Impact of recent climate change on corn, rice, and wheat in southeastern USA

Ramandeep Kumar Sharma1, Sunny Kumar2, Kamal Vatta2, Raju Bheemanahalli3, Jagmandeep Dhillon1✉ & Krishna N. Reddy3

Climate change and its impact on agriculture productivity vary among crops and regions. The southeastern United States (SE-US) is agro-ecologically diversified, economically dependent on agriculture, and mostly overlooked by agroclimatic researchers. The objective of this study was to compute the effect of climatic variables; daily maximum temperature ($T_{\text{max}}$), daily minimum temperature ($T_{\text{min}}$), and rainfall on the yield of major cereal crops i.e., corn (Zea mays L.), rice (Oryza sativa L.), and wheat (Triticum aestivum L.) in SE-US. A fixed-effect model (panel data approach) was used by applying the production function on panel data from 1980 to 2020 from 11 SE-US states. An asymmetrical warming pattern was observed, where nocturnal warming was 105.90%, 106.30%, and 32.14%, higher than the diurnal warming during corn, rice, and wheat growing seasons, respectively. Additionally, a shift in rainfall was noticed ranging from 19.2 to 37.2 mm over different growing seasons. Rainfall significantly reduced wheat yield, while, it had no effect on corn and rice yields. The $T_{\text{max}}$ and $T_{\text{min}}$ had no significant effect on wheat yield. A 1 °C rise in $T_{\text{max}}$ significantly decreased corn (−34%) and rice (−8.30%) yield which was offset by a 1 °C increase in $T_{\text{min}}$ increasing corn (47%) and rice (22.40%) yield. Conclusively, overall temperature change of 1 °C in the SE-US significantly improved corn yield by 13%, rice yield by 14.10%, and had no effect on wheat yield.

Climate change is characterized as substantial long-term shifts in meteorological parameters such as temperature and rainfall1–3. Changing climate is an inevitable phenomenon and its effects are felt across the universe4. This is alarming considering variations in meteorological parameters impact crop production1. This is even more concerning considering that cereal production needs to be increased by 70–100% to ensure food security for the 9.8 billion people by 20508. Cereals provide largest number of calories and nutrients to humans and animals, hence, cover most area than any other crop7. Human intervention via the use of fossils, deforestation, and land-cover alteration, lead to increased production of greenhouse gases, which is the main cause of global temperature increase8,9. Furthermore, throughout the twenty-first century, the duration and intensity of drought have become severe, reducing agricultural water reserves fivefold8. Unabated, global average temperature is expected to rise by 1.50 °C through 205010. By the end of the twenty-first century, this increase could be as much as 3–5 °C at certain locations8. Moreover, the pace of global climate change over the next 20–70 years is expected to be more rapid and intense than in the previous 10,000 years11,12.

The shifting climate constitutes increases in nocturnal and diurnal warming along with irregular rainfall patterns13. Changes in these factors impact cereal production directly via inducing abiotic stresses14 and indirectly via biotic stresses such as insect and weed pests3 pressure, decreased beneficial soil microorganism community, etc.15. Increasing temperature reduces yield by reducing the grain filling period16. Extreme temperatures during the blooming stage also reduce cereal kernel count, thickness, and quality17,18. Timely rainfall could mitigate rising temperature variations, however, extreme fluctuations in rainfall could create significant harvest losses13.

Severity of climate impact on yield differ by crop, geographical location, and magnitude, as well as the direction of shift in the climatic variables19,20. Worldwide climate change impacts are uneven, particularly in nations with vast land areas21,22. Scientific community agrees to some extent that the present trends would be detrimental to the tropical and subtropical areas of Africa, middle east, south, and southeast Asia23–26, and advantageous to Russia, Ireland27, Canada28,29, and Finland30,31 in the context of cereal yield. Similarly, scientists have mixed opinions on climate change impact on US cereal production where Adams et al.32, Knox et al.33, Wolfe et al.34,
and Petersen\textsuperscript{35}, deduced it to be beneficial, and Schlenker et al.\textsuperscript{23}, NDRC\textsuperscript{24}, You et al.\textsuperscript{25}, Raza et al.\textsuperscript{36} and Su et al.\textsuperscript{20} to be detrimental.

Farming in the SE-US may be highly susceptible to changing climate. Prevailing summer daily maximum temperature (T\text{max}) in this region frequently surpasses 32 °C, evaporation outpaces cropping period rainfall, and soils have poor water retention. The viability of agribusiness in the SE-US is dependent on lower capital inputs, eliminating certain choices in reducing the effects of changing climate\textsuperscript{37}. Even though numerous past studies using different crop circulation models have already measured the potential climatic scenarios affecting crop yields at the global scale, regional level inferences, particularly in the SE-US, and on cereal crops remain under-researched\textsuperscript{38}. As a result, the difficulties, and benefits to producers in the SE-US region remain unknown. Therefore, the objective of this study was to investigate and quantify the impact of climate changes (rainfall, T\text{max}, and T\text{min}) in the previous 41 years on corn, rice, and wheat yields in SE-US.

### Material and methods

#### Region and timespan of study.

The SE-US is among the most diverse agro-ecological region, with an economy that largely relies on agriculture\textsuperscript{39,40}. A total of 15.7% of the land area of the SE-US is dedicated to crop production and it constitutes about 13% of total US agricultural land\textsuperscript{41}. Owing to its latitudinal, topographical, and geographical position relative to the Gulf of Mexico and the Atlantic Ocean, the SE-US is overly sensitive to extreme occurrences i.e., rising sea levels, hurricanes, heat waves, and dry spells, which further aggravates the nocturnal and diurnal temperature peaks\textsuperscript{42}. These extreme events or natural disasters occur more frequently in the SE-US than in other parts of the nation altogether\textsuperscript{43,44}. Furthermore, the SE-US groundwater resources are stressed owing to seasonal water scarcity and are expected to worsen by 2050, impacting agricultural production and forestry\textsuperscript{45}.

The study utilized recent 41 years (1980–2020) of data. Generally, a minimum 30-year is required to sufficiently capture climate variations\textsuperscript{46}. As of 1970 in the SE-US, the incidences of average days with temperatures exceeding 95°F and nights above 75°F have increased, while the prevalence of exceptionally cold days has decreased\textsuperscript{47}. Moreover, the study encompassed 1983–2012 period during which the northern hemisphere witnessed the warmest 30 years stretch in the last 800 years\textsuperscript{48}.

#### Data.

This study utilized a panel dataset commonly used in literature\textsuperscript{19–54} to predict the effect of climate change on cereal crop yield. In the panel dataset, the cross-sectional data is spread over a continuous time series\textsuperscript{49,55}. The T\text{max}, T\text{min}, daily average temperature (T\text{avg}), rainfall, and crop yields represent cross-sectional data, and the years (1980–2020) represent the time-series data to complete a panel data set of 451 (row-wise) observations (41 years of data from 11 states), and 15 (T\text{max}, T\text{min}, T\text{avg}, rainfall, and yields × 3 crops) column-wise observations in a fixed-effect model.

The explanatory variables were rainfall, T\text{max}, T\text{min} and the response variables were corn, rice, and wheat yield from the past 41 years (1980–2020) of 11 states of the SE-US region (Table 1; Fig. 1). The yield statistics for each crop were derived from the National Agricultural Statistics Service’s repository\textsuperscript{56}. The county based daily weather data for all states from 1980 to 2020 for each month were collected by accessing US Climate Divisional Database\textsuperscript{57}. This daily weather (T\text{max}, T\text{min} and rainfall) data from all counties where respective crops are grown were averaged. The data source\textsuperscript{57} calculates county values by area-weighted mean of grid point observations.
transcoded from monitoring stations. A nominal 5-km grid-resolution was adopted to confirm spatial suf-
ficiency in sampling.

The data of explanatory variables were collected for all 11 states in the SE-US, however, the response vari-
bles (crop yields) data was collected for the states listed in the respective panel districts column in Table 1. All
states that had their continuous yield statistics available on the USDA-NASS website from 1980 to 2020 for the
required crops (corn, rice, and wheat), were grouped together to form crop-specific panel districts mentioned
in Table 1. The fixed-effect model is not applicable to non-continuous datasets58, as such the entire data was
ensured to be continuously consistent from 1980 to 2020. The corn growing season (CGS) was from March to
September, wheat growing season (WGS) from September to May, and rice-growing season (RGS) from April
to September, respectively, as per the agricultural handbook of USDA on sowing and harvesting dates for field
crop56. The daily temperatures for each crop were converted into the average growing period temperature, and
the daily rainfall was summed to cumulative total rainfall for each crop growing period similar to the calcula-
tions suggested by others51,59.

The results of the collinearity test among explanatory variables are shown in Table 2. Variance inflating factor
(VIF) less than 10 indicates no collinearity among covariances in each  crop60.

| Particulars | VIF | SQRT VIF | Tolerance |
|-------------|-----|----------|-----------|
| WT (min)    | 12.49 | 3.53 | 0.08 |
| WT (max)    | 13.27 | 3.64 | 0.08 |
| WR          | 1.91  | 1.38  | 0.52 |
| Mean VIF    | 9.22  |       |          |
| RT (min)    | 7.43  | 2.73  | 0.13 |
| RT (max)    | 5.75  | 2.40  | 0.17 |
| RR          | 3.87  | 1.97  | 0.26 |
| Mean VIF    | 5.68  |       |          |
| CT (min)    | 13.93 | 3.73  | 0.07 |
| CT (max)    | 12.10 | 3.48  | 0.08 |
| CR          | 2.96  | 1.72  | 0.34 |
| Mean VIF    | 9.66  |       |          |

Table 2. Multicollinearity statistics. WT, RT, and CT represent the Wheat temperature, Rice temperature, and
corn temperature, respectively. WR, RR, and CR represent the Wheat rainfall, Rice rainfall, and Corn rainfall,
respectively. VIF represents Variance inflating factor, and SQRT VIF is square root of VIF.

Panel data approach and analysis. The panel data analysis is an accepted approach to assess the impact
of temperatures and rainfall on crop yields and is widely used61–68. The panel-data model is regarded as superior
to other econometric models, and is robust in the context of heterogeneity verification, increasing the degrees
of freedom, and decreasing correlations between unobserved factors affecting the response variable, yield69,70.

Under the panel-data approach, either a random effect model or a fixed-effect model is generally considered.
Our study utilized a fixed-effect model to account for the relationship between regressors (crop yields) and the
time-independent distinctions of unobserved variables. These time-independent parameters include soil features, topographic factors, and farmers’ self-governing adjustments, for example, altering planting time or cultivars, and varying input amounts due to yearly variations in meteorological parameters. Contrarily, the random-effects model indicates no relation of time-independent attributes with explanatory factors. Fixed-effect model has also been supported by subsequent relevant studies. Panel analysis of data quantifies the impact of climate on agricultural output by calculating a production function using regression. Empirical estimates of such functions, on the other hand, are centered on a panel set of data, which comprises an observational dataset in a single component cross-sectional unit (corn, rice, and wheat yields). The spatially fixed model effects in the panel dataset absorb the region-specific time-dependent determinants of agricultural yields, which might be associated with meteorological variables. Rainfall and temperatures (T_max and T_min) are recognized to be the key factors for crop yield. Hence, the fixed effects panel model used for climate effects in the present study is as follows:

\[ \ln y_{it} = S_i + T_t + \beta X_{it} + \epsilon_{it} \]  

(1)

The states are denoted by i and the time is denoted by t in the above equation. The crop yield in the model is the response variable which is denoted by y, and the fixed effects of the state are denoted by S. The study has a hypothesis that the state fixed effects (S) incorporate all unconsidered state-specific characteristics that change over time, affect yields, and reduce noise caused by extraneous variables in the study model. The yield estimation model has T to symbolize time fixed effects, which might be caused by infrastructural advancement factors, changes in technologies, human assets improvements, etc. The climatic factors are denoted by X, whereas \( \beta \) is related to explanatory variable parameters, and \( \epsilon \) is the random term.

Then, the panel data of T_max, T_min, rainfall, and crop yields were analyzed using Stata” version-16 statistical software. We calculated the magnitude and rate (per year) of change (Table 4) that occurred in climatic variables from 1980 to 2020, during each crop growing season. The annual rate of change is important, as a greater value of climatic variables allows a shorter time for ecosystems for readjustment.

Each crop yield was separately regressed on positive variation in climatic factors during its growing season, and the respective regression coefficients with p values were calculated (Table 5). These coefficients revealed the exact change (increase/decrease) in crop yields due to changes in climatic variables. A series of studies conducted by Schlenker and Roberts, Guiteras, Jacoby et al., and Birthal et al. revealed that the effect of temperature and rainfall on crop yield is generally non-linear. Hence, the squared factor of each climatic variable was introduced along with the climatic variables in the equation to account for this non-linearity issue. These squared terms caused the inordinate variability in yield (y_{it}). The Eq. (1) was transformed to log-linear (logarithmic function) to control the large variability in y_{it}. The coefficients of the log-linear function can be easily interpreted as proportionate changes using marginal effects. Therefore, the marginal effects of temperature and rainfall were determined by calculating the net response of crop yields to climatic factors equating mean average values for each variable in the equation. Then, the net change in crop yield by a 10 mm shift in rainfall and a 1 °C shift in temperatures (T_max and T_min) was mathematically derived.

To determine the pattern in T_max, T_min, and rainfall throughout the crop growing seasons, the log (natural) values of these variables were regressed over time by applying district (state) fixed effects to control the time dependent parameters.

Diagnostic testing. Before applying regression to the fixed-effect model for estimation, a sequence of diagnostic procedures was performed to test assumptions of autocorrelation among individual time-dependent attributes, by the model’s error components. Since every entity is unique, its error, as well as constant term, must be uncorrelated. If error terms correlate, the fixed-effect model is inapplicable, and inferences drawn would be false. There is a chance of non-stationarity with the response (y_{it}) and explanatory variables (temperatures and rainfall) that could lead to an autocorrelation problem, which is a more serious issue with the explanatory variables.

We used the panel unit root tests, such as Levin, Lin, and Chu; Im, Pesaran, and Shin and Fisher-type tests, for testing the stationarity and rejected the null hypothesis for all the series (Table 3). Conclusively, all meteorological variables in the datasets were stationary, and the problem of autocorrelation was non-significant in the data.

Results and discussions

The climatic variations, their effect along with their marginal effect on crop yield are discussed under three different sections i.e., corn, rice, and wheat as follow.

Corn. Changes in climatic variables during CGS. T_max, T_min, T_avg, and rainfall (Table 4) averaged 28 °C, 15.50 °C, 21.70 °C, and 308 mm over the 41-year period, respectively. Between 1980 and 2020 during CGS, T_max, T_min, T_avg, and rainfall had an increasing trend, however, slope was significant for temperatures only (Fig. 2), and all shifted by 0.64 °C, 1.40 °C, 1.02 °C, and 36.3 mm, respectively (Table 4).

During CGS, T_min and T_max contributed 68.63% and 31.37%, respectively, to overall warming (Table 4), indicating that the nocturnal temperature explains the majority of the CGS heating trend, consistent with findings of Peng et al. and Screen. This overall warming could be advantageous or deleterious to crops depending on the growth stage of the crop when it occurs. For example, high temperature during initial reproductive or delayed vegetative corn stages reduce the ripening span, stress the plant, and decrease the overall yield. T_min (0.035 °C per year) changed at a faster annual rate than T_max (0.017 °C per year) and T_avg (0.026 °C per year), indicating that...
the nocturnal warming rate (annual) was 105.90% quicker than the diurnal warming (Table 4). A similar trend in warming was documented in other parts of the US corn belt91, and is continuously progressing with time92–97. Impact of climate change on corn yield. The estimated Tmax and Tmin regression coefficients were significant, indicating temperature to be the major variable affecting corn production in the SE-US (Table 5). The Tmax exhibited a significantly negative regression coefficient meaning a deleterious effect on corn yield (Table 5). Similar results for corn were noted by Stooksbury and Michaels98, Mourtzinis et al.90, and Eck et al.99 in the SE-US. The increased Tmax stimulates water stresses (up to 60%), decreases photosynthetic activity, and negatively affects the antioxidant enzyme in the corn plant100–102. Moreover, the average Tmax of CGS was 28 °C (Table 4) which is greater than the optimum temperature (26.40 °C) for corn103 and is approaching 29 °C which could be detrimental to corn104. The regression coefficient for Tmin was significantly positive (Table 5), implying that Tmin increased corn yield. Similar effects were documented by Stooksbury and Michaels98 in the SE-US, and Chen et al.105. Increased Tmin increases corn kernel weight by remobilizing the stored dry matter from other parts of the plant106. The overall impact of incremental changes in Tmax and Tmin was still beneficial to the corn yield, which may be statistically inferred as every 1 °C increment in net temperature enhances corn yield. The positive effects of Tmin compensated for the negative effects of Tmax on corn, resulting in an overall yield increase. These findings agree with Ruane et al.107, Kukal et al.108, Petersen35, and Ding and Shi109, but contradict Lin et al.110, and Chen Table 3. Various tests to check the stationarity in the data. WT, RT, and CT represent the Wheat temperature, Rice temperature, and Corn temperature, respectively. WR, RR, and CR represent the Wheat rainfall, Rice rainfall, and Corn rainfall, respectively.

| Variables     | Levin-Lin-Chu Unit root test | Im-Pesaran-Shin Unit root test | Fisher-type Unit root test |
|---------------|-----------------------------|-------------------------------|---------------------------|
|               | Unadjusted t | Adjusted T | p value | Unadjusted t | Adjusted T | p value | Unadjusted t | Adjusted T | p value |
|               |               |               |         |               |               |         |               |               |         |
| WT (min)      | − 12.331     | − 8.590      | 0.00    | − 7.806      | 0.00    | 139.966   | 0.00    |
| RT (min)      | − 6.8925     | − 4.853      | 0.00    | − 4.456      | 0.00    | 46.886    | 0.00    |
| CT (min)      | − 9.8770     | − 6.606      | 0.00    | − 7.136      | 0.00    | 122.845   | 0.00    |
| WT (max)      | − 15.165     | − 11.810     | 0.00    | − 9.175      | 0.00    | 188.179   | 0.00    |
| RT (max)      | − 9.153      | − 6.783      | 0.00    | − 5.856      | 0.00    | 76.699    | 0.00    |
| CT (max)      | 15.791       | − 11.738     | 0.00    | − 10.764     | 0.00    | 272.529   | 0.00    |
| WR            | − 15.482     | − 10.00      | 0.00    | − 11.396     | 0.00    | 322.525   | 0.00    |
| RR            | − 7.962      | − 4.828      | 0.00    | − 6.606      | 0.00    | 108.058   | 0.00    |
| CR            | − 14.602     | − 9.118      | 0.00    | − 12.089     | 0.00    | 369.165   | 0.00    |
| Ln (yield wheat) | − 6.019     | − 3.133      | 0.00    | − 6.819      | 0.00    | 127.437   | 0.00    |
| Ln (yield rice) | − 2.982      | − 1.945      | 0.00    | − 1.181      | 0.10    | 10.465    | 0.23    |
| Ln (yield corn) | − 6.726      | − 3.499      | 0.00    | − 7.486      | 0.00    | 152.610   | 0.00    |

Table 4. Overall mean, change and the annual rate of change in temperature and rainfall during different crop growing seasons in the SE-US, 1980–2020. ***Denote significance at 1% level, Figures in parentheses are standard errors.

| Particulars | Tmax (°C) | Tmin (°C) | Tavg (°C) | Rainfall (mm) |
|-------------|-----------|-----------|-----------|---------------|
| Wheat       | 20.0 (0.002) | 7.3 (0.002) | 13.7 (0.002) | 369 (0.027) |
| Change      | 1.12      | 1.48      | 1.30      | 19.2          |
| Annual rate of change | 0.028*** | 0.037*** | 0.033*** | 0.48*** |
| Rice        | 28.9 (0.005) | 16.4 (0.003) | 22.7 (0.004) | 292 (0.035) |
| Change      | 0.64      | 1.28      | 0.96      | 37.2          |
| Annual rate of change | 0.0158 | 0.033 | 0.024 | 0.93 |
| Corn        | 28.0 (0.003) | 15.5 (0.002) | 21.7 (0.003) | 308 (0.021) |
| Change      | 0.64      | 1.40      | 1.02      | 36.3          |
| Annual rate of change | 0.017*** | 0.035*** | 0.026*** | 0.91*** |
et al.\textsuperscript{111}. Disagreement in the literature could be attributable to a number of factors associated with different studies such as different study periods taken, spatial diversity (different growing seasons), the magnitude of change in climatic variables, diversity in crop models, and statistical approaches\textsuperscript{112–116}. Another explanation as per Lobell et al.\textsuperscript{61}, is that if the \( T_{avg} \) of CGS is below the optimum (23 °C), the overall influence of temperature warming will increase yield, and above 23 °C, the yield will drop. In our study \( T_{avg} \) was 21.70 °C (Table 4).

The rainfall regression coefficient (Table 5) and marginal effect (Table 6) were found to be non-significant for corn and the same was noted by Lobell et al.\textsuperscript{117} and Guntukula\textsuperscript{118}. Most of the corn cultivation in the SE-US is based on irrigated systems\textsuperscript{119}, which, according to Chen et al.\textsuperscript{105}, may be the reason for the weak relationship of rainfall with corn yield in most studies.

**Figure 2.** (A) \( T_{max}, T_{min} \), and \( T_{avg} \) showed significant slopes throughout CGS in the SE-US between 1980 and 2020. (B) The rainfall showed a non-significant trend in the SE-US over CGS between 1980 and 2020.

**Table 5.** Regression estimates of the impact of temperature and rainfall on the yield of major cereal crops in the SE-US, 1980–2020. ***Denote significance at the 1% level; C, SE, and RF represent regression coefficient, standard error, and rainfall, respectively.

| Particulars | Wheat \( T_{min} \) (°C) | SE | \( p \) value | Rice \( T_{min} \) (°C) | SE | \( p \) value | Corn \( T_{min} \) (°C) | SE | \( p \) value |
|-------------|-----------------|---|-----------|-----------------|---|-----------|-----------------|---|-----------|
|             | −0.01 0.08 0.89 |   | 0.18***   | 0.29 0.01 0.39*** |   | 0.18 0.01 0.67 |
|             | 0.00 0.00 0.51 |   | 0.00 0.01 0.88 | 0.00 0.00 0.01 0.67 |
|             | 0.14 0.19 0.45 |   | −1.09***  | 0.38 0.01 −1.12*** |   | 0.30 0.01 0.67 |
| RF (mm)     | −0.03*** 0.01 |   | 0.01 0.41 0.01 0.01 | −0.01 0.01 0.02 0.88 |
| RF (Square) | −0.0004*** 0.00 |   | 0.00 0.00 0.00 0.00 0.22 | −0.0003 0.00 0.00 0.24 |
| Constant    | 1.33 1.77 0.45 |   | 22.10 5.11 0.00 | 18.49 3.65 0.00 |
| District    | Yes Yes Yes |   | Yes Yes Yes | Yes Yes Yes |
| Time        | Yes Yes Yes |   | Yes Yes Yes | Yes Yes Yes |
| No of observations | 410 164 451 |   | 164 451 | 451 451 |
Marginal impact of climate change on corn yield. The marginal coefficient of regression (Table 6) for $T_{\text{max}}$ was $-0.34$ (significant), implying a 34% yield reduction for every 1 °C increase in $T_{\text{max}}$. Others have noted a reduction of up to 10%120, 15%90, and 30%121, or even up to 80% in worst scenarios122. The $T_{\text{min}}$ (Table 6) marginal regression coefficient was found to be 0.47 (significant), indicating that every 1 °C increase in $T_{\text{min}}$ increased corn yield by 47%. $T_{\text{min}}$ never reached the threshold that could have shifted $T_{\text{avg}}$ (Table 4) out of the corn optimal range of 20–30 °C, reducing corn yield106,123. Therefore, corn benefited comparatively more from the increase in $T_{\text{min}}$. Moreover, $T_{\text{min}}$ is of greater importance compared to $T_{\text{max}}$ in governing yield-determining developmental and grain filling processes124,125, and $T_{\text{min}}$ impact has a comparatively higher magnitude ($47% > 34%$) in our study results (Table 6). Consequently, the magnitude of the positive effect of $T_{\text{min}}$ surpassed the negative effect of $T_{\text{max}}$ implying that each 1 °C increase in net temperature resulted in a 13% increase in corn yield (Table 6) which is in line with Zhang et al.126 who documented the overall positive effect of an increase in net temperature on corn yield.

Rice. Changes in climatic variables during RGS. Over the 41-year period, the average values (Table 4) for $T_{\text{max}}, T_{\text{min}}, T_{\text{avg}},$ and rainfall were 28.90 °C, 16.40 °C, 22.70 °C, and 292 mm during RGS. $T_{\text{max}}, T_{\text{min}}, T_{\text{avg}}$, and rainfall have all shifted (Table 4) by 0.64 °C, 1.28 °C, 0.96 °C, and 37.2 mm following an increasing trend (Fig. 3) between 1980 and 2020.

### Table 6. Marginal effects of climate change on major cereal crop yields in the SE-US, 1980–2020. ***Denotes significance at the 1% level; C represents the regression coefficient of marginal effects.

| Particulars | Wheat | Rice | Corn |
|-------------|-------|------|------|
| $T_{\text{min}}$ (°C) | $-0.04$ | $-1.27$ | $0.20$ | $0.224^{***}$ | $6.87$ | $0.01$ | $0.47^{***}$ | $13.46$ | $0.01$ |
| $T_{\text{max}}$ (°C) | $0.04$ | $1.44$ | $0.15$ | $-0.083^{***}$ | $-2.48$ | $0.01$ | $-0.34^{***}$ | $-9.15$ | $0.01$ |
| Rainfall (mm) | $-0.0009^{***}$ | $-0.39$ | $0.01$ | $-0.002$ | $-0.61$ | $0.542$ | $-0.01$ | $-3.55$ | $0.21$ |

![Figure 3](https://example.com/figure3.png)
The increase in $T_{\text{max}}$ (0.64 °C) and $T_{\text{min}}$ (1.40 °C) noted during RGS in the SE-US (Table 4) were higher than the global $T_{\text{max}}$ (0.40 °C) and $T_{\text{min}}$ (0.80 °C) increases. In rice, the reproductive phase is undoubtedly more vulnerable than the vegetative phase to these increased temperatures. $T_{\text{min}}$ and $T_{\text{max}}$ contributed 66.70% and 33.30%, respectively, to total warming (Table 4), and a similar asymmetric warming trend was previously confirmed by Donat and Alexander and Peng et al. Overall, the $T_{\text{min}}$ and $P_{\text{avg}}$ rate of change of the RGS heating trends in SE-US. Rainfall has changed by 0.93 mm per year (Table 4). The yearly rate of change of $T_{\text{max}}$ (0.033 °C per year) was greater than the rates of change of $T_{\text{max}}$ (0.016 °C per year) and $T_{\text{avg}}$ (0.024 °C per year), implying that the nocturnal warming ($T_{\text{min}}$) was 106.30% quicker than diurnal warming ($T_{\text{max}}$). These annual rates of increase are unproblematic until they can keep the resulting temperature within the optimal range and below the extreme cardinal value (35 °C). These optimum temperature ranges for rice are 30–32 °C as per TNAU and 22–31 °C as per Yoshida.

**Impact of climate change on rice yield.** The computed $T_{\text{max}}$ and $T_{\text{min}}$ regression coefficients for rice indicated that diurnal and nocturnal temperatures are the most important variables in rice production (Table 5). The calculated regression coefficient for $T_{\text{max}}$ was negative (significant) (Table 5), implying a decrease in rice yield by every 1 °C rise in $T_{\text{max}}$. Zhang et al., Dubey et al., and Guntukula reported similar results where increased $T_{\text{max}}$ lowered rice yield by increasing spikelet sterility. The rise in $T_{\text{max}}$ causes increased plant respiration, evapotranspiration, plant water, and nutrient losses, and decreased crop durations, leading to lower water and nutrient use efficiency in rice. Oh-e et al. concluded that any additional increase in mean $T_{\text{max}}$ above 28 °C could diminish rice yields, and this study noted $T_{\text{max}}$ (Table 4) to be 28.90 °C (> 28 °C), negatively influencing rice yield. The $T_{\text{min}}$ coefficient of regression was significantly positive (Table 5), indicating a significant increase in rice yield for every 1 °C increase in $T_{\text{min}}$. Supporting the findings of Zhang et al., Guntukula, and Tan et al., but contradicting Zhang et al. and Ghadirinezhad and Fallah. However, Cooper et al. found no change in rice yield with rising $T_{\text{min}}$. According to Agrawal et al., the increased $T_{\text{min}}$ had a positive effect over the early, delayed vegetative, or reproductive phases, and a negative effect throughout the ripening phase. Moreover, according to Mohammed and Tarpley and Nagarajan et al., increased $T_{\text{min}}$ between 21 and 32 °C has a negative impact on the plant respiratory system, reducing rice yield, but SE-US $T_{\text{min}}$ average (16.40 °C) (Table 4) was outside this range, and not even hit the threshold level to start impacting rice yields negatively. Therefore, this study revealed that increasing $T_{\text{max}}$ and $T_{\text{min}}$ has a net beneficial effect on rice yield, as indicated by the fact that every 1 °C overall increase in temperature improves rice grain yield. The positive effect of $T_{\text{max}}$ outpaced the negative effect of $T_{\text{min}}$ on rice yield, increasing rice yield. Similar findings showing a net beneficial effect of changing temperatures on rice yield were reported by Kim and Pang, Petersen, and Ding and Shi.

Rainfall increments numerically improved rice yield but were not statistically significant (Table 5). Despite rice's water sensitivity, the impact of rainfall on rice yield was statistically insignificant because most of the rice is grown on assured irrigation systems in the SE-US.

**Marginal impact of climate change on rice yield.** The marginal regression coefficient (Table 6) for $T_{\text{max}}$ in rice was $-0.083$ (significant), indicating a 1 °C surge in $T_{\text{max}}$ significantly decreased rice yield by 8.30%. Contrarily, every 1 °C rise in $T_{\text{min}}$ significantly increased rice yield by 22.40% since the marginal coefficient for $T_{\text{min}}$ was computed as 0.224 (significant). Consequently, the net marginal effect of both $T_{\text{max}}$ and $T_{\text{min}}$ increased the rice yield by 14.10%. These findings are in line with the results of Kim and Pang, who documented a 10–20% increase in rice yield, whereas Saseendran et al. calculated only a 6% net increase. Although statistically insignificant every 10 mm rise in rainfall was found to increase the rice yield by 0.20%.

**Wheat. Changes in climatic variables during WGS.** The average values for $T_{\text{max}}, T_{\text{min}}, T_{\text{avg}}$, and rainfall were noted as 20 °C, 7.30 °C, 13.70 °C, and 369 mm over the 41-year timespan (Table 4). From 1980 to 2020, the $T_{\text{max}}, T_{\text{min}}, T_{\text{avg}}$, and rainfall followed a significant increasing trend (Fig. 4) and shifted by 1.12 °C, 1.48 °C, 1.30 °C, and 19.2 mm (Table 4).

These shifts in warming are comparable with those experienced in other parts of the US and worldwide. $T_{\text{min}}$ and $T_{\text{max}}$ contributed 56.92% and 43.08%, respectively, to overall warming throughout the 41-year period of WGS. This warming could benefit wheat yields in certain environments, but it may diminish yield in areas where optimum temperatures already prevail. The annual rate of change of $T_{\text{min}}$ (0.037 °C per year) was greater than the rate of change of $T_{\text{max}}$ (0.028 °C per year) and $T_{\text{avg}}$ (0.033 °C per year), however, the rainfall changed by 0.48 mm per year. The $T_{\text{min}}$ is increasing at a 32.14% faster rate than $T_{\text{max}}$, implying an unsymmetrical warming trend of 32.14% quicker nocturnal warming than the diurnal warming during WGS. Dhakwa and Campbell noted that asymmetric warming may have a less devastating impact on yield than uniform warming.

**Impact of climate change on wheat yield.** The $T_{\text{max}}$ showed a non-significant but numeric yield gain during WGS. These results are in parallel with the findings of Zhang et al. and Fang et al. who inferred positive effects of $T_{\text{max}}$ on wheat yield. Past studies also showed a weak relationship (insignificant) of $T_{\text{max}}$ with the wheat yield. Normally, $T_{\text{max}}$ above 32 °C during grain filling has a negative impact on wheat yield but this has not been the case with our study, because in the SE-US, these elevated $T_{\text{max}}$ values are likely to occur in July and August and wheat harvesting season ends in May. Although the coefficient of regression (Table 5) for $T_{\text{max}}$ during WGS was also noted to be statistically insignificant, $T_{\text{min}}$ numerically decreased wheat yield. Similarly, past studies also deduced that $T_{\text{min}}$ did not affect wheat yield, but numeric yield reduction was noted by Prasad et al. Moreover, some of the estimated $T_{\text{max}}$ and $T_{\text{min}}$ weaknesses (statistical insignificance) are due to fluctuation during the months of October, November, and December in WGS, not present for maize and rice. The results reported no change in wheat yield by the net effect of $T_{\text{max}}$ and $T_{\text{min}}$ in the SE-US during WGS over the
studied period. Rainfall significantly reduced wheat yield (Table 5), which means that for every 1 mm increase in rainfall, wheat grain yield decreased in SEUS.

**Marginal impact of climate change on wheat yield.** Table 6 indicates that the marginal regression coefficient for Tmin was $-0.04$ implying a 4% reduction in wheat yield with every 1 °C rise in Tmin. Tmax, on the other hand, was 0.04 indicating that every 1 °C rise enhanced yield by 4%. Despite producing statistically insignificant results, the equation's robustness, and coefficient's strength (Table 6) were found to be better in the case of Tmax compared to Tmin indicating that Tmax is comparatively more associated with wheat yield than Tmin. This is in line with the study of Jha and Tripathy who also concluded Tmax to be more impactful than Tmin on wheat yield. The results had shown that there was no change in final wheat yield due to the net effect of Tmax and Tmin.

Rainfall significantly affected wheat yield negatively, but the effect was meager only a 0.09% decrease in wheat yield with every 10 mm rainfall increment as per the marginal regression coefficient ($-0.0009$). These results are in line with the findings of Bhardwaj et al., Ureta et al., and Guntukula who also realized a decrease in wheat yield due to an increase in rainfall.

Furthermore, it is suggested to explore the similar impacts targeting different growth stages of cereals for a more detailed understanding of how this impact varies with the different growth stages for each crop. A more detailed county-wise study for each state could also generate a better understanding of the SE-US agro-climatic scenario.

**Conclusion**

The results of fixed-effect model revealed a significant temporal variability in rainfall and temperatures across the SE-US, and an asymmetrical pattern of nocturnal and diurnal warmings throughout the CGS, RGS, and WGS. Tmin contribution was higher during CGS (68.63% > 31.37%), RGS (66.70% > 33.30%), and WGS (56.92% > 43.08%) than Tmax in overall warming. Furthermore, the rate of increasing Tmin was noted to be 105.90%, 106.30%, and 32.14% higher than the Tmax during CGS, RGS, and WGS, respectively. During CGS, RGS, and WGS, rainfall had shifted by 36.3 mm, 37.2 mm, and 19.2 mm, with annual rates of change of 0.91 mm/year, 0.93 mm/year, and 0.48 mm/year, respectively. Rainfall had a negative (non-significant), positive (non-significant), and negative (significant) effect on corn, rice, and wheat yields, respectively. Overall, climate change in the SE-US had no net effect on wheat yield but significantly increased corn yield by 13%, and rice yield by 14.10%.
Data availability
The data used is collected from National Agricultural Statistics Service’s repository (USDA-NASS) and US Climate Divisional Database, (NOAA).

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References
1. World Meteorological Organization. International Meteorological Vocabulary 2nd edn. (WMO, 1992).
2. Allen, M. Liability for climate change. Nature 421(6926), 891–892 (2003).
3. Werndl, C. On defining climate and climate change. Br. J. Philos. Sci. https://doi.org/10.1093/bjps/axz48 (2020).
4. Baig, I. A. et al. Assessing the long-and short-run asymmetrical effects of climate change on rice production: Empirical evidence from India. Environ. Sci. Polul. Res. 29(23), 34209–34230 (2022).
5. Neupane, D. et al. Does climate change affect the yield of the top three cereals and food security in the world?. Earth 3(1), 45–71 (2022).
6. Ranjan, R. & Yadav, R. Targeting nitrogen use efficiency for sustained production of cereal crops. J. Plant Nutr. 42(9), 1086–1113 (2019).
7. MacCracken, M. C. Prospects for future climate change and the reasons for early action. J. Air Waste Manag. Assoc. 58(6), 735–786 (2008).
8. Patnaik, Z. et al. The fingerprints of climate warming on cereal crops phenology and adaptation options. Sci. Rep. 10(1), 1–21 (2020).
9. IPCC. Summary for Policymakers. Global Warming of 1.5°C: An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways. Context Strength Glob response to Threat. Clim Chang Sustain Dev efforts to eradicate poverty. (World Meteorological Organization, Geneva, 2018). Available: https://www.ipcc.ch/site/assets/uploads/sites/2/2018/07/SR15_SPM_version_stand_alone_LR.pdf.
10. Reddy, K. R. & Hodges, H. F. (eds) Climate Change and Global Crop Productivity (CABI, 2000).
11. National Research Council. Abrupt Impacts of Climate Change: Anticipating Surprises (National Academies Press, 2013).
12. getDescription(13).
13. Malhi, G. S., Kaur, M. & Kaushik, P. Impact of climate change on agriculture and its mitigation strategies: A review. Sustainability 13(3), 1318 (2021).
14. Parashchivu, M., Cotuna, O., Parashchivu, M. & Olaru, A. Effects of interaction between abiotic stress and pathogens in cereals in the context of climate change: An overview. Ann. Univ. Craiova Agric. Montanol. Cadastre Ser. 49(2), 413–424 (2020).
15. Shahzad, A. et al. Nexus on climate change: Agriculture and possible solution to cope future climate change stresses. Environ. Sci. Pollut. Res. 28(12), 14211–14232 (2021).
16. Abendroth, L. J. et al. Lengthening of maize maturity time is not a widespread climate change adaptation strategy in the US Midwest. Glob. Change Biol. 27(11), 2426–2440 (2021).
17. Tashiro, T. W. I. F. & Wardlaw, I. F. The effect of high temperature on kernel dimensions and the type and occurrence of kernel damage in rice. Aust. J. Agric. Res. 42(3), 485–496 (1991).
18. Hutsch, B. W., Jahn, D. & Schubert, S. Grain yield of wheat (Triticum aestivum L.) under long-term heat stress is sink-limited with stronger inhibition of kernel setting than grain filling. J. Agron. Crop Sci. 205(1), 22–32 (2019).
19. Challinor, A. J. et al. A meta-analysis of crop yield under climate change and adaptation. Nat. Clim. Change 4(4), 287–291 (2014).
20. Xu, Y., Gabrielle, B. & Makowski, D. The impact of climate change on the productivity of conservation agriculture. Nat. Clim. Change 11(7), 628–633 (2021).
21. Godee, R. V., Pythier, A. I. & Zander, E. V. Does climate change influence Russian agriculture? Evidence from panel data analysis. Sustainability 14(2), 718 (2022).
22. Guiteras, R. The Impact of Climate Change on Indian Agriculture. Working paper, Massachusetts Institute of Technology (MIT), USA (2007).
23. Schlenker, W., Hanemann, W. M. & Fisher, A. C. Will US agriculture really benefit from global warming? Accounting for irrigation in the hedonic approach. Am. Econ. Rev. 95(1), 395–406 (2005).
24. NDRE. National Development Reform Commission. China’s National Climate Change Program (NDRC, 2007).
25. You, L., Rosegrant, M. W., Wood, S. & Sun, D. Impact of growing season temperature on wheat productivity in China. Agric. For. Meteorol. 149(6–7), 1099–1104 (2009).
26. Carroll, E. et al. The State of Agricultural Commodity Markets 2018: Agricultural Trade, Climate Change and Food Security (CABI, 2018).
27. Holden, N. M., Bretonet, A. J., Fealy, R. & Sweeney, J. Possible change in Irish climate and its impact on barley and potato yields. Agric. For. Meteorol. 116, 181–196 (2003).
28. Brassard, J. P. & Singh, B. Effects of climate change and CO2 increase on potential agricultural production in Southern Québec, Canada. Clim. Res. 34(2), 105–117 (2007).
29. Wang, Z. et al. Modeling impacts of climate change on crop yield and phosphorus loss in a subsurface drained field of Lake Erie region, Canada. Agric. Syst. 190, 103110 (2021).
30. Saarikko, R. A. Applying a site-based crop model to estimate regional yields under current and changed climates. Ecol. Model. 131(2–3), 191–206 (2000).
31. Peltonen-Sainio, P., Jauhiainen, L., Hakala, K. & Öijen, H. Climate change and prolongation of the growing season: Changes in the regional potential for field crop production in Finland. J. Plant Nutr. 103110 (2021).
32. van Vuuren, D. P. et al. Global climate change and US agriculture. Nature 435(7022), 219–224 (1990).
33. Knox, P., Griffin, M., Sarkar, R. & Ortiz, B. V. El Niño, La Niña and Climate Impacts on Agriculture: Southeastern U.S. (United States Department of Agriculture, 2015).
34. Wolfe, D. W. et al. Unique challenges and opportunities for northeastern US crop production in a changing climate. Clim. Change 146(1), 231–245 (2018).
35. Petersen, L. K. Impact of climate change on twenty-first century crop yields in the US. Climate 7(3), 40 (2019).
36. Raza, A. et al. Impact of climate change on crops adaptation and strategies to tackle its outcome: A review. Plants 8(2), 34 (2019).
37. Carbone, G. J. et al. Response of soybean and sorghum to varying spatial scales of climate change scenarios in the southeastern United States. In Issues in the Impacts of Climate Variability and Change on Agriculture (ed. Meers, L. O.) 73–98 (Springer, 2003).
38. Kunkel, et al. Climate of the Southeast U.S. National Climate Assessment, U.S. Global Change Research Program (2012).
39. Asseng, S. Agriculture and climate change in the southeast USA. In Climate of the Southeast United States (eds Ingram, K. T. et al.) 128–164 (Island Press, 2013).
40. Sharma, R. K., Kumar, S., Vatta, K., Dhillon, J. & Reddy, K. N. Impact of recent climate change on cotton and soybean yields in the southeastern United States. J. Agric. Food Res. 9, 100348 (2022).

41. Nickerson, C., Ebel, R., Borchers, A. & Carriazo, F. Major uses of land in the United States, 2007 (No. 1476–2019–2783) (2011).

42. Carter, L. M., Jones, J. W., Berry, L., Burkett, V., Murley, J. F., Obeysekera, J., Sachramm, P. J., Wear, D., Melillo, J. M., Richmond, T. C. & Yohe, G. W. (2014). Southeast and the Caribbean. In Climate Change Impacts in the United States: The Third National Climate Assessment, 396–417 (2014).

43. NOAA. Billion-Dollar Weather/Climate Disasters, List of Events. National Oceanic and Atmospheric Administration. Available online at: http://www.ncdc.noaa.gov/billions/. Accessed 26 January 2022 (2013).

44. Melillo, J. M., Richmond, T. T., & Yohe, G. (2014). Climate change impacts in the United States. Third national climate assessment, 52.

45. Sun, G. Impacts of climate change and variability on water resources in the Southeast USA. In Climate of the Southeast United States (eds Ingram, K. T. et al.) 216–236 (Island Press, 2013).

46. ANL. Argonne National Laboratory. Guidance for Vulnerability and Adaptation Assessments, 205 (US Country Studies Program, Washington, 1994).

47. Kunkel, K. E. et al. Regional climate trends and scenarios for the US National Climate Assessment Part 4. The climate of the US Great Plains (NOAA, 2013).

48. Stocker, T. F. Close Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (2013).

49. Schlenker, W. & Lobell, D. B. Robust negative impacts of climate change on African agriculture. Environ. Res. Lett. 5(1), 014010 (2010).

50. Singh, R., Devi, G., Parmar, D. & Mishra, S. Impact of rainfall and temperature on the yield of major crops in the Gujarat state of India: A panel data analysis (1980–2011). Carr. J. Appl. Sci. Technol. 24(5), 1–9 (2017).

51. Kumar, S. & Sidana, B. K. Climatic variability and its impact on rice and wheat productivity in Punjab. J. Agrometeorol. 19(4), 359–362 (2017).

52. Kumar, S. & Kaur, B. S. Impact of climate change on the productivity of rice and wheat crops in Punjab. Econ. Polit. Wkly. 54(46), 38–44 (2019).

53. Ougdandi, K. & Onyeagahala, P. The effects of climate change on African agricultural productivity growth revisited. Environ. Sci. Pollut. Res. 28(23), 30035–30045 (2021).

54. Eruyugur, O. & Ozokcu, S. Impacts of climate change on wheat yield in Turkey: A heterogeneous panel study. Econ. Yakfasim 27(101), 219–219 (2022).

55. Ahumada, H. & Cornejo, M. Are soybean yields getting a free ride from climate change? Evidence from argentine time series data. Econometrics 9(2), 24 (2021).

56. USDA-National Agricultural Statistics Service (2021). https://www.nass.usda.gov/Publications/Todays_Reports/reports/fcdat e10.pdf. Accessed 29 November 2021.

57. NOAA. National Oceanic and Atmospheric Administration (2021). https://www.ncei.noaa.gov/billions/. Accessed 29 November 2021.

58. Keilbar, G., Rodriguez-Poo, J. M., Soberan, A. & Wang, W. A Projection-Based Approach for Interactive Fixed Effects Panel Data Models. arXiv preprint https://arxiv.org/abs/2201.11482 (2022).

59. Ginbo, T. Heterogeneous impacts of climate change on crop yields across altitudes in Ethiopia. Clim. Change 170(1), 1–21 (2022).

60. Guiteras, R. Major uses of land in the United States, 2007 (No. 1476–2019–2783) (2013).

61. Jacoby, H., Rabassa, M. & Skouas, E. Distributional Implications of Climate Change in India. Policy Research Working Paper No WPS 5623 (World Bank, Washington, 2011).

62. Birthal, P. S., Khan, T. M., Negi, D. S. & Agarwal, S. Impact of climate change on yields of major food crops in India: Implications and welfare impacts on farmers in Senegal: A panel data approach. Agric. Syst. 195, 103309 (2022).

63. Belyaeva, M. & Bokusheva, R. Will climate change benefit or hurt Russian grain production? Statistical evidence from a panel data analysis. Am. J. Agric. Econ. 95(1), 014010 (2013).

64. Ozdemir, D. The impact of climate change on agricultural productivity in Asian countries: A heterogeneous panel data approach. Environ. Sci. Pollut. Res. 6, 1–13 (2021).

65. Tan, B. T., Fam, P. S., Firdaus, R. B., Tan, M. L. & Gunaratne, M. S. Impact of climate change on rice yield in Malaysia: A panel data analysis. Agriculture 11(6), 569 (2021).

66. Rehman, F. U. & Ahmad, E. The effect of climate patterns on rice productivity in Pakistan. J. Agronomy 10(4), 333–336 (2015).

67. Chiputwa, B., Blundo-Canto, G., Steward, P., Andrieu, N. & Ndiaye, O. Co-production, uptake of weather and climate services, and welfare impacts on farmers in Senegal: A panel data approach. Agric. Syst. 195, 103309 (2022).

68. Abbas, S. Global warming and export competitiveness of agriculture sector: Evidence from heterogeneous econometric analysis of Pakistan. Environ. Sci. Pollut. Res. 29, 1–13 (2022).

69. Cui, X. & Xie, W. Adapting agriculture to climate change through growing season adjustments: Evidence from corn in China. J. Agrometeorol. 38–44 (2019).

70. Rehman, F. U. & Ahmad, E. The effect of climate patterns on rice productivity in Pakistan. J. Agronomy 10(4), 333–336 (2015).

71. Isik, M. & Devadoss, S. An analysis of the impact of climate change on crop yields and yield variability. Appl. Econ. 38(7), 835–844 (2006).

72. Cui, X. & Xie, W. Adapting agriculture to climate change through growing season adjustments: Evidence from corn in China. J. Agrometeorol. 38–44 (2019).

73. Rehman, F. U. & Ahmad, E. The effect of climate patterns on rice productivity in Pakistan: an application of Driscoll and Kraay estimator. Environ. Sci. Pollut. Res. 29, 1–12 (2022).

74. Tan, B. T., Fam, P. S., Firdaus, R. B., Tan, M. L. & Gunaratne, M. S. Impact of climate change on rice yield in Malaysia: A panel data analysis. Agriculture 11(6), 569 (2021).

75. Cui, X. & Xie, W. Adapting agriculture to climate change through growing season adjustments: Evidence from corn in China. J. Agrometeorol. 38–44 (2019).

76. Rehman, F. U. & Ahmad, E. The effect of climate patterns on rice productivity in Pakistan. J. Agronomy 10(4), 333–336 (2015).

77. Isik, M. & Devadoss, S. An analysis of the impact of climate change on crop yields and yield variability. Appl. Econ. 38(7), 835–844 (2006).

78. Gunahilaka, R. P., Smart, J. C. & Fleming, C. M. The impact of changing climate on perennial crops: The case of tea production in Sri Lanka. Clim. Change 140(3), 577–592 (2017).

79. Diffenbaugh, N. S., Davenport, F. V. & Burke, M. Historical warming has increased US crop insurance losses. Environ. Res. Lett. 16(8), 084025 (2021).

80. Guiteras, R. The Impact of Climate Change on Indian Agriculture (Department of Economics, University of Maryland, 2009).

81. Jacoby, H., Rabassa, M. & Skouas, E. Distributional Implications of Climate Change in India. Policy Research Working Paper No WPS 5623 (World Bank, Washington, 2011).
82. Crossley, T. E., McDonald, J. T. & Worswick, C. Immigrant benefit receipt revisited: Sensitivity to the choice of survey years and model specification. J. Hum. Resour. 36, 379–397 (2001).

83. Levin, A., Lin, C. F. & Chu, C. S. J. Unit root tests in panel data: Asymptotic and finite-sample properties. J. Economet. 108, 1–24 (2002).

84. Im, K. S., Pesaran, M. H. & Shin, Y. Testing for unit roots in heterogeneous panels. J. Econom. 115, 153–74 (2003).

85. Pesaran, M. H. A simple panel unit root test in the presence of cross-section dependence. J. Appl. Econom. 22, 265–312 (2007).

86. Yin, Y. & Wu, S. Stationarity tests in heterogeneous panels. In Nonstationary Panels, Panel Cointegration, and Dynamic Panels (eds Balatagi, B. & et al. Emerald Group Publishing Limited, 2001).

87. Peng, S. et al. Rice yields decline with higher night temperatures from global warming. Proc. Natl. Acad. Sci. 101, 9971–9975 (2004).

88. Screen, J. A. Arctic amplification decreases temperature variance in northern mid-to-high latitudes. Nat. Clim. Change 4, 577–582 (2014).

89. Range, M. Effects of climate change on cotton growth and development. Aust. Cotton Grower 28(3), 41–45 (2007).

90. Mouritzis, S., Ortu, B. V. & Damianidis, D. Climate change and ENSO effects on Southeastern US climate patterns and maize yield. Sci. Rep. 6(1), 1–7 (2016).

91. Hladik, J. Warming Nighttime Temperatures and Crop Health in the Corn Belt (2012).

92. Karl, T. R., Jones, P. D., Knight, R. W., Kukla, G., Plummer, N., Razuvayev, V., Gallo, K. P., Lindsay, J., Charlson, R. J. & Peterson, T. C. Asymmetric trends of daily maximum and minimum temperature. Nat. Resour. 185 (1993).

93. Alward, R. D., Detling, J. K. & Milchunas, D. G. Grassland vegetation changes and nocturnal global warming. Proc. Natl. Acad. Sci. 102, 223–229 (1999).

94. IPCC Climate change 2001: The scientific basis. Contribution of working group I. In Third Assessment Report of the Intergovernmental Panel on Climate Change (ed. Houghton, J.) 881 (Cambridge University Press, 2001).

95. Peng, S. et al. Asymmetric effects of daytime and nighttime warming on Northern Hemisphere vegetation. Nature 501, 745–746 (2013).

96. Davy, R., Esau, L., Chernokulsky, A., Outten, S. & Zlitininkievich, S. Diurnal asymmetry to the observed global warming. Int. J. Climatol. 37(1), 79–93 (2017).

97. Du, Z., Zhao, J., Liu, X., Wu, Z. & Zhang, H. Recent asymmetric warming trends of day versus nighttime warming and their linkages with vegetation greenness in temperate China. Environ. Sci. Pollut. Res. 26(35), 35717–35727 (2019).

98. Stooksbury, D. E. & Michaels, P. J. Climate change and large-area corn yield in the Southeastern United States. Agron. J. 86(3), 564–569 (1994).

99. Eck, M. A., Murray, A. R., Ward, A. R. & Konrad, C. E. Influence of growing season temperature and rainfall anomalies on crop yield in the southeastern United States. Agric. For. Meteorol. 121, 108053 (2003).

100. Gong, M., Chen, S. N., Song, Y. Q. & Li, Z. G. Effect of calcium and calmodulin on intrinsic heat tolerance in relation to anti-oxidant systems in maize seedlings. Funct. Plant Biol. 24(3), 371–379 (1997).

101. Dhakwa, G. B. & Campbell, C. L. Potential effects of differential day-night warming in global climate change on crop production. Clim. Change 40(3), 647–667 (1998).

102. Ben-Asher, J., García y Garcia, A. & Hoogenboom, G. Effect of high temperature on photosynthesis and transpiration of sweet corn (Zea mays L. var. rugosa). Photosynthetica 46(4), 595–603 (2008).

103. Sanchez, B., Rasmussen, A. & Porter, J. R. Temperatures and the growth and development of maize and rice: A review. Glob. Change Biol. 20(2), 408–417 (2014).

104. Hoffman, A. L., Kemanian, A. R. & Forest, C. E. The response of maize, sorghum, and soybean yield to growing-phase climate revealed with machine learning. Environ. Res. Lett. 15(9), 094013 (2020).

105. Chen, C. et al. Will higher minimum temperatures increase corn production in Northeast China? An analysis of historical data over 1965–2008. Agric. For. Meteorol. 151(12), 1580–1588 (2011).

106. Badu-Apraku, A., Hunter, R. B. & Tollenaar, M. Effect of temperature during grain filling on whole plant and grain yield in maize (Zea mays L.). Can. J. Plant Sci. 63(2), 357–363 (1983).

107. Ruane, A. C. et al. Climate change impact uncertainties for maize in Panama: Farm information, climate projections, and yield sensitivities. Agric. For. Meteorol. 170, 132–145 (2013).

108. Kukal, M. S. & Irmak, S. Climate-driven crop yield and yield variability and climate change impacts in the US Great Plains agricultural production. Sci. Rep. 8(1), 1–18 (2018).

109. Ding, R. & Shi, W. Contributions of climate change to cereal yields in Tibet, 1993–2017. J. Geophys. Res. 32(1), 101–116 (2012).

110. Lin, Y., Wu, W. & Ge, Q. CERES-Maize model-based simulation of climate change impacts on maize yields and potential adaptive measures in Heilongjiang Province, China. J. Sci. Food Agric. 95(4), 2838–2849 (2015).

111. Chen, Y. et al. An assessment of climate change impacts on maize yields in Hebei Province of China. Sci. Total Environ. 581, 507–517 (2017).

112. Tao, F., Yokozawa, M., Xu, Y., Hayashi, Y. & Zhang, Z. Climate changes and trends in phenology and yields of field crops in China, 1981–2000. Agric. For. Meteorol. 138(1–4), 82–92 (2006).

113. Li, X., Takahashi, T., Suzuki, N. & Kaiser, H. M. The impact of climate change on maize yields in China and the United States. Agric. Syst. 104(4), 348–353 (2011).

114. Zhang, J., Yao, F., Hao, C. & Boken, V. Impacts of temperature on rice yields of different rice cultivation systems in southern China over the past 40 years. Phys. Chem. Earth Parts A/B/C 35, 153–159 (2015).

115. Leng, G. & Huang, M. Crop yield response to climate change varies with crop spatial distribution patterns. Sci. Rep. 7(1), 1–10 (2017).

116. Ober, K., Crespo, O., Seid, J. & Mequenat, F. Simulating the impact of climate change on maize production in Ethiopia, East Africa. Environ. Syst. Res. 7(1), 1–12 (2018).

117. Lobell, D. B. et al. The critical role of extreme heat for maize production in the United States. Nat. Clim. Change 3(3), 497–501 (2013).

118. Guntukula, R. Assessing the impact of climate change on Indian agriculture: evidence from major crop yields. I. Public Affairs 20(1), e2040 (2020).

119. USDA-National Agricultural Statistics Service (2022). (https://quickstats.nass.usda.gov/). Accessed 29 March 2022.

120. Hatfield, J. L. & Dold, C. Climate Change Impacts on Corn Phenology and Productivity 95 (Production and Human Health in Changing Climate, 2018).

121. Murray-Tortarolo, G. N., Jaramillo, V. J. & Larsen, J. Food security and climate change: the case of rainfed maize production in Mexico. Agric. For. Meteorol. 253, 124–131 (2018).

122. Hatfield, J. L. & Prueger, J. H. Temperature extremes: Effect on plant growth and development. Weather Clim. Extremes 10, 4–10 (2015).

123. Cairns, J. E. et al. Adapting maize production to climate change in sub-Saharan Africa. Food Secur. 5(3), 345–360 (2013).

124. Lobell, D. B. & Field, C. J. Impacts of day versus night temperatures on spring wheat yields: A comparison of empirical and CERES model predictions in three locations. Agron J. 99(2), 467–477 (2007).

125. Singh, A. et al. Growth phase-specific evaporative demand and nighttime temperatures determine maize (Zea mays L.) yield deviations as revealed from a long-term field experiment. Agric. For. Meteorol. 308, 108543 (2021).
126. Zhang, Y., Zhao, Y. & Sun, Q. Increasing maize yields in Northeast China are more closely associated with changes in crop timing than with climate warming. *Environ. Res. Lett.* 16(5), 054052 (2021).

127. NOAA. *National Oceanic and Atmospheric Administration Global Climate Report—Annual*. (Department of Commerce, U.S.A, 2018). https://www.ncdc.noaa.gov/sotc/global/201813. Accessed 4 April 2022.

128. Xiong, D., Ling, X., Huang, J. & Peng, S. Meta-analysis and dose–response analysis of high-temperature effects on rice yield and quality. *Environ. Exp. Bot.* 141, 1–9 (2017).

129. Donat, M. G. & Alexander, L. V. The shifting probability distribution of global daytime and night-time temperatures. *Geophys. Res. Lett.* https://doi.org/10.1029/2012GL052459 (2012).

130. Yin, X., Kropff, M. J. & Goudriaan, J. Differential effects of day and night temperature on development to flowering in rice. *Annu. Bot.* 77, 203–213 (1996).

131. TNAU. *Tamil Nadu Agricultural University, Agrometeorology: Temperature and Plant growth* (2022) https://agritech.tnau.ac.in/agriculture/agri_agrometeorology_temp.html. Accessed 3 April 2022.

132. Yoshida, S. *Fundamentals of Rice Crop Science* Vol. 22, 1067–1074 (IRRI, Los Banos, 1981).

133. Dubey, A. N., Verma, S., Goswami, S. P. & Devedee, A. K. Effect of temperature on different growth stages and physiological process of rice crop—A review. *Bull. Environ. Pharmacol. Life Sci* 7(11), 129–136 (2018).

134. Oh-e, I., Saitoh, K. & Kuroda, T. Effects of high temperature on growth, yield and dry-matter production of rice grown in the paddy field. *Plant Prod. Sci.* 10(4), 412–422 (2007).

135. Zhang, Y. et al. Effects of high night temperature on yield and agronomic traits of irrigated rice under field chamber system condition. *Aust. J. Crop Sci.* 7(1), 7–13 (2013).

136. Ghadirnezhad, R. & Fallah, A. Temperature effect on yield and yield components of different rice cultivars in the flowering stage. *Int. J. Agron.* https://doi.org/10.1155/2014/846707 (2014).

137. Cooper, N. T. W., Siebenmorgen, T. J. & Counce, P. A. Effects of nighttime temperature during kernel development on rice physiochemical properties. *Cere. Chem.* 85(3), 276–282 (2008).

138. Agrawal, R., Jain, R. C. & Jha, M. P. Models for studying rice crop-weather relationship. *Mausam* 37(1), 67–70 (1986).

139. Mohammed, A. R. & Tarpily, L. Impact of high nighttime temperature on respiration, membrane stability, antioxidant capacity, and yield of rice plants. *Crop Sci.* 49(1), 313–322 (2009).

140. Nagarajan, S. et al. Local climate affects the growth, yield, and grain quality of aromatic and non-aromatic rice in northwestern India. *Agric. Ecosyst. Environ.* 138(3–4), 274–281 (2010).

141. Kim, M. K. & Pang, A. Climate change impact on rice yield and production risk. *J. Rural Dev. Nongchon-Gyeongje* 32, 17–29 (2009).

142. Saseendran, S. A., Singh, K. K., Rathore, L. S., Singh, S. V. & Sinha, S. K. Effects of climate change on rice production in the tropical humid climate of Kerala, India. *Clim. Change* 44(4), 495–514 (2000).

143. Nemani, R. R. et al. asymmetric warming over coastal California and its impact on the premium wine industry. *Clim. Res.* 19(1), 25–34 (2001).

144. Cohen, J. L., Furtado, J. C., Barlow, M., Alexeev, V. A. & Cherry, J. E. Asymmetric seasonal temperature trends. *Geophys. Res. Lett.* https://doi.org/10.1029/2011GL050582 (2012).

145. Ortiz, R. et al. Climate change: Can wheat beat the heat?. *Agric. Ecosyst. Environ.* 126(1–2), 46–58 (2008).

146. Zhang, X. et al. Contribution of cultivar, fertilizer, and weather to yield variation of winter wheat over three decades: A case study in the North China Plain. *Eur. J. Agron.* 50, 52–59 (2013).

147. Fang, S., Cammarano, D., Zhou, G., Tan, K. & Ren, S. Effects of increased day and night temperature with supplemental infrared heating on winter wheat growth in North China. *Eur. J. Agron.* 64, 67–77 (2015).

148. Lobell, D. B. et al. Analysis of wheat yield and climatic trends in Mexico. *Field Crops Res.* 94(2–3), 250–256 (2005).

149. Prasad, P. V., Pujapati, S. R., Rustic, Z., Bukovnik, U. R. S. K. A. & Fritz, A. K. Impact of nighttime temperature on physiology and growth of wheat. *Crop Sci.* 48(6), 2372–2380 (2008).

150. Jha, B. & Tripathi, A. Isn’t climate change affecting wheat productivity in India?. *Indian J. Agric. Econ.* 66, 1–13 (2011).

151. Bhardwaj, M., Kumar, P., Kumar, S., Dagar, V. & Kumar, A. A district-level analysis for measuring the effects of climate change on production of agricultural crops, ie, wheat, and paddy: Evidence from India. *Environ. Sci. Pollut. Res.* 29(21), 31861–31885 (2022).

152. Ureta, C. et al. Maize yield in Mexico under climate change. *Agric. Syst.* 177, 102697 (2020).

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R.S. and J.D. conceptualized and designed the study. R.S. (data collection), S.K., and J.D. performed data analysis. R.S. and J.D. wrote the first draft. K.V., R.B., and K.R. commented on previous versions and wrote the text for the manuscript. All authors read and approved the final manuscript.

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Additional information
Correspondence and requests for materials should be addressed to J.D.

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