 columns (Tmax, Tmin, Tavg, precipitation, and yields x 2 crops), as guided by Liu and Cheng [54], and Ozdemir [55]. The data on explanatory variables were accessed from the NOAA data repository [53] (Table 1), while response variables were accessed from the USDA-NASS data repository [43]. The NOAA (data source for climatic variables) uses the area-weighted average method on grid point readings (5-km resolution) transcoded from weather stations to compute county-level values [53]. The unit of Tmin, Tmax, and Tavg is °C, precipitation is millimeter, and yield is Mg ha^{-1}. The growing season averages for daily temperature and the growing season cumulative sum for daily precipitation were computed for analysis, as guided by Lobell and Burke [56] and Blanc and Schlenker [57]. The oats growing season (OGS) and sorghum growing season (SGS) was taken from September to December, and March to June, respectively as per USDA's handbook guiding sowing and harvest dates [43].

2.2. Panel data approach

Out of the current approaches used for evaluating crop-climate links, econometric techniques outperform the rest, in terms of reducing complexities, and higher accuracy in predictions, especially at a regional scale with clustered datasets [56,58,59]. Within econometric methods, the panel data approach is considered more robust against omitted variables, unobservable heterogeneity validation, and a greater degree of freedom [48,60].

The panel data approach utilizes two model types fixed, or random effects [48]. The most recent climate-crop studies utilized a fixed effects model [29,50]. In our study, many unobservable variables such as edaphic parameters, topographical parameters, and growers self-regulatory modifications such as switching between different sowing dates, crop mix, seed varieties, and different input rates might influence crop yields. Therefore, the fixed effect model fits best in this study to account for the unobserved factors in purely (to maximum extent) capturing the climatic effect [50]. This model uses the first differencing as a method to minimize the unobservable variations, making the model more effective in generating inferences [61,62]. The climate-crop relationship was computed by building a production function with panel data analysis utilizing regression [29,63]. The main yield determinant variables were precipitation and temperatures (Tmax and Tmin) [64]. Hence, the model previously adopted by Birthal et al. [65] and applied in this study as follows:

$$l\,n\,y_{it} = S_i + T_t + \beta X_{it} + \varepsilon_{it}$$

Table 1
Data description.

Crops	Growing Period	Panel Districts	No of years	Variables Considered	Data sources
Oats	September to December	• Georgia • North Carolina • Texas	41 years (1980–2020)	• Maximum Temperature (°C) • Minimum Temperature (°C) • Mean Temperature (°C) • Precipitation (mm) • Oats Yield (Mg ha^{-1}/Mega gram per hectare)	• Oats yield [43] Tmax, Tmin, Tavg, and Precipitation [53]
Sorghum	March to June	• Arkansas • Georgia • Louisiana • Mississippi • Texas	41 years (1980–2020)	• Maximum Temperature (°C) • Minimum Temperature (°C) • Mean Temperature (°C) • Precipitation (mm) • Sorghum Yield (Mg ha^{-1}/Mega gram per hectare)	• Sorghum yield [43] • Tmax, Tmin, Tavg, and Precipitation [53]

In the above equation, "*i*" represents a region (state), and "*t*" is time. The "*S*" represents the state-bound fixed effect, and "*y*" is the model's response variable. As per our hypothesis, the state-bound fixed effects (*S*) assimilate all the unobservable time-variant variables related to the state that may or may not impact crop yields and controls the noise created by the model's exogenous variables [61]. "*T*" signifies the time-fixed effects of the yield computation model that may be driven by factors such as infrastructure improvements, technology advances, and human resource enhancements. The "X", "β", and "ε" represents climatic parameters, independent variable-related parameters, and the random-error term.

The statistical software Stata® version-16 [66] was used for analyzing the panel data. The oats and sorghum yields were regressed independently over the climatic parameters, generating regression coefficients and p-values (Table 5). The climate-crop relationships are often nonlinear [58]. To tackle the problem of non-linearity, the squared component of Tmax, Tmin, and precipitation was incorporated with these variables into the model's equation. This squared factor gave rise to unnecessary variation in the response variable (y_{it}) which was controlled by transforming equation (1) into a logarithmic-linear function. The logarithmic-linear function coefficients are simply understood as proportional changes exhibiting marginal effects. The marginal impacts computed the magnitude (%) of change in yield led by a unit change in temperature (1 °C) or precipitation (1 mm), by equating various values of variable arithmetic mean [67,68], as shown in Table 6. The natural logarithmic of values of explanatory variables were regressed independently across time using state-bound fixed effects to regulate time-reliant parameters for establishing climatic trends over OGS and SGS.

2.3. *Diagnostic testing*

Initially, multicollinearity among independent variables was tested before applying regression analyses (Table 2).

Both variance inflation factor (VIF <10) and tolerance values (>0.1) were within the permissible limits for each crop, confirming no collinearity between the variables [69]. Another set of diagnostic testing was done to validate the presumptions of the erroneous elements of the model before applying regression. The model's presumption includes no autocorrelation among unobservable variables [61]. It implies that all individual time unvarying features need to be unique and uncorrelated and hence the constant and erroneous terms are also uncorrelated [61,62]. When such error components are correlated, the fixed-effect model is invalid, and the conclusions obtained are misleading [55]. Another presumption was that the yield, Tmax, Tmin, and precipitation variables data should be stationary, otherwise non-stationary data could raise the problem of autocorrelation [55,68]. The autocorrelation effect may be more problematic regarding independent variables [70].

Table 2
Multi-collinearity statistics.

Variable	VIF	SQRT VIF	Tolerance	VIF	SQRT VIF	Tolerance
Oats				Sorghum		
Tmin	6.82	2.61	0.15	4.30	2.07	0.23
Tmax	9.35	3.06	0.11	4.64	2.15	0.22
Precipitation	3.15	1.77	0.32	1.93	1.39	0.52
Mean VIF	6.44			3.62		

Tmin is minimum temperature, Tmax is maximum temperature, VIF is the Variance inflating factor, and SQRT VIF represents the square root of VIF.

The stationarity of all datasets was confirmed after rejecting the null hypothesis for the various panel unit root tests, namely "Levin-Lin-Chu", "lm, Pesaran, and Shin", and "Fisher-type" (Table 3). Since stationarity denotes the absence of a trend, absence of seasonal variation, but a constant variation in the time series, the autocorrelation function rapidly drops to nearly zero for a stationary time series [61,70]. Therefore, autocorrelation was not a significant issue with our dataset.

3. Results and discussion

3.1. *Changes in climatic variables during OGS and SGS in SE-US (1980–2020)*

Throughout the study period (1980–2020), the Tavg, Tmax, and Tmin for SGS were 19.6 °C, 25.9 °C, and 13.3 °C, respectively, and 15.2 °C, 21.5 °C, and 8.8 °C for OGS (Table 4).

The slope of Tavg, Tmax, and Tmin showed a significantly positive trend throughout OGS and SGS for the recent 41 years (Figs.. 1A and 2A). The SE-US had average growing season precipitation of 133 mm from 1980 to 2020 (Table 4), demonstrating a non-significant positive trend for OGS. However, a non-significant negative trend was noted for SGS, with average growing season precipitation of 191 mm (Figs.. 1B and 2B).

The analysis of the magnitude of shifts in temperature from 1980 to 2020 exhibited a significant upsurge of 1.20 °C and 1.12 °C in Tavg of OGS and SGS, respectively (Table 4). These results are comparable with the estimations of other studies in the context of the magnitudes of the warming observed globally [2,71] and regionally (especially SE-US) [15,29,50]. Also, it signifies that the SE-US witnessed 7.14% more overall warming in OGS than in SGS, which may have an unfairly negative effect on oats yield (Table 4). This warming can be advantageous or harmful to crops depending on whether the occurrence of elevated Tavg coincides or not with high temperature-sensitive growth processes/stages [72]. In cereal crops, the flowering and gametogenesis phases are most sensitive to high temperatures [73,74], which is the primary cause of a decrease in seed number, seed size, and yield [75]. For the previous 41 years, the degrees by which the Tmax has shifted during OGS (1.08 °C) were greater than the degrees by which it had shifted during SGS (0.92 °C) by 0.16 °C (Table 4). However, the Tmin has shifted by the same magnitude (1.32 °C) during OGS and SGS (Table 4). These statistics for OGS and SGS's Tmax (1.08 °C and 0.92 °C) and Tmin (1.32 °C and 1.32 °C) shifts for SE-US (Table 4) are markedly higher than the corresponding global figures for Tmax (0.40 °C) and

Table 3
Stationarity testing.

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
	H_0: Panel contains a unit root			H_0: All panels contain unit roots		H_0: All panels contain unit roots	
	H_1: Panel are stationary			H_1: Some panels are stationary		H_1: At least one panel is stationary	
OT (min)	−6.4293	−4.227	0.001	−5.311	0.001	64.202	0.001
ST (min)	−9.9665	−7.390	0.001	−6.281	0.001	92.144	0.001
OT (max)	−8.093	−5.579	0.001	−6.360	0.001	97.756	0.001
ST (max)	−9.743	−6.857	0.001	−6.139	0.001	89.857	0.001
OP	−9.646	−7.095	0.001	−7.331	0.001	148.992	0.001
SP	−8.049	−3.770	0.001	−7.361	0.001	141.126	0.001
Ln (yield oats)	−6.945	−4.852	0.001	−5.714	0.001	86.102	0.001
Ln (yield sorghum)	−6.946	−3.799	0.001	−5.669	0.001	80.522	0.001

OT and ST represent the Oats Temperature, and Sorghum Temperature, respectively. OP and SP represent the Oat's precipitation, and Sorghum precipitation, respectively.

Table 4
Overall mean, change, and the annual rate of change of climatic variables during oats and sorghum growing seasons in SE-US, 1980–2020.

Growing season	Variables	Maximum Temperature (Tmax) (°C)	Minimum Temperature (Tmin) (°C)	Mean Temperature (Tavg) (°C)	Precipitation (mm)
Oats	Mean	21.5 (0.006)	8.8 (0.007)	15.2 (0.005)	133 (0.301)
	Change	1.08	1.32	1.20	23.2
	Annual rate of change	0.027***	0.033***	0.030***	0.58***
Sorghum	Mean	25.9 (0.006)	13.3 (0.005)	19.6 (0.085)	191 (0.036)
	Change	0.92	1.32	1.12	−5.2
	Annual rate of change	0.023***	0.033***	0.028***	−0.13***

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

Table 5
Regression estimation coefficients for the impact of change in temperature (Tmax and Tmin) and precipitation on oats and sorghum yields in the SE-US, 1980–2020.

Particulars	C	SE	p-value	C	SE	p-value
	Oats Growing Period			Sorghum Growing Period		
Tmin (°C)	−0.09***	0.10	0.36	0.02***	0.23	0.01
Tmin (Square)	−0.01	0.01	0.15	0.01	0.01	0.52
Tmax (°C)	−0.29***	0.21	0.16	−0.19***	0.50	0.01
Tmax (Square)	0.01	0.00	0.11	0.002	0.01	0.82
PP (mm)	0.02^{NS}	0.02	0.15	-0.02^{NS}	0.02	0.23
PP (Square)	−0.0003	0.00	0.44	−0.0009	0.00	0.04
Constant	6.34	2.04	0.00	6.60	5.69	0.25
District	Yes			Yes		
Time	Yes			Yes		
No of Observations	123			156		

Notes: *** denote significance at the 1% level; C and SE represent Regression Coefficient and Standard Error, respectively, NS: Non-Significant, and PP represents precipitation.

Table 6
Marginal effect of temperature (Tmax and Tmin) and precipitation on the yield of oats and sorghum in the SE-US, 1980–2020.

Particulars	C	z-value	p-value	C	z-value	p-value
	Oats Growing Period			Sorghum Growing Period		
Tmin (°C)	−0.05***	−2.12	0.01	0.13***	3.77	0.01
Tmax (°C)	−0.04***	1.54	0.13	−0.07***	−1.79	0.01
Precipitation (mm)	0.01^{NS}	2.44	0.14	-0.01^{NS}	−1.82	0.07

Note: ***, **, and × denote significance at 1, 5, and 10% levels, respectively, NS: Non-Significant, C represents the Marginal Regression Coefficient.

Tmin (0.80 °C) [76–78], indicating that the SE-US is more vulnerable climatically. Diurnal warming was increased by 17.39% in OGS in comparison to SGS, but nocturnal warming was noted to be the same for both (Table 4). This may be more harmful to oats as elevated diurnal temperatures negatively impact the oats' grain-filling timespan (eventually the yield) [79]. Over the last 41 years, 22.22% and 43.47% more nocturnal warming than diurnal warming was noted with OGS and SGS, respectively (Table 4). However, nocturnal warming attributed 58.93% (in SGS) and 55% (in OGS) to overall warming in the SE-US, compared to diurnal warming's 41.07% (in SGS) and 45% (in OGS) (Table 4). Hence, the nocturnal temperature (Tmin) explicates most of the heating upswing trend for the past 41 years of SE-US throughout OGS and SGS. These findings are corroborated by similar studies [80,81] that also observed the Tmin warming rate to be 40% or 1.4 times faster than the Tmax.

Pinpointing the rate or speed at which the climatic variables (Tmax, Tmin, and precipitation) are shifting every year is also important as it provides an estimate of the time, speed, or tendency of ecosystems to readapt, readjust, or revive [76]. From 1980 to 2020, the yearly rate of change of Tmax, Tmin, Tavg, and precipitation in OGS was 0.027 °C, 0.033 °C, 0.030 °C, and 0.58 mm, respectively, while in SGS it was 0.023 °C, 0.033 °C, 0.028 °C, and −0.013. The negative sign (−0.013) indicates that SGS witnessed a decrease in precipitation every year throughout the past 41 years (Table 4). It can be inferred that the pace of nocturnal and diurnal warming in OGS was 1.22:1, but in SGS it was 1.43:1. However, in the OGS and SGS, the rate of diurnal warming was 1.17:1, whereas the rate of nocturnal warming was 1:1. Figs. 1B and 2B demonstrated a notable rise in precipitation during OGS while a reduction in precipitation during SGS. Overall, the 41-year trend indicated that Tmax and Tmin are the major significant driving factors of climate change in SE-US.

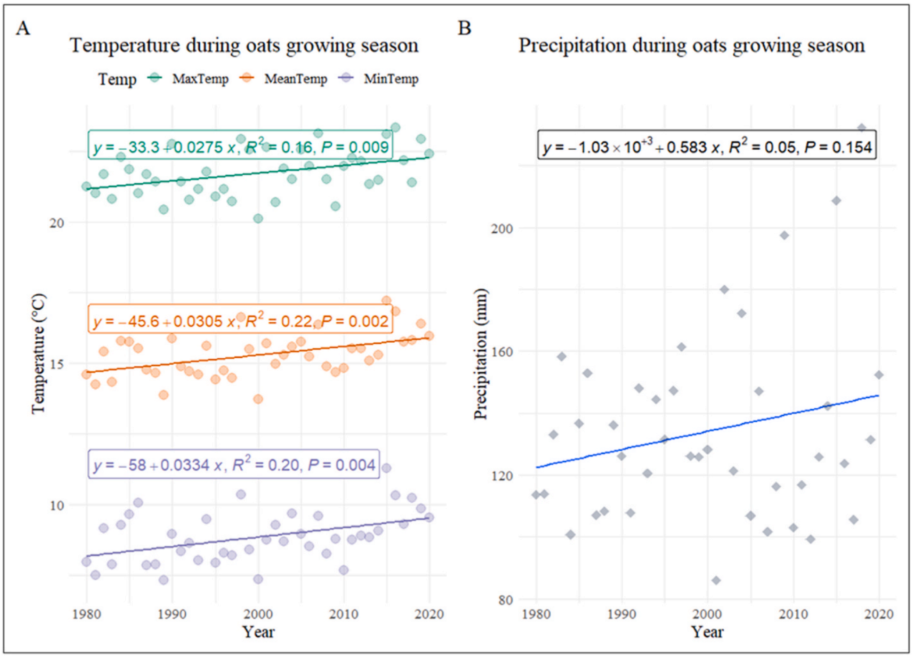

Fig. 1. A. Tmax, Tmin, and Tavg, showed significant slopes throughout OGS in the SE-US between 1980 and 2020. **B.** The precipitation showed a non-significant (increasing) trend in the SE-US over OGS between 1980 and 2020.

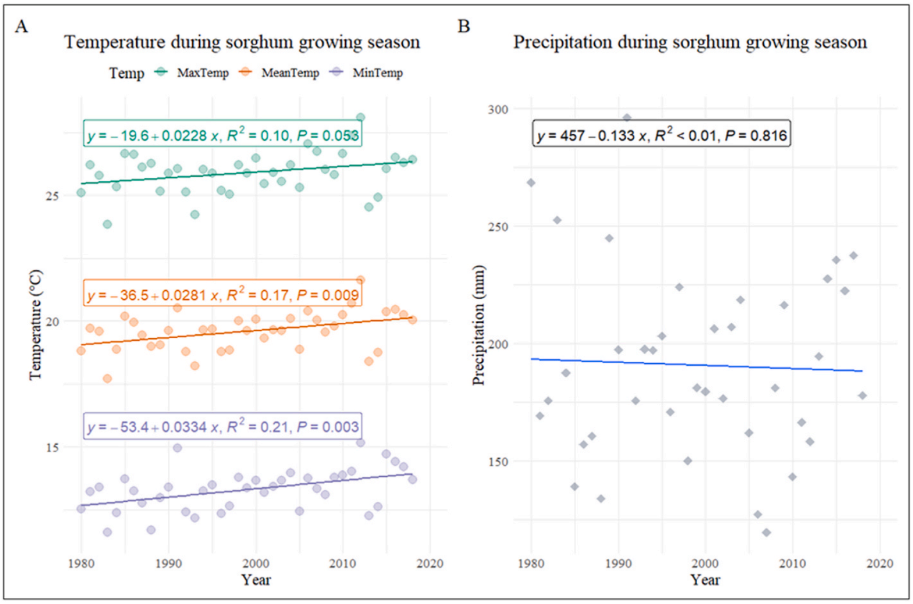

Fig. 2. A. Tmax, Tmin, and Tavg showed significantly positive slopes throughout SGS in the SE-US between 1980 and 2020. **B.** The precipitation showed a non-significant (decreasing) trend in the SE-US over SGS between 1980 and 2020.

3.2. *Impact of climate change during 41-yr. Period (1980–2020) on oats and sorghum yield*

The regression coefficients of Tmin and Tmax were shown to be significant on oats and sorghum yields while precipitation was non-significant, implying Tmin and Tmax as the major variables driving oats and sorghum production in SE-US (Table 5). These findings agree with O'Donnell and Adkins [82], Ortiz-Bobea et al. [83], Zhang et al. [84], and Chadalavada et al. [2].

The regression coefficient for Tmin and Tmax was noted to be significantly (99% confidence level) negative (−0.09 and −0.29) for oats (Table 5), confirming an adverse effect of both (Tmin and Tmax) on oats yield. These findings are consistent with those of Hellewell et al. [79], and Klink et al. [85] in the context of Tmin, and Ehlers [86], Saastamoinen [87], Sánchez-Martín et al. [88], and Agnolucci et al. [89] about Tmax. The higher Tmin raises nocturnal respiration rates and reduces the carbon supply to support this increased respiration rate in oats [90]. Thereby, limiting the availability of photo-assimilates essential for plant biomass production and seed/grain development [91,92] and thus decreasing yield. The elevated Tmax, on the other hand, negatively affects the phenological processes in oats, notably the flowerhead (panicle) breakout, the period of flowerheads (panicle) formation upon its shoots tip, grain filling, anthesis [79,93], number of spikelets per panicle [94], and hence the yield. According to Hedhly et al. [95], a minor increase in temperature could either improve or reduce yield based on whether the already existing growing season temperature is below or close to the photosynthetic optimal temperature. However, the OGS temperature in SE-US during the study period was noted to be 21.5 °C (Table 4), which is greater than the oats' photosynthetic optimal temperature of 20°C–21.1 °C [85], thereby penalizing yield. Eck et al. [15] recognized that in the SE-US, diurnal temperatures frequently exceed the optimal growth range. This increased temperature intensifies the crop water demands to the extent of 60% [96]. This increased temperature of OGS in SE-US could be even more detrimental, given that oats are a cool season crop with poor tolerance to high temperatures and drought, as well as having higher water demands compared to other small grains [86,88].

In the case of sorghum, the regression coefficient for Tmin was calculated as significantly (99% confidence level) positive (0.02) (Table 5), indicating that Tmin had a positive effect on sorghum yield. This is consistent with the recent findings of Bekuma Abdisa et al. [16]. However, there is still no consensus on Tmin's physiological effects on plants (particularly sorghum) [97–99]. Furthermore, most sorghum growing areas have a Tmin of 22 °C or higher [100], so even a slight increase in Tmin could put them at risk of crossing the optimum Tmin of 22 °C for sorghum [95,101,102]. However, this study found a SE-US Tmin of 13.3 °C (Table 4). This indicates that the sorghum in the SE-US can still withstand or benefit from further nocturnal warming until the actual Tmin crosses the optimal Tmin of 22 °C because of SE-US's comparatively wider window for the difference between optimum Tmin and existing Tmin (22 °C minus 13.3 °C). In contrast, this study found that Tmax had a negative impact on sorghum yield since the regression coefficient was assessed to be significantly (99% confidence level) negative (−0.19). The same findings have been established by Singh et al. [103], Prasad et al. [104], Chadalavada et al. [2], Bekuma Abdisa et al. [16], Sime and Demissie [105], and Araya et al. [18]. The increased Tmax accelerates evapotranspiration and respiratory rates, shortens the growing season, and reduces granular (seed) number and size, resulting in reduced yields [106,107]. Changing Tmax and Tmin had an overall positive effect on sorghum yield, as evidenced by the improvement in sorghum yield for every 1 °C increase in SE-US temperature (Table 6). This was also confirmed by Adejuwon [108], Boomiraj et al. [109], Msongaleli et al. [110], Bosire [111], and Chadalavada et al. [112]. It is worth noting that, as per Prasad et al. [100], and Sunoj et al. [113] regarding sorghum, temperatures greater than 32 °C (the cutoff point) begin to negatively affect the RUBISCO mechanism, hampering photosynthesizing performance and, eventually, yield. RUBISCO is an enzyme responsible for converting CO_2 to glucose and other useful chemicals in plants during photosynthesis [114]. Contrarily, SE-US Tmax (25.9 °C) is well below the cutoff point throughout the study period (Table 4). Furthermore, the SE-US's SGS temperature (25.9 °C) was even slightly lower than the optimal range (27 °C) for sorghum [101,102], and Hedhly et al. [95] claim that a slight temperature increase in this situation could improve yields. Consequently, our study documented that Tmax's negative effects were offset by Tmin's positive effects, with the same supported by Turnbull et al. [115] and Bekuma Abdisa et al. [16].

Though the regression coefficients for precipitation were found to be non-significant in both the OGS and SGS (Table 5), the precipitation changing pattern numerically increased oats yield but decreased sorghum yield. The non-significant/weak relationship of yield with precipitation is not uncommon [116–118], because of the increased crops' dependency on better irrigation systems rather than on precipitation [119]. The same is the case with SE-US [43].

3.3. Marginal impact of climate change (1980–2020) on oats and sorghum yield

In oats, the marginal coefficient of regression for both Tmax and Tmin was noted to be significantly (95% confidence level) negative (−0.04 and −0.05), implying that both Tmax and Tmin had negatively affected oats yield *i.e.,* oats yield was reduced by 4% and 5% with every 1 °C rise in Tmax and Tmin, respectively. Consequently, it is inferred statistically that the net 1 °C upsurge in the overall temperature of SE-US during OGS penalized the oats yield by 9%. Klink et al. [85], Sánchez-Martín et al. [88], and Agnolucci et al. [89] also discovered similar results for oats. Sorghum's marginal coefficients of regression were significantly (99% confidence level) negative (−0.07) and positive (0.13) for Tmax and Tmin, respectively, inferring a 7% yield reduction and a 13% yield improvement with each 1 °C increase in Tmax and Tmin. Further examination indicated that the total impact of marginal shift patterns in Tmax and Tmin was beneficial to sorghum yield, which may be inferred statistically as a net 1 °C upsurge in overall temperature ameliorated sorghum yield (by 6%). Adejuwon [108], Msongaleli et al. [110], Bosire [111], and Chadalavada et al. [112] also found similar results in terms of the positive effects of overall temperature-increasing patterns on sorghum. Recently, Mumo et al. [120] estimated that yield increases due to temperature changes in the future could reach up to 80.7% in the case of sorghum (2050–2070), based on the current rate of temperature warming.

There is a clear indication that sorghum benefitted (+13% "*yield improved*") by Tmin (per 1 °C rise) compared to oats (−5% "*yield reduced*"), and hence from overall temperature (+6% "*yield improved*") compared to oats (−9% "*yield reduced*") (Table 6). Therefore, the SE-US changing climate (temperatures) affected oats more harshly than sorghum. This is attributable to the fact that the severity of yield penalty from rising temperatures is proportional to the magnitude and rate of warming during respective growing seasons, which are higher in oats (compared to sorghum) *i.e.*, magnitude (1.20 °C > 1.12 °C) and pace (0.030 °C > 0.028 °C) (Table 4). For C3 crops like oats, the photosynthetic optimal temperature is comparatively lower (20 °C–21.1 °C) [85] than the C4 crops like sorghum (27°C–31 °C) [100,102], making oats more sensitive to rising temperatures. Moreover, at higher temperatures, oxygen has a better binding affinity to CO_2 than RUBISCO reducing photosynthetic activity in C3 plants such as oats.

Although the marginal coefficients for precipitation were calculated as non-significant but positive (0.01) and negative (−0.01) for oats and sorghum, respectively. This indicates a 1% yield improvement in oats and a 1% yield reduction in sorghum with every 1 mm rise in precipitation (Table 6). These results were corroborated by Peltonen [121] and Peltonen-Sainio et al. [122] for oats, and Sharma et al. [123] for sorghum. Overall, the negative effects of elevated warmings (caused by Tmax and Tmin) were not completely offset by precipitation effects; however, precipitation had a minor (non-significant) impact on oats and sorghum production in SE-US.

3.4. Model robustness testing

Following the analysis of the marginal effects using the estimates from the fixed effect panel data (regression) model, it is suggested (in literature) to ensure the robustness and validity of results obtained, for which, there should not be serial correlation and heteroscedasticity in the model [124,125]. Hence, the study conducted two diagnostic tests, namely the Breusch-Godfrey LM test (for serial correlation) to determine whether the error terms of the model's output regression equation are serially correlated with their lag values and the Breusch-Pagan-Godfrey test (for heteroscedasticity) to determine whether the error terms of the model's output regression equation are uniformly scattered or not [125–127]. The results for both statistics are shown in Table 7 about both oats and sorghum. The Breusch-Godfrey LM test result signifies that there is no serial autocorrelation in the model. The Breusch–Pagan–Godfrey test results indicated that the model is free from heteroscedasticity problem.

Table 7
Diagnostic tests for fixed effect model.

Test	Chi^2	Probability value
Oats		
BPG test for Heteroscedasticity	1.83	0.18
BG LM test for serial correlation	3.63	0.97
Sorghum		
BPG test for Heteroscedasticity	29.00	0.41
BG LM test for serial correlation	47.74	0.92

4. Limitations of the study

The present study is limited to explanatory variables such as daily Tmax, Tmin, and precipitation which are most extensively used in climate-crop studies [49,54,58]. However, the additional data on hourly temperature, hours of sunlight, wind speed, and humidity that was not available, may provide a better conceptual insight into the crop-climate link.

5. Conclusions and policy suggestions

The panel data analysis revealed that the SE-US had seen a significant increasing trend in Tavg, Tmax, and Tmin for both OGS and SGS over the past 41 years, but precipitation trends were seen increasing in OGS and decreasing in SGS. The SE-US had asymmetric warming over OGS and SGS (from 1980 to 2020), with 22.22% more nocturnal warming than diurnal warming in OGS but 43.47% more nocturnal warming than diurnal warming in SGS. However, nocturnal warming attributed 58.93% (in SGS) and 55% (in OGS) to overall warming in the SE-US, compared to diurnal warming's 41.07% (in SGS) and 45% (in OGS). The diurnal warming was 17.39% greater in OGS than in SGS. On comparing the pace of warming, the nocturnal and diurnal warming in OGS was 1.22:1, but in SGS it was 1.43:1. As a result, the nocturnal temperature (Tmin) explicates most of the heating upswing trend for the past 41 years of SE-US throughout OGS and SGS. Tmax, Tmin, Tavg, and precipitation have changed by 1.08 °C, 1.32 °C, 1.20 °C, and 23.2 mm in OGS but by 0.92 °C, 1.32 °C, 1.12 °C, and −5.2 mm in SGS over the last 41 years. However, these climatic changes affected oats and sorghum yields differently. Precipitation in the SE-US had a non-significant positive (+1%) and negative (−1%) effect on oats and sorghum yields, respectively. With every 1 °C increase in Tmin and Tmax, oats yield was reduced by (−5%) and (−4%), whereas sorghum yield was increased by (+13%) and decreased by (−7%), respectively. Altogether, a 1 °C net rise in overall temperature reduced oats yield (−9%) while increasing sorghum yield (+6%).

Substantive policy suggestions from this study include the requirement of similar efforts in the future to explore the crop-climate link for other crops of SE-US and then redistribute crop mix and cropland based on the findings. The crops having positive (as sorghum in this study) interaction with the SE-US climate should allocate more cropland and vice versa for the crops like oats showing negative interaction with the local climate.

Declaration of competing interest

The authors of this manuscript have no conflict interests to disclose.

Data availability

Data will be made available on request.

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