Agriculture
and Food

AIMS Agriculture and Food, 3(4): 406–425.
DOI: 10.3934/agrfood.2018.4.406
Received: 23 July 2018
Accepted: 24 October 2018
Published: 06 November 2018

http://www.aimspress.com/journal/agriculture

Research article

American agricultural commodities in a changing climate

Tineka R. Burkhead* and Vincent P. Klink

Department of Biological Sciences, Mississippi State University, Mississippi State, MS, USA

* **Correspondence:** Email: trburkheadsci@gmail.com; Tel: +6625460496.

Abstract: Although climate change research is largely focused on models to predict how environmental conditions will differ in the future, observations from the recent past should be analyzed closely to uncover patterns among temperature, precipitation, and yield. Presented are yield and climate data associated with five American agricultural commodities: corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), rice (*Oryza sativa* L.), soybean (*Glycine max*), and winter wheat (*Triticum aestivum*). Yield data from 2000–2016, departures from usual maximum and minimum temperatures, and drought data are assessed for each crop during its growing season for the top-producing state in the United States. Juxtaposed to temperature and drought data from 2000–2016 are maximum and minimum temperatures from a base period of 1980–1999 to display the degree of change since the new millennium. A correlational analysis between crop yield and Palmer Drought Severity Index (PDSI) was performed for the 2000–2016 timeframe. Of the five crops examined, corn and cotton were statistically significant at the 5% confidence level, indicating a relationship exists between yield and PDSI. In addition to analyses presented, a literature search was conducted to discover other studies on the impacts of climatic factors on these five agricultural commodities and large-scale climate systems.

Keywords: agriculture; climate change; yield; temperature; drought

---

Abbreviations: PDSI: Palmer Drought Severity Index; US: United States; IGSM-CAM: Integrated Global System Model-Community Atmosphere Model; MG: Maturity Group; AT: Ambient Temperature; ENSO: El Niño/Southern Oscillation

1. Introduction

Climate change is currently a booming area of research. The volume of climate change literature is understandable given the past, present, and future impacts on humans, wildlife, plants, and the Earth's biophysical processes. The United States (US), as a frequent site for climate change research, has an array of climatic zones with distinct species unique to each zone; consequently, there is not a universal prediction as to how climate change will affect the zones as a unit [1]. Typically, forecasts are regional rather than national [1]. According to the Massachusetts Institute of Technology's Integrated Global System Model-Community Atmosphere Model (IGSM-CAM), fewer frosts, a lengthened growing season, and a rise in heat stress are expected nationally; however, regional agricultural changes differ based on latitude [1,2]. In New England and the Great Lakes area, fewer frosts are expected resulting in the cultivation of several crops in a single season; by contrast, warmer temperatures may increase insect and disease vulnerability [2]. The southern portion of the country will likely experience more heat stress but no lengthening of the growing season while the western US will probably contend with more heat stress and drought periods in an already arid landscape [2].

As the IGSM-CAM predictions show, temperature is likely to remain a key climatic factor as it has been previously. Over the past hundred years, the temperature in the US has risen 0.6 ℃, but regional differences exist [1]. The Northeast, upper portion of the Midwest, Southwest, and some areas in Alaska have experienced average temperatures nearly 2 ℃ higher over the past century [1]. The Southeast and southern portion of the Midwest cooled slightly over the 1900s; however, since the 1970s, these areas have experienced rising temperatures [1]. From a broader perspective, the five hottest years for the lower 48 states in the US have occurred since 2006 [3]. The warmest year was 2012 with an average annual temperature of 12.9 ℃ [3]. The second and third warmest years were 2016 (12.7 ℃) and 2017 (12.6 ℃), respectively [3]. More staggering is that record high temperatures outnumber record lows by a 3:1 margin [4].

Besides temperature, carbon dioxide concentration is another indicator of climate change. Carbon dioxide, as a greenhouse gas, captures heat near the Earth leading to warming [5]. For the past 650,000 years, the global atmospheric carbon dioxide concentration had not exceeded 300 parts per million (ppm) [6]. The carbon dioxide concentration is currently a little above 400 ppm [7].

In addition to temperature and carbon dioxide, precipitation patterns are expected to change. Over the past century, less precipitation now falls along the East Coast, Rocky Mountains, and the Southwest while more falls on the northwestern, central, and southern portions of the country [4]. Rainfall intensity has strengthened even in areas receiving less precipitation [4]. One metric used to estimate drought is the Palmer Drought Severity Index (PDSI); its range is from −10 (dry) to 10 (wet) [8]. The index is accurate at assessing droughts over an extended period at low and mid latitudes [8]. Because the PDSI has been used for an extended time period since its development in 1965, it has been validated in many instances [9]. Additionally, it incorporates temperature and soil conditions while assuming precipitation is in a readily available form [8,9]. Because it is a standardized index, comparisons among distinct climatic regions are easily performed [9]. The PDSI is separated into categories: extreme drought (−4.00 and below), severe drought (−3.00 to −3.99), moderate drought (−2.00 to −2.99), midrange (1.99 to −1.99), moderately moist (2.00 to 2.99), very moist (3.00 to 3.99), and extremely moist (4.00 and above) [10].

Perhaps the largest impact of climate change might occur on agriculture, which generates economic value and nourishment for citizens across the world. Climate change research on agriculture is most heavily focused on likely effects in developed countries largely because more prosperous nations produce a large portion of agricultural crops due to a more temperate climatic zone [11]. Agriculture, particularly the US agricultural sector, is a vital industry domestically and internationally. The United States exports a little less than $140 billion in agricultural products annually [4]. The most commonly cultivated crops worldwide are wheat, rice, corn, and soybeans; as a group, these four crops account for three-fourths of caloric intake globally [11,12]. The US produces 41% of corn and 38% of soybeans worldwide [13]. To confront the effects of climate change on crops, several strategies have been used including: crop rotation alterations, sowing periods, genetic engineering, fertilizer use, pest control, water use, and changes in the regions of crop cultivation [14]. The methods above have contributed to continued increases in crop production despite increasing temperatures, elevated carbon dioxide, and precipitation changes associated with climate change [14]. Much of the published literature about the relationship between climate change and agriculture is focused on modeling to predict how different regions' crops might be affected. This research avenue is an important component to understand climate change; however, it is crucial to have a retrospective view towards agricultural productivity to observe how it has changed in the past few decades due to the effects of climate change.

Several climatic variables exert effects on plants including temperature, precipitation, carbon dioxide, radiation, humidity, and wind [4]. These variables' impacts on plants differ by plant type [4]. C_3 plants, which are approximately 95% of all plant species, uptake carbon dioxide and form a 3-carbon compound as the first step of carbon fixation [4,15]. C_4 plants, as exemplified by sugarcane and corn, form a 4-carbon compound during the beginning phases of photosynthesis [4].

The uptake of carbon dioxide and the impact on growth varies based on categorization as a C_3 or a C_4 plant [15]. Generally, as the level of atmospheric carbon dioxide increases, plants display increased photosynthesis rates and biomass accumulation [1]. Additionally, the elevated levels of carbon dioxide can cause the partial closing of open stomata on leaves of C_3 and C_4 plants leading to a reduction in transpiration [1,16]. C_3 plants, such as wheat and oats, rapidly respond to elevated carbon dioxide as evidenced by hastened photosynthesis and growth; however, C_4 plants do not respond as strongly [1].

Aside from carbon dioxide, environmental temperatures are fluctuating. Plant growth rates decrease as temperatures rise above the optimum for the species; growth stops at the species' maximum temperature [17]. Above the optimal temperature threshold, yield drops precipitously [4]. Perhaps the most significant temperature is the daily low, which is expected to rise due to climate change [4]. Daily lows impact evening respiration rates and yield [4]. Plants, particularly crops, may be somewhat sensitive to elevated temperatures while in a vegetative state but tend to be extremely sensitive while in a reproductive state [18]. Within the reproductive portion of the life cycle, pollination is an especially vulnerable stage in development as elevated temperatures in the day and evening during this stage can reduce yield [14]. For example, the elevated evening temperatures during the grain-filling stage speed up the rate of grain-filling while shortening the grain-filling stage overall resulting in less productive yields [14]. An offshoot of elevated temperatures may result in the likely range expansion of pests; a 2 ℃ increase in temperature can lead to one to five more generations of insects resulting in lower yields [19].

Alongside temperature, precipitation acts in tandem to impact crop yields [20]. Unsurprisingly, an excess of precipitation can be just as harmful to crops as drought [17]. Erosion, leaching of nutrients and disease are some of the possible consequences [17]. On the other hand, drought can cause disastrous outcomes for the agricultural sector. Drought is a natural hazard whose beginning and end is challenging to determine as its effects are cumulative over time and can have lingering impacts after the drought is considered to be over [9]. For this reason, drought is a 'creeping phenomenon' with far-reaching effects over broad geographical regions [9]. When plants are exposed to drought, the capacity of their leaves to fix carbon is reduced as a result of stomata closing to decrease water loss [21]. Another coping mechanism is leaf senescence [22]. By losing older leaves, plants can redistribute resources to younger leaves [22]. As more leaves senesce, fewer sugars are synthesized, which can lead to a reduction of fruit produced during the dry conditions [22].

An interesting web exists among temperature, precipitation, and growth. Rising air temperatures allow for crops to be planted sooner in spring given that the soil moisture and temperature are conducive, leading to a longer growing season [4]. An elongated season results in more weeks to accumulate biomass provided temperatures remain optimal; at the same time, elevated temperatures increase the amount of water crops need [4]. Irrigation is one method to combat the effects of climate change as well-irrigated plants in a dry area may experience conditions 10 ℃ cooler than the measured air temperature due to evapotranspiration [4]. In the US, about 80% of consumptive water use is for agricultural purposes; in the western states, the amount is over 90% [23]. In 2012, about 7.6% of agricultural lands for crops and pasture was irrigated [23]. Almost three-fourths of irrigated acres of land were in the West [23]. Thirteen states were responsible for 78.8% of irrigated land in 2012, including Nebraska (14.9%), California (14.1%), Arkansas (8.6%), Texas (8.0%), Idaho (6.0%), Kansas (5.2%), Colorado (4.5%), Montana (3.4%), Mississippi (3.0%), Washington (2.9%), Oregon (2.9%), Florida (2.7%), and Wyoming (2.6%) [23]. In 2012, 24.5% of irrigated acres in the seventeen western states was cultivated with corn, and 24.5% was cultivated with forage [23]. The third highest percentage was 9.8% of irrigated land as orchards [23]. The remainder of the lower 48 states was planted with soybeans (29.6%), corn for grain (24.3%), and rice (13.1%) [23]. As the aforementioned data show, irrigation is essential for US agricultural productivity.

This article aims to address the observed effects of climate change on five American agricultural commodities: corn, cotton, rice, soybean, and winter wheat. By performing a correlational analysis between crop yields and PDSI from 2000–2016, the relationship between the two can be assessed. Crop yield and climate data juxtaposed to temperature and precipitation means of the base period (1980–1999) may display how climate change has concretely altered yields in the past few decades. Bolstering the findings presented are results of numerous studies conducted that display the influence of temperature and precipitation by crop and location.

2. Materials and methods

Using the United States Department of Agriculture's database, the state with the largest yield for each of the five crops was chosen as a study area to examine how yields have varied over time. Maximum temperatures, minimum temperatures, and PDSI data from 2000–2016 for the highest-yielding state were collected from the National Centers for Environmental Information database for corn, cotton, rice, soybeans, and winter wheat. Additionally, temperature and drought data from a base period of 1980–1999 were collected from the same database. A correlational analysis, specifically Kendall's tau correlation coefficient, was performed for each crop using two variables, yield and PDSI, to observe any association given the importance of water to agricultural productivity. To perform the analysis, SPSS Statistics® (IBM, version 25) and MedCalc® (MedCalc Software, version 18.10) were used.

3. Results and discussion

3.1. Major agricultural crops

3.1.1. Corn

American farmers cultivate and export more corn (*Zea mays* L.) than any other nation [24]. Over 80% of American corn is cultivated in the Corn Belt with Iowa as the top producer [25]. Iowa has a humid climate with a loam and silty clay loam soil type that requires little irrigation; however, corn can be affected by drought [24]. According to the USDA [25], Iowan corn is planted from April 19 to May 26; harvest occurs from September 21 to November 21.

The climatic variables that exert the greatest impact on yield are precipitation and temperature; both are largely responsible for annual yield fluctuations [26]. During 2000–2016, the trend of Iowan corn yields was positive. Each year represents an average of a given climate parameter (minimum temperature, maximum temperature, and PDSI) for the growing season from earliest planting date to the latest harvesting date. The growing season of corn in Iowa is from April through November [25]. PDSI, as a measure of drought, fluctuated substantially from the driest in 2012 (−3.24) to the wettest in 2010 (5.48) [27]. The third lowest yield occurred in 2012. Compared to the base period of 1980–1999, the PDSI in 2012 was 4.44 lower, indicating a serious drought [27]. The 2012 maximum temperature (23.1 ℃) was about 2.1 ℃ higher while the minimum temperature (9.3 ℃) was approximately 0.4 ℃ higher than the base period averages [27]. The PDSI assessments of the past three years (2014–2016) indicate moist conditions; to remedy water stress, many Iowan farmers have installed subsurface drainage infrastructure to remove excess water from fields [14]. Despite PDSI and yield fluctuations, as Figure 1 shows, a positive relationship exists between Iowan corn yield and PDSI, $\tau = 0.515$, 95% bootstrap confidence interval [0.164, 0.742], $p = 0.0045$. The importance of precipitation in adequate amounts at particular times during corn's growing season is the subject of a set of experiments by Hu and Buyanovsky [26].

Hu and Buyanovsky [26] examined high corn-yielding years and low corn-yielding years in Missouri. Several patterns became evident in years with high yield. Low precipitation in April with a greater amount from May to August before a reduction in September and early October contributes to a higher yield [26]. As for temperature, elevated temperatures from April to June before a period of cooler temperatures from July to August stimulates yield [26]. Essentially, warmer and drier conditions in April and May with moist and cool conditions in July and August represent an optimal scenario for corn growth [26]. During the growing season, 105 mm of precipitation fell during high-yielding years with a mean temperature of 20.7 ℃ whereas 100 mm of precipitation fell during low-yielding years with an average temperature of 20.5 ℃ [26]. The substantial difference in yield despite miniscule disparities in average precipitation and temperature suggest monthly differences in precipitation and temperature are responsible for the differing yield [26]. Dry Aprils are conducive to sowing, and elevated temperatures reduce the likelihood of frost damage to corn seeds, resulting in germination [26]. The dryness causes the seedlings to develop an extensive root system [26]. After sowing, precipitation increases in May as does temperature [26]. From late June to August, precipitation is abundant, but the temperature decreases [26]. The cool and moist environment stimulates important growth stages of silking and kernel filling, which are crucial to productive yield [26]. Lastly, September and October are dry and warm, which favors ripening of corn [26]. Essentially, successful corn harvests result from ideal environmental conditions on a monthly timeline. While Hu and Buyanovsky [26] focused on the monthly conditions for yield, other studies have examined the importance of optimal temperatures and precipitation across the growing season as a whole for successful corn harvests.

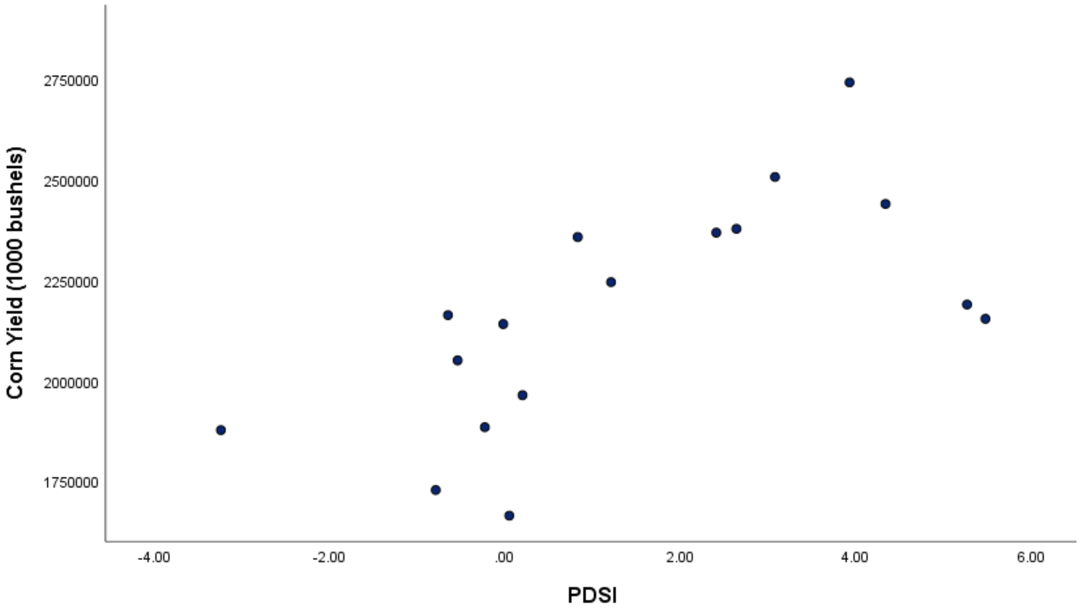

Figure 1. Iowa corn yield and drought index. The annual corn yield of Iowa is represented in a unit of 1000 bushels. The scatterplot shows the statistically significant relationship between corn yield and PDSI from 2000–2016 [27–33].

A study was conducted to examine the relationship between climatic factors and yield of corn using data from 1982–1998 [34]. Temperature, rainfall, solar radiation, and yield data were examined from two areas, one in the Midwest and a smaller area in the Northern Great Plains [34]. Spatial differences emerged as the Midwestern yield increased during cooler, moist years as compared to the Northern Great Plains yield flourishing during warmer, dry years [34]. Through statistical analysis, about 25% of corn yield variation can be attributed to temperature changes from 1982–1998; however, no significant relationship was observed between rainfall or solar radiation with corn yield [34]. This finding of no significant relationship between corn yield and rainfall is directly opposed to our finding of a statistically significant relationship between Iowan corn yield and PDSI from 2000–2016. The discrepancy could be explained due to temperature, precipitation, and irrigation differences between the two timeframes given the findings by Kukal and Irmak [35].

A broader, more recent analysis was performed using agricultural and climate data from the Great Plains from 1968–2013 [35]. About 46% of US corn is grown in this region [35]. Over this timeframe, elevated temperatures adversely impacted corn yields in eastern Nebraska and Iowa, with up to a 22% yield reduction with a 1 ℃ increase in temperature [35]. In western Nebraska and eastern North Dakota, a temperature increase positively impacted corn yields [35]. Over this time period, sensitivity to precipitation increased for non-irrigated crops as opposed to irrigated crops [35]. Non-irrigated corn became 43 times more sensitive than irrigated corn [35]. Kukal and Irmak's [35] results display the sensitivity of corn has increased over time bolstering our results of a positive association between corn yield and PDSI.

Leng et al. [13] analyzed the relationship among temperature, precipitation, and radiation to assess their impacts on US corn on a county-level scale in the lower 48 states from 1983–2012 over the growing season from June to August [13]. Across the country as a whole, precipitation and temperature together accounted for 35% of variability in corn yields; by incorporating radiation as a factor with precipitation and temperature, 40% of corn yield variability was explained [13]. Each region of the US typically has one or more primary factors that exert the greatest influence on yield [13]. In the Central Great Plains, temperature was the primary factor for corn yield variability at the 90% confidence level [13]. In 20% of counties, particularly in the Southeast, precipitation was the primary factor for corn variability [13]. Overall, temperature was the primary factor influencing 20% of corn-cultivating counties, which contributed 30% of US corn yield [13]. In opposition to our findings, neither the maximum nor minimum temperature was associated with yield to a statistically significant degree; however, PDSI does incorporate both temperature and moisture [8].

Moreover, an Indiana corn yield study found an inverted U-shape best characterizes the relationship between yield and precipitation during the growing season using data from 1950–2005 [11]. Two possible reasons for this relationship are more irrigation in years with less precipitation and the development of drought-tolerant corn cultivars [11]. Similar to most crops, corn has an optimal water range, and adverse effects can result when exposed to water levels outside its range.

3.1.2. Cotton

The majority of cotton cultivated in the United States is Upland cotton (*Gossypium hirsutum* L.) and is produced largely in Texas as it tends to be more tolerant of higher temperatures [4,11,25,36]. Upland cotton has a staple length of 2.54–3.175 cm [25]. Although cotton is grown throughout Texas, the South Plains region is the largest cotton-producing area in the state [37]. The South Plains region is composed of 19 counties north of Caprock Escarpment with a focus at Lubbock [37]. The average temperature in the region is 22.8 ℃ from May through October; average annual precipitation is 457.2 mm per year from May through September [37]. According to the USDA [25], cotton is planted from March 22 to June 20 with harvesting from August 10 to January 11.

Similar to other crops, cotton is vulnerable to elevated temperatures above its optimum range and drought at all stages of development; however, the reproductive stage is when the crop is most vulnerable [4,38]. Drought can negatively impact yield via a decrease in photosynthesis [39]. As Figure 2 shows, a positive relationship exists between cotton yield and PDSI, $\tau = 0.406$, 95% bootstrap confidence interval [0.141, 0.687], $p = 0.0256$. From 2000–2016, cotton yield in Texas was at its lowest level in 2011. The PDSI for 2011 (−6.24) displays the state was gripped by extreme drought [27]. Compounding the drought was elevated maximum and minimum temperatures during the growing season of March to January. Compared to the base period of 1980–1999, the maximum temperature (28.4 ℃) in 2011 was 2.7 ℃ higher with a minimum temperature increase of

1.1 ℃ [27]. Despite the shifts in PDSI and elevated maximum and minimum temperatures, the overall trend for Texas cotton yield over the past 16 years is slightly positive.

Several experiments have been conducted on cotton's response to temperature, which is a component of PDSI. One particular study was conducted on cotton in growth chambers. Cotton was cultivated for four weeks to the pinhead square stage in growth chambers set to a day temperature of 32 ℃ and a night temperature of 24 ℃ [40]. After four weeks elapsed, the plants were separated into two groups with one group experiencing the same conditions as the previous four weeks [40]. The other group was exposed to 32 ℃ during the day and 30 ℃ at night [40]. Plants exposed to 30 ℃ at night exhibited fewer flower buds, nearly half the number of flower buds relative to plants grown at 32 ℃ during the day and 24 ℃ at night [40]. These results display the effects of elevated nighttime temperatures on reproduction.

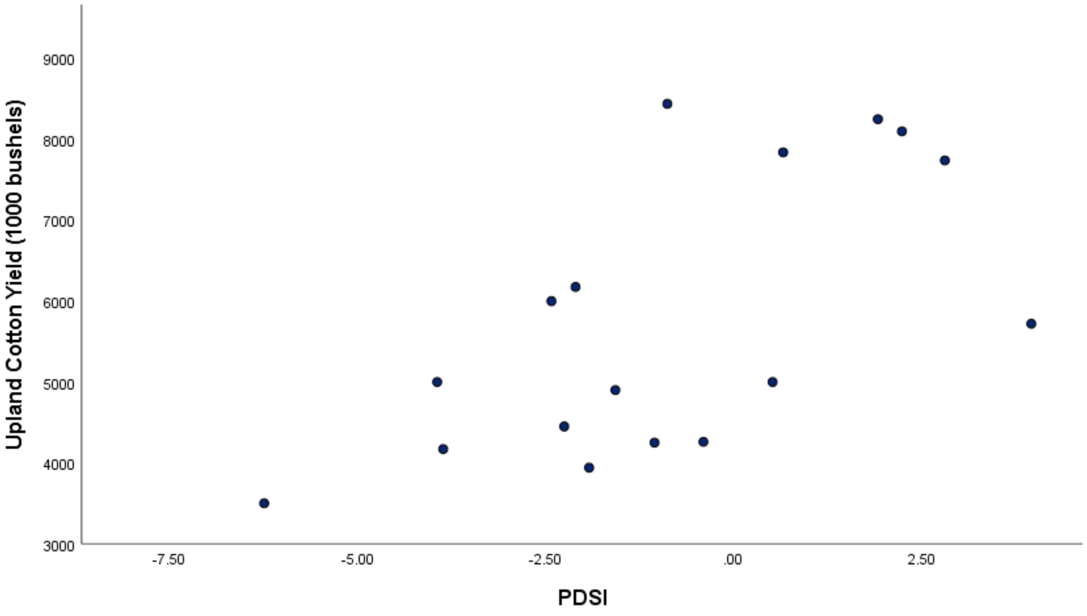

Figure 2. Texas cotton yield and drought index. Cotton yield is represented in a unit of 1000 bushels. The figure displays the statistically significant association between cotton yield and PDSI over the 16 year period [27–33].

A more extensive cotton study was carried out at the experimental station of Wulanwusu in northwest China in well-irrigated fields [41]. The region experiences short, hot, and dry summers [41]. In spring and fall, low nighttime temperatures restrict yield; as such, only cultivars that mature early can be grown [41]. The purpose of the study was to assess the impact of climate variability on each stage of cotton growth and yield during 1981–2010 at the experimental station [41]. Cotton growth stages include planting seeds, seedling emergence, three-leaf phase, five-leaf phase, budding, anthesis, complete bloom, cleft boll, unfurling of bolls, filling of bolls, and termination of growth [41]. Researchers found that each growth stage occurred sooner over the 1981–2010 timeframe [41]. Each stage from planting seeds to complete bloom was statistically significant; however, phases from the cleft boll stage to termination of growth were not significant [41]. Of all the stages, seedling emergence occurred most in advance by 0.873 days per year [41]. After examining the relationship between growth stage and average monthly temperature, stages from planting seeds to complete bloom were negatively associated with average monthly temperature [41]. Growth stages occurred sooner by approximately 2.17–4.76 days for a 1 ℃ increase in average monthly temperature [41]. The only growth stage positively correlated to average monthly temperature was growth termination, which was delayed by 3.46 days for every 1 ℃ increase in minimum temperature during October [41]. For every 1 ℃ increase in average monthly temperature during October, growth termination was prolonged by 2.49 days [41]. Table 1 shows the yield change categorized by growth stage after exposure to a 1 ℃ increase in minimum, maximum, and mean temperatures [41]. A 1 ℃ increase in temperature resulted in yield reductions from seedling emergence to the three-leaf phase [41]. The same degree of temperature increase resulted in positive yield changes during the other growth stages [41].

Table 1. Effects of elevated temperature on Chinese cotton yields.

Growth Stage	1 ℃ Increase in T_{min}, T_{mean}, and T_{max}	Correlation Coefficient (*R*)	Yield Change (kg/ ℃ ·hectare)
Seedling emergence to three-leaf phase	$T_{mininum}$	−0.506	−443.09**
	T_{mean}	−0.546	−425.08**
	$T_{maximum}$	−0.587	−429.12**
Complete bloom to cleft boll	$T_{mininum}$	0.423	229.02*
	T_{mean}	0.427	338.75*
Unfurling of bolls to termination of growth	$T_{mininum}$	0.392	218.03*
	T_{mean}	0.406	188.38*

Notes: 1. T_{max} refers to maximum temperature, and T_{min} refers to minimum temperature while T_{mean} is average temperature.

2. * indicates significance at $p < 0.05$, and ** indicates significance at $p < 0.01$. 3. Table is adapted from [41].

3.1.3. Rice

Rice (*Oryza sativa* L.) is cultivated worldwide in tropical and semi-tropical areas in well-irrigated soils [42−44]. Rice is a primary food source for approximately 1.6 billion, and another 400 million consume it as one-fourth to one-half of their caloric intake [15]. In the United States, rice is cultivated in three primary regions: coastal prairies of southwestern Louisiana and southeastern Texas; eastern Arkansas, southeastern Missouri, and northwestern Mississippi; and the Sacramento and northern San Joaquin Valleys of California [25]. Of the three regions, Arkansas produces the most rice [25]. According to the USDA [25], rice is planted from April 6 to June 2 with harvest occurring from August 29 to October 24.

As a water-intensive crop, rice is uniquely susceptible to drought [4]. Morphological manifestations of drought stress in rice are a decrease in germination rate, a decrease in plant height and growth rate, and increase in number of rolled leaves [45]. No statistically significant relationship exists between rice yield and PDSI likely due to prolonged irrigation despite precipitation levels (Figure 3). The lowest rice yield in the past 16 years occurred in 2011 during a moderate drought as indicated by a PDSI of −2.05 [27]. The 2011 maximum and minimum temperatures during the April to October growing season increased relative to the 1980–1999 base period [27]. The 2011 maximum temperature (29.5 ℃) was 1.4 ℃ higher with a minimum temperature (16.1 ℃) about 0.7 ℃ higher [27]. Overall, Arkansas rice yield has been relatively stable over the past 16 years.

A study conducted in China assessed the relationships between climatic factors and grain yields in China from 1980–2008 [47]. Similar to other geographic areas, temperatures in China increased during this timeframe, especially minimum temperatures in nine of twelve provinces [47]. Yearly precipitation shifts were not statistically significant, but the Heilongjiang and Sichuan Provinces experienced 30 mm less per decade [47]. Spatial differences were observed in rice yields with increasing daytime and nighttime temperatures [47]. As minimum temperatures increased, rice yield was reduced in the Shaanxi Province but increased in the Heilongjiang, Yunnan, and Guangxi Provinces [47]. Overall, in 14.8% of rice-growing areas, yield increased after exposure to elevated nighttime temperatures whereas elevated daytime temperatures decreased yield 20.7% [47]. The influence of precipitation exhibited a stronger effect on yield than temperature on a crop-specific and locale-specific basis [47]. Rice yield decreased with more precipitation affecting 32.5% of growing areas; this reduction was observed in central and southern China where yearly precipitation totals are more than 1000 mm per year [47]. Like corn, rice has an optimal water range. Although it is sensitive to drought, excess water can be just as disastrous for successful harvest. Because of this, rice farmers in the US must maintain their fields at a midpoint between drought and flooded conditions.

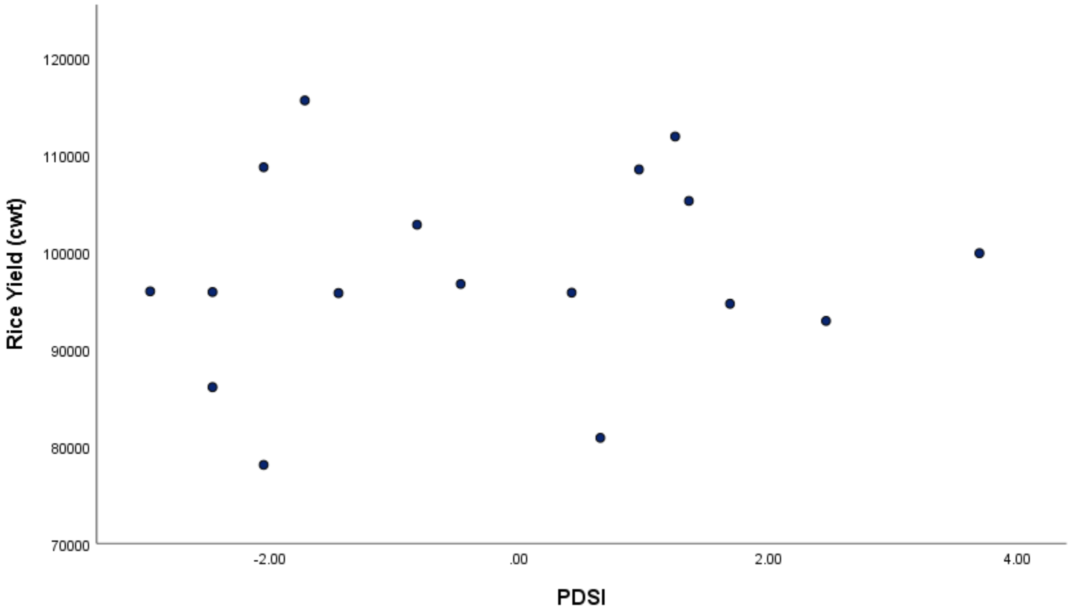

Figure 3. Arkansas rice yield and drought index. Yield is expressed in hundredweight (cwt). A hundredweight is equivalent to 45.36 kg of whole or broken and unhulled rice [46]. The scatterplot shows the non-statistically significant relationship between rice yield and PDSI [27–33].

Although precipitation and temperature act in tandem to influence yield, each exerts individual control. Rice was cultivated hydroponically in growth chambers with four day/night temperature combinations: 19/16 ℃, 25/19 ℃, 30/24 ℃, and 37/31 ℃ [48]. The highest photosynthetic assimilation rate was 30–35 ℃ [48]. The greatest amount of biomass accumulation was at 30/24 ℃; accumulation decreased at 19/16 ℃ to a level 16% of the accumulation of plants grown at 25/19 ℃, indicating the crop is suited to tropical and semi-tropical temperatures [42,48].

While Nagai’s [48] experiment focused on overall growth, Jagadish et al. [44] focused on rice reproduction. An experiment was performed on two subspecies of rice, indica and japonica [44]. A lowland indica, IR64, and an upland japonica, Azucena, were exposed to a series of temperature regimes during their reproductive stage to assess the impact of temperature on reproductive capability [44]. At a control temperature of 29.6 ℃, the average number of spikelets (rice flowers) approaching anthesis for IR64 over the first three days of flowering was 49.7 [44]. For Azucena, there were 44.3 spikelets approaching anthesis [44]. At an elevated temperature of 36.2 ℃, statistically significant results were observed as the number of IR64 and Azucena spikelets dropped to 59.3 and 28.3, respectively [44].

3.1.4. Soybean

Soybean (*Glycine max*) is the most commonly cultivated legume in the world [49]. Most commonly, soybeans are grown for oil and meal [25]. In the United States, soybeans are primarily cultivated in the Corn Belt and the Lower Mississippi Valley [25]. Iowa frequently is the country’s top soybean producer; however, Illinois eclipses Iowa in some years [28–33]. According to the USDA [25], Iowan soybeans are planted from May 2 to June 16 and harvested from September 21 to October 31.

Like other agricultural commodities and crops generally, precipitation and temperature exert effects on yield. Of note, Iowan soybean farmers experienced the second lowest yield in 2012. In 2012, the state’s PDSI during the May to October growing season was −3.35, indicating a severe drought [27]. The 2012 maximum temperature (26.2 ℃) and minimum temperature (12 ℃) were 1.9 ℃ and 0.2 ℃ above the base period maximum and minimum temperatures, respectively [27]. Overall, no statistically significant association was observed between soybean yield and PDSI possibly due to irrigation or some combination of climatic factors (Figure 4).

About 36% of soybean grown in the US is found in the Great Plains [35]. Yield and climate data from 1968–2013 was analyzed during a regional study [35]. Soybean yield was positively affected by elevated temperatures in central Nebraska and eastern South Dakota; however, yields in Kansas were negatively impacted [35]. Moreover, sensitivity to precipitation was 3.6 times higher for non-irrigated soybean than irrigated soybean [35]. More irrigated acres of soybean could explain the lack of association between yield and PDSI.

As the focus of a national study, Leng et al. [13] analyzed the impact of climatic factors on soybean yield in the contiguous US from 1983–2012 over the June to August growing season. Across the nation, precipitation and temperature accounted for 32% of soybean yield variability; by incorporating radiation as a factor, the percentage increased to 37% [13]. Most of the areas where precipitation was the most significant factor for soybean yield variability were located in North Dakota, Nebraska, and Kansas [13]. As a single factor, precipitation was most significant in 24% of counties, representing 20% of US soybean production [13]. Temperature was the primary factor in Arkansas, North Carolina, and Nebraska [13].

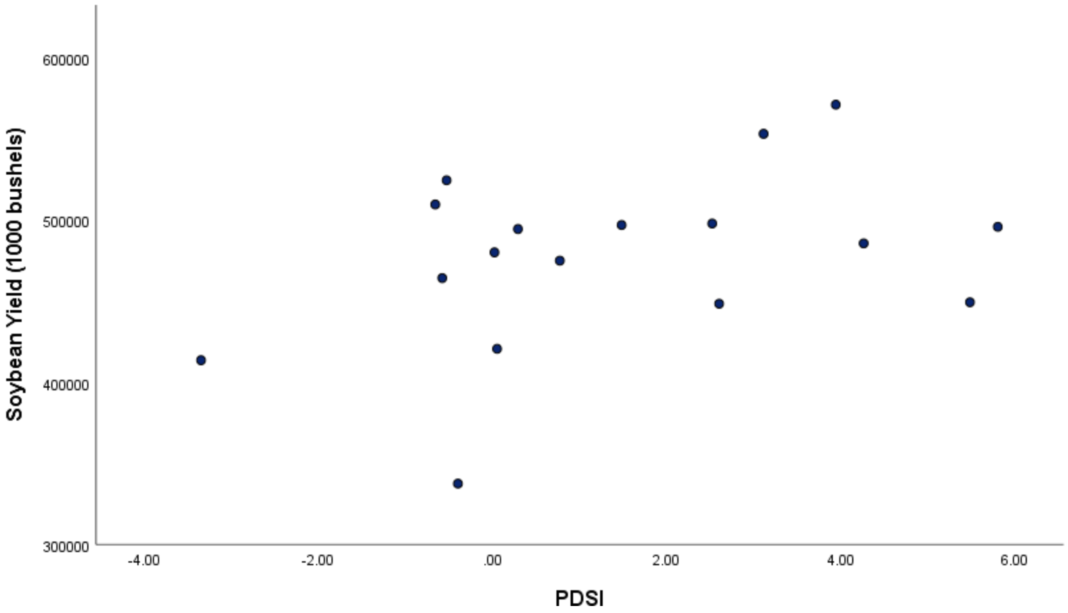

Figure 4. Iowa soybean yield and drought index. All data shown is based on Iowan yield and climate information; however, Illinois was the top producer of soybeans in 2003, 2013, 2014, and 2016 [27–33]. The figure displays the non-statistically significant association between soybean yield and PDSI.

To further illustrate the impact of temperature on yield, a study was conducted on a farm in the North China Plain where seeds were sown on June 1 and harvested on October 6 [49]. A treatment group of soybeans was exposed to a mean plant canopy temperature of 29.5 ℃ via the use of heaters with a range of 17.9–37.3 ℃ while the control group experienced a mean temperature 0.4 ℃ lower [49]. One temperature sensor was placed in the soybean canopy to measure air temperature while another sensor was placed 10 cm below the surface of the ground to measure soil temperature [49]. Throughout the study, soybean canopy temperature increased from flowering to the setting of pods before declining until the maturity phase [49]. The mean soil temperature for the treatment group was 27.5 ℃ with a range of 20.6–34.2 ℃; the mean soil temperature for the control group was 0.7 ℃ lower than the treatment group's mean [49]. Elevated temperatures over 30 ℃ decreased seed yield by 45%, increased the rate of flowering by 3.8 days, and decreased the length of the entire growth stage by 4.5 days [49]. These results indicate the temperature threshold for soybean productivity and impacts on reproduction.

Moreover, to assess the impact of temperature on seed yield across a span of four years, researchers in South Korea chose the Sinpaldalkong [maturity group (MG) IV] and Daewonkong (MG IV) soybean cultivars [50]. Seeds were sown in pots in the middle of June [50]. Four temperature regimes were chosen: ambient temperature (AT), 1.5 ℃ above AT, 3.0 ℃ above AT, and 5.0 ℃ above AT for each cultivar [50]. In 2009, AT was 22.1 ℃; AT in 2013 was 23.9 ℃ [50]. In 2014, AT was 22.9 ℃; a year later, AT was 24.0 ℃ [50]. As Table 2 shows, the cultivars were not statistically different in seed yield at any temperature regime, except AT + 5.0 ℃ [50]. For the two cultivars, seed number per pot increased at AT + 3.0 ℃ compared to seed number at AT [50]. At AT + 5.0 ℃, seed number per pot decreased to a level lower than that at AT [50].

Table 2. Effects of elevated temperatures on South Korean soybean seed yields.

Cultivar	Temperature	Seed Number (per pot)	Seed Yield (g per pot)
Sinpaldalkong	AT	174a	33.4a
Sinpaldalkong	AT + 1.5 ℃	180a	33.0a
Sinpaldalkong	AT + 3.0 ℃	186a	33.8a
Sinpaldalkong	AT + 5.0 ℃	130b	24.7b
Daewonkong	AT	134b	34.7b
Daewonkong	AT + 1.5 ℃	155a	38.0a
Daewonkong	AT + 3.0 ℃	155a	37.2a
Daewonkong	AT + 5.0 ℃	127b	32.0b

Notes: 1. Different letters represent significance at a 5% confidence level. 2. Table is adapted from [50].

3.1.5. Winter wheat

Wheat is most intensely cultivated in the Great Plains region, specifically Kansas [4,25]. Winter wheat is planted in autumn, enters dormancy during the winter, and is harvested in the spring [25]. Under ideal conditions, the crop is harvested once before entering dormancy and again in early spring [25]. According to the USDA [25], winter wheat is planted from September 10 to November 1 in Kansas [25]. The following year, it is harvested from June 15 to July 15 [25].

Winter wheat progresses through its growth stages on a somewhat regular monthly schedule beginning with seedling establishment in moist, warm conditions in October [51]. From October to November, winter wheat enters a hardening period with declining temperatures; during the first two months of the following year, the plants withstand the winter [51]. March is a recovery period during a warming spring followed by reproductive development in April [51]. Heading through flowering occurs in May; from late May through June, grain-filling occurs, and the plants reach maturity [51]. Winter wheat is sensitive to drought, water stress, elevated temperatures, and seasonal shifts; however, it is most vulnerable during its reproductive and grain-filling stages [17,18].

Despite susceptibility to climatic variability, Kansas winter wheat yields have been relatively stable over the past 16 years. The lowest yield of the time period occurred during the September to July growing season in 2014. Interestingly, the maximum temperature was 17.9 ℃, which was the fourth lowest during the time period [27]. The minimum temperature was 3.5 ℃ [27]. Compared to the 1980–1999 base period, the 2014 maximum temperature (17.9 ℃) was 0.2 ℃ lower, and the minimum temperature (3.5 ℃) was 0.9 ℃ lower [27]. The data suggest cooler than normal temperatures may exert detrimental effects as do elevated temperatures. PDSI in 2014 was −0.98 compared to the PDSI of 1.38 during the base period [27]. As shown in Figure 5, no statistically significant relationship exists between winter wheat yield and PDSI.

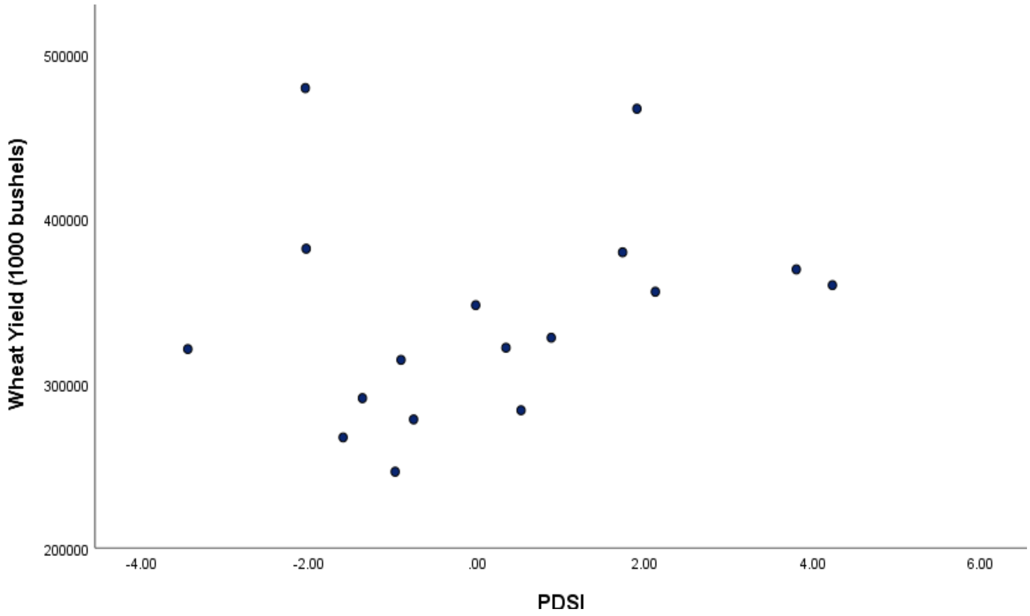

Figure 5. Kansas winter wheat yield and drought index. Wheat yield is expressed in 1000 bushel units. The scatterplot shows the non-statistically significant relationship between winter wheat and PDSI from 2000–2016 [27–33].

A cereals study was conducted in China to assess the relationship between climate and wheat yield [47]. The correlation between wheat yield and nighttime temperatures was not statistically significant in most areas with the exception of a temperature increase reducing yield in northeastern China [47]. Elevated daytime temperatures resulted in reduced yield in 10.3% of wheat-growing regions [47]. Precipitation exerted a greater influence than temperature as yields were reduced with more precipitation affecting 18.4% of wheat-cultivating areas [47]. These reductions were observed in central and southern China where yearly precipitation totals were more than 1000 mm per year [47]. The finding of precipitation exerting a stronger influence on wheat yield is directly opposed to our result of no significant association. Interestingly, the two highest-yielding years, 2003 and 2016, had opposite PDSI measurements [27]. In 2003, the PDSI was −2.05, indicating a moderate drought whereas the PDSI in 2016 was 1.9, indicating midrange moisture [10,27].

Temperature, as an individual factor, has a powerful influence on winter wheat yield. A study was performed involving the hydroponic cultivation of winter wheat in growth chambers [48]. Winter wheat was cultivated at five day/night temperature combinations: 13/10 ℃, 19/16 ℃, 25/19 ℃, 30/24 ℃, and 37/31 ℃ [48]. The highest photosynthetic assimilation rate was 25–30 ℃; the greatest amount of biomass accumulation occurred at 25/19 ℃ [48]. For wheat grown at 37/31 ℃, the biomass accumulation was 13% of the accumulation of plants grown at 25/19 ℃, which suggests winter wheat is intolerant of elevated temperatures [48].

3.2. Correlational analysis summary

The aforementioned observed climate and yield data of five American agricultural commodities display the impact of temperature and precipitation fluctuations on agricultural productivity, which is forecasted to continue due to climate change [17]. Of the five crops examined, only corn and cotton yields were correlated with PDSI. Both exhibited positive associations. Rice, soybean, and winter wheat were not found to have a significant correlation with PDSI possibly due to irrigation reducing the significance of precipitation or monthly differences in precipitation being more significant based on life cycle stage. Of particular importance is to remember that PDSI incorporates temperature and precipitation to assess moisture of an area [8]. The crucial nature of the temperature component of PDSI is easily observable based on the results of a global study conducted on the number of days during a crop's reproductive cycle in which temperature exceeded the crop's critical temperature [52]. Wheat (34 ℃), corn (35 ℃), rice (36 ℃), and soybean (39 ℃) were examined [17,52]. Of the four crops studied, wheat is cultivated at the lowest temperature while rice is at the warmest with corn and soybean cultivated between them [52]. Globally, the four crops are cultivated in areas with vastly different growing season temperatures [52]. Despite elevated temperatures, most agricultural areas have not been continuously exposed to higher than typical temperatures during a crop's reproductive stage in the past three decades [52]. About half of wheat-growing and corn-growing areas experienced less than a day of temperatures higher than the critical temperature annually from 2000–2011 [52]. Of the four crops, soybean is the least vulnerable to elevated temperatures during its reproductive period given its higher critical temperature [52]. As exemplified by the aforementioned study, much work has been performed to examine the effect of temperature on crops, particularly during reproduction. What remains to be performed is a series of experiments to measure the optimal levels of precipitation required for each agricultural crop by cultivar and location. Results from these experiments could further illuminate the complex association between precipitation and temperature on yields.

3.3. Large-scale climate phenomena

As sea surface temperatures increase due to climate change, typical patterns associated with El Niño/Southern Oscillation (ENSO) may shift [53]. ENSO is a regular pattern of changes in sea surface temperatures (El Niño) and changes in the air pressure of the atmosphere (Southern Oscillation) across the Pacific Ocean at 0° latitude at measurement stations in Darwin, Australia and Tahiti [54]. ENSO has three stages: El Niño, La Niña, and neutral [55]. El Niño is a stage of ENSO that involves heating of the ocean in the central and eastern portions of the tropical Pacific Ocean [55]. Precipitation decreases over Indonesia and the tropical Pacific Ocean [55]. Easterly winds typically blow west along the equator, but during El Niño, these winds are reduced or begin blowing in the opposite direction [55]. During La Niña, the ocean cools, or sea surface temperatures are reduced in the central and eastern tropical Pacific Ocean [55]. Precipitation increases over Indonesia but is reduced over the tropical Pacific Ocean [55]. Easterly winds blow more intensely along the equator [55]. During a neutral stage, sea surface temperatures in the Pacific are near average [55]. Additionally, ENSO exerts substantial effects on crop yields as exemplified by a study by Iizumi et al. [53].

A study was conducted to chart the effects of ENSO on global yields of corn, rice, wheat, and soybean in which researchers examined whether reproductive stages of crops occurred during El Niño, La Niña, or neutral periods in their particular areas of cultivation [53]. By examining yield departures from the five-year mean from 1984–2004, researchers found El Niño adversely affected yields in 22–24% of harvested regions globally [53]. Those affected included corn in the southeastern US, China, eastern and western Africa, Mexico, and Indonesia [53]. Soybean was impacted in areas of China and India [53]. Rice in southern China, Myanmar, and Tanzania along with wheat in parts of China, the US, Australia, Mexico, and some portions of Europe were negatively affected [53]. El Niño years are typically warmer and drier, and these conditions negatively impacted crops in several of the aforementioned cultivation areas [53]. However, positive effects of El Niño on yields were observed in 30–36% of areas harvested, including corn in Brazil and Argentina; soybean in the US and Brazil; rice in portions of China, Indonesia, and areas of Brazil; and wheat in Argentina, Kazakhstan, and portions of South Africa [53]. These areas experience cooler and wetter conditions during El Niño years [53]. La Niña impacts yields differently than El Niño [53]. Adverse effects of La Niña were evident in portions of North America, Central America, South America, and Ethiopia whereas positive impacts were observed in portions of southern and western Africa [53]. Negative effects of La Niña on corn and soybean were found in the US as it caused warmer and drier conditions; however, these effects were somewhat mitigated by more irrigation in some areas compared to rainfed areas [53]. Globally, the adverse effects comprised 9–13% of the harvested area [53]. Only about 2–4% of harvested acres were positively affected by La Niña [53]. The mean yields of corn, rice, and wheat worldwide in El Niño and La Niña years were typically −4.0 to −0.2% below average [53]. Soybean yield worldwide was −1.6 to −1.0% below average during La Niña years whereas yield was 2.9–3.5% above average during El Niño years due to positive impacts in its primary producing regions in the US and Brazil [53].

4. Conclusions

The analysis of yield data and associated climate parameters from the recent past can and should be applied to other crops and regions of the world. This retrospective assessment could help researchers discern patterns to construct more encompassing models, which leads to more accurate projections of climate both worldwide and regionally. Accurate forecasts are essential to the ability to predict the impact on agriculture. One such area where the aforementioned analysis should be applied is California's Central Valley, which is known for its abundance of fruit and nut orchards [56]. Approximately $8.7 billion in US currency is generated annually from Californian orchards [56]. Given that California is expected to become drier and hotter as climate change progresses, yield of fruits, nuts, and other crops cultivated in California are almost certain to be affected [2,19]. Californian perennial fruits and nuts, such as grapes and almonds, persist upwards of 20 years; consequently, it is important to understand how climate change will affect crops that have already been cultivated [57]. One of the primary difficulties of studying perennials is their susceptibility to weather throughout the year whereas annuals are only impacted by weather during their growing season [57]. Crops requiring much water will be particularly susceptible to the changing climate; consequently, comprehending trends of the recent past are vital to continued agricultural productivity [19]. Discovering hidden patterns in the relationship between climate patterns and yield might facilitate new research into ameliorative methods to reduce the impact of climate change. Retrospective analysis must begin presently to avoid a chaotic situation of global food and economic insecurity due to climate change.

Acknowledgments

The authors would like to thank Mississippi State University for providing software for this research.

Conflict of interest

All authors declare no conflicts of interest in this paper.

References

1. Motha RP, Baier W (2005) Impacts of present and future climate change and climate variability of agriculture in the temperate regions: North America. *Clim Change* 70: 137–164.
2. Monier E, Xu L, Snyder R (2016) Uncertainty in future agro-climate projections in the United States and benefits of greenhouse gas mitigation. *Environ Res Lett* 11: 055001.
3. National Centers for Environmental Information, Assessing the U.S. Climate in 2017. National Oceanic and Atmospheric Administration, 2018. Available from: https://www.ncei.noaa.gov/news/national-climate-201712.
4. Walthall CL, Hatfield J, Backlund P, et al., Climate Change and Agriculture in the United States: Effects and Adaptation. United States Department of Agriculture, University Corporation for Atmospheric Research, National Center for Atmospheric Research, 2012. Available from: https://www.usda.gov/oce/climate_change/effects_2012/. CC%20and%20Agriculture%20Report%20(02–04–2013)b.pdf.
5. National Aeronautics and Space Administration, Global climate change vital signs of the planet: causes. NASA Jet Propulsion Laboratory, 2017. Available from: https://climate.nasa.gov/causes/
6. National Aeronautics and Space Administration, Global climate change vital signs of the planet: evidence. NASA Jet Propulsion Laboratory, 2017. Available from: https://climate.nasa.gov/evidence/.
7. Mira de Orduña R (2010) Climate change associated effects on grape and wine quality and production. *Food Res Int* 43: 1844–1855.
8. Dai A, National Center for Atmospheric Research Staff, The Climate Data Guide: Palmer Drought Severity Index (PDSI). University Corporation for Atmospheric Research, 2017. Available from: https://climatedataguide.ucar.edu/climate-data/palmer-drought-severity-index-pdsi.
9. Mishra AK, Singh VP (2010) A review of drought concepts. *J Hydrol* 391: 202–216.
10. National Centers for Environmental Information, Historical Palmer Drought Indices. National Oceanic and Atmospheric Administration, 2017. Available from: https://www.ncdc.noaa.gov/temp-and-precip/drought/historical-palmers/.
11. Roberts M, Schlenker W (2011) The evolution of heat tolerance of corn: implications for climate change, In: Libecap GD, Steckel RH. Editors, *The economics of climate change: adaptations past and present*, Chicago: University of Chicago Press, 225–251.
12. Lobell DB, Field CB (2007) Global scale climate-crop yield relationships and the impacts of recent warming. *Environ Res Lett* 2: 014002.

13. Leng G, Zhang X, Huang M, et al. (2016) The role of climate covariability on crop yields in the conterminous United States. *Sci Rep* 6: 1–11.
14. Hatfield J, Takle G, Grotjahn R, et al. (2014) Chapter 6: Agriculture, In: Melillo, J.M., Richmond, T.C., Yohe, G.W. (Eds), *Climate Change Impacts in the United States: The Third National Climate Assessment*. Washington, D.C.: U.S. Global Change Research Program, 150–174.
15. Moya TB, Ziska LH, Namuco OS, et al. (1998) Growth dynamics and genotypic variation in tropical, field-grown paddy rice (*Oryza sativa* L.) in response to increasing carbon dioxide and temperature. *Glob Chang Biol* 4: 645–656.
16. Leakey ADB, Uribelarrea M, Ainsworth EA, et al. (2006) Photosynthesis, productivity, and yield of maize are not affected by open-air elevation of CO_2 concentration in the absence of drought. *Plant Physiol* 140: 779–790.
17. Hatfield JL, Boote KJ, Kimball BA, et al. (2011) Climate impacts on agriculture: implications for crop production. *Agron J* 103: 351–370.
18. Steiner JL, Briske DD, Brown DP, et al. (2018) Vulnerability of Southern Plains agriculture to climate change. *Clim Change* 146: 201–218.
19. Jackson LE, Wheeler SM, Hollander AD, et al. (2011) Case study on potential agricultural responses to climate change in a California landscape. *Clim Change* 109: S407–S427.
20. Nahar K, Ullah SM (2011) Effect of water stress on moisture content distribution in soil and morphological characters of two tomato (*Lycopersicon esculentum* Mill) cultivars. *Bangladesh J Sci Res* 3: 677–682.
21. Chaves MM, Oliveira MM (2004) Mechanisms underlying plant resilience to water deficits: prospects for water-saving agriculture. *J Exp Bot* 55: 2365–2384.
22. Chaves MM, Maroco JP, Pereira JS (2003) Understanding plant responses to drought-from genes to the whole plant. *Funct Plant Biol* 30: 239–264.
23. United States Department of Agriculture, Irrigation & water use. Economic Research Service, 2018. Available from: https://www.ers.usda.gov/topics/farm-practices-management/irrigation-water-use/.
24. Xu H, Twine TE, Girvetz E (2016) Climate change and maize yield in Iowa. *PLoS ONE* 11: e0156083.
25. United States Department of Agriculture, Field Crops Usual Planting and Harvesting Dates. National Agricultural Statistics Service, 2010. Available from: http://usda.mannlib.cornell.edu/usda/current/planting/planting-10–29–2010.pdf.
26. Hu Q, Buyanovsky G (2003) Climate effects on corn yield in Missouri. *J Appl Meteorol* 42: 1626–1635.
27. National Centers for Environmental Information, Climate at a Glance: Statewide Time Series. National Oceanic and Atmospheric Administration, 2018. Available from: https://www.ncdc.noaa.gov/cag/statewide/time-series.
28. United States Department of Agriculture, Agricultural Statistics 2003. National Agricultural Statistics Service, 2003. Available from: https://www.nass.usda.gov/Publications/Ag_Statistics/2003/index.php.
29. United States Department of Agriculture, Agricultural Statistics 2004. National Agricultural Statistics Service, 2004. Available from: https://www.nass.usda.gov/Publications/Ag_Statistics/2004/index.php.

30. United States Department of Agriculture, Agricultural Statistics 2007. National Agricultural Statistics Service, 2007. Available from: https://www.nass.usda.gov/Publications/Ag_Statistics/2007/index.php.
31. United States Department of Agriculture, Agricultural Statistics 2010. National Agricultural Statistics Service, 2010. Available from: https://www.nass.usda.gov/Publications/Ag_Statistics/2010/index.php.
32. United States Department of Agriculture, Agricultural Statistics 2016. National Agricultural Statistics Service, 2016. Available from: https://www.nass.usda.gov/Publications/Ag_Statistics/2016/index.php.
33. United States Department of Agriculture, Agricultural Statistics 2017. National Agricultural Statistics Service, 2017. Available from: https://www.nass.usda.gov/Publications/Ag_Statistics/2017/index.php.
34. Lobell DB, Asner GP (2003) Climate and management contributions to recent trends in U.S. agricultural yields. *Science* 299: 1032.
35. Kukal MS, Irmak S (2018) Climate-driven crop yield and yield variability and climate change impacts on the U.S. Great Plains agricultural production. *Sci Rep* 8: 1–18.
36. Downton J, Slatyer RO (1972) Temperature dependence of photosynthesis in cotton. *Plant Physiol* 50: 518–522.
37. Texas A&M AgriLife Extension, Cotton Production Regions of Texas. Texas A&M University, 2018. Available from: https://cottonbugs.tamu.edu/cotton-production-regions-of-texas/.
38. Loka DA, Oosterhuis DM (2012) Chapter 5: Water stress and reproductive development in cotton, In: Oosterhuis DM, Cothren JT, Robertson WC. (Eds), *Flowering and Fruiting in Cotton*. Cordova, TN: The Cotton Foundation, 51–58.
39. Ullah A, Sun H, Yang X, et al. (2017) Drought coping strategies in cotton: increased crop per drop. *Plant Biotechnol J* 15: 271–284.
40. Loka DA, Oosterhuis DM (2016) Increased night temperatures during cotton's early reproductive stage affect leaf physiology and flower bud carbohydrate content decreasing flower bud retention. *J Agron Crop Sci* 202: 518–529.
41. Huang J, Ji F (2015) Effects of climate change on phenological trends and seed cotton yields in oasis of arid regions. *Int J Biometeorol* 59: 877–888.
42. Prasad PVV, Boote KJ, Allen Jr. LH (2006) Adverse high temperature effects on pollen viability, seed-set, seed yield and harvest index of grain-sorghum [*Sorghum bicolor* (L.) Moench] are more severe at elevated carbon dioxide due to higher tissue temperatures. *Agric For Meteorol* 139: 237–251.
43. Arshad MS, Farooq M, Asch F, et al. (2017) Thermal stress impacts reproductive development and grain yield in rice. *Plant Physiol Biochem* 115: 57–72.
44. Jagadish SVK, Craufurd PQ, Wheeler TR (2007) High temperature stress and spikelet fertility in rice (*Oryza sativa* L.). *J Exp Bot 58*: 1627–1635.
45. Pandey V, Shukla A (2015) Acclimation and tolerance strategies of rice under drought stress. *Rice Sci* 22: 147–161.
46. Barber T, Cartwright RD, Counce P, et al. (2013) Chapter 19: Glossary of rice industry terms, In: Hardke, JT. (Ed), *Arkansas Rice Production Handbook*. Little Rock, AR: University of Arkansas Division of Agriculture Cooperative Extension Service, 203–206.

47. Zhang T, Huang Y (2012) Impacts of climate change and inter-annual variability on cereal crops in China from 1980 to 2008. *J Sci Food Agric* 92: 1643–1652.
48. Nagai T, Makino A (2009) Differences between rice and wheat in temperature responses of photosynthesis and plant growth. *Plant Cell Physiol* 50: 744–755.
49. Zhang L, Zhu L, Yu M, et al. (2016) Warming decreases photosynthates and yield of soybean [*Glycine max* (L.) Merrill] in the North China Plain. *Crop J* 4: 139–146.
50. Choi DH, Ban HY, Seo BS, et al. (2016) Phenology and seed yield performance of determinate soybean cultivars grown at elevated temperatures in a temperate region. *Plos One* 11: e0165977.
51. Morgounov A, Haun S, Lang L, et al. (2013) Climate change at winter wheat breeding sites in central Asia, eastern Europe, and USA, and implications for breeding. *Euphytica* 194: 277–292.
52. Gourdji SM, Sibley AM, Lobell DB (2013) Global crop exposure to critical high temperatures in the reproductive period: historical trends and future projections. *Environ Res Lett* 8: 024041
53. Iizumi T, Luo JJ, Challinor AJ, et al. (2014) Impacts of El Niño Southern Oscillation on the global yields of major crops. *Nat Commun* 5: 1–7.
54. National Centers for Environmental Information, ENSO-what is it? National Oceanic and Atmospheric Administration, 2018. Available from: https://www.ncdc.noaa.gov/teleconnections/enso/enso-tech.php.
55. Heureux ML (2014) What is the El Niño–Southern Oscillation (ENSO) in a nutshell? ENSO Blog, 2014. Available from: https://www.climate.gov/news-features/blogs/enso/what-el-niño–southern-oscillation-enso-nutshell.
56. Luedeling E, Zhang M, Girvetz EH (2009) Climatic changes lead to declining winter chill for fruit and nut trees in California during 1950–2099. *PLoS ONE* 4: e6166.
57. Lobell DB, Field CB (2011) California perennial crops in a changing climate. *Clim Change* 109: S317–S333.

AIMS Press