Agricultural Sciences, 2023, 14, 154-175
https://www.scirp.org/journal/as
ISSN Online: 2156-8561
ISSN Print: 2156-8553

The El Niño-Southern Oscillation (ENSO) Effects on Cowpea and Winter Wheat Yields in the Semi-Arid Region of the Southern US

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How to cite this paper: Woli, P., Smith, G.R., Long, C.R. and Rouquette Jr., F.M. (2023) The El Niño-Southern Oscillation (ENSO) Effects on Cowpea and Winter Wheat Yields in the Semi-Arid Region of the Southern US. *Agricultural Sciences*, **14**, 154-175.
https://doi.org/10.4236/as.2023.142011

Received: January 11, 2023
Accepted: February 12, 2023
Published: February 15, 2023

Abstract

Information is limited on the effects of climate variability on cowpea (*Vigna unguiculata* L.) and winter wheat (*Triticum aestivum* L.) yields in the semiarid region of the southern US. Using the Decision Support System for Agrotechnology Transfer (DSSAT) crop model and weather data spanning 81 years, we assessed the impact of El Niño-Southern Oscillation (ENSO) on the grain yields of these crops in the Llano Estacado region of the southern US as affected by cowpea and wheat planting dates and N application rate. Simulated results showed that the El Niño phase of ENSO produced about 30% more yields of mono-cropped cowpea than those produced under the La Niña phase, especially with the cowpeas planted in July. The cowpea yields under El Niño were about 10% more than the 81-year average normal yield, whereas those under La Niña were about 20% less. At the N rates of 0, 50, and 100 $kg \cdot ha^{-1}$, regardless of wheat planting dates, the El Niño years produced, respectively, about 8%, 40%, and 60% higher wheat yields than those produced in the La Niña years, and about 5%, 20%, and 27% more than the 81-year average normal yield. In the La Niña years, the wheat yields at 0, 50, and 100 kg N ha^{-1} were, respectively, about 5%, 15%, and 20% less than the normal yield with similar N levels. The impact of ENSO on wheat yields under cowpea-wheat double-cropping systems was significant, especially for the wheat crops planted on October 15 (October 30) or later following the cowpea crops planted in June (July). At zero N, the mono-cropped wheat yields were not impacted by ENSO due to N limitation. However, the double-cropped wheat yields were impacted by ENSO even when no N fertilizer was applied due to high soil N status caused by N transfer from cowpea stover residues and roots. Results indicated that management strategies need to be attentive to ENSO forecasts and adjust potential planting dates and N application rates with the ENSO phase to avert risks of crop failure and economic loss.

Keywords

Climate, Cowpea, DSSAT, Double-Crop, El Niño, ENSO, Model, Semi-Arid, Wheat

1. Introduction

Double cropping agricultural systems are designed to increase total crop production, make efficient use of all available resources, and provide a continuous soil cover, reducing wind and water erosion [1] [2]. Double cropping using winter wheat (*Triticum aestivum* L.) and soybean (*Glycine max* [L.] Merr.) has been successful and sustainable in eastern Oklahoma [3] and Argentina [4]. However, in a five-year study conducted in North Carolina, a humid region in the US, using winter wheat and multiple warm-season crops, no economic advantage was noted in 80% of the crop-year combinations [5].

Winter wheat is a crop with multiple production options in the Texas High Plains, including livestock grazing, the combination of grazing and grain, and grain only [6]. Cowpea (*Vigna unguiculata* [L.] Walp.) is a drought- and heat-tolerant summer legume pulse or hay crop that can be grown worldwide using no fertilizer nitrogen inputs [7]. In the US, the state of Texas is a major region where a dry pulse crop of cowpea is produced [8]. Because of low water requirements, cowpea and wheat are generally considered better suited for production under dryland conditions [7] [9]. In the semi-arid region of the southern US, including the Texas High Plains, therefore, cowpea may be used successfully as a double crop with wheat. The growing seasons of cowpea and winter wheat allow the possibility of double cropping, but climate constraints in semi-arid regions may severely limit crop production.

One of the most important factors that define the productivity of an agroecosystem is the weather, and the key factor that defines the interannual variability in crop production in a region is the climate. The annual fluctuation of climate in the southeastern US has been linked to El Niño-Southern Oscillation (ENSO), an ocean-atmosphere phenomenon that occurs across the equatorial Pacific Ocean [10] [11]. The ENSO phenomenon consists of three phases: El Niño, La Niña, and Neutral. An ENSO episode is unique, generally lasts about 14 to 22 months, and returns after about 2 to 7 years [12]. The strength of ENSO varies across regions and seasons [13] [14]. In the southeastern US, the ENSO signal is stronger during winter than during summer and stronger in lower latitudes than in mid-latitudes [13] [15]. In this region, El Niño events are generally wetter than usual during fall, winter, and spring [13] [16] [17]; whereas La Niña events tend to have wetter summers and drier winters and springs [18]. The ENSO has been found to significantly affect crop production in the southeastern United States [19]. Due to the strong precipitation-related teleconnection between ENSO and weather patterns in this region, an ENSO phase may be successfully forecast for this region up to a year in advance [20]. Accordingly, ENSO forecasts may potentially be helpful for crop production in this region. The ENSO-based forecast of weather conditions may reduce climate uncertainty for improved crop production. For this reason, a number of studies have been conducted to explore associations between various field crops in this region and ENSO [21]-[31]. For Piney Woods, a humid region in the southern US, reference [32] studied the effects of ENSO on cowpea and wheat as influenced by soil type and N application rate. For the Texas High Plains, a semi-arid region in the southern US, on the other hand, reference [33] evaluated ENSO effects on wheat and grain sorghum using about 19 years' yield data on each crop.

There are a number of factors that generally influence the effect of ENSO on crop production such as region [13], season [14], soil type [25] [31], planting date [24] [25], soil fertility level [31] [32], pest and disease outbreaks [23] [27], and crop type and tolerance to water and cold stresses [19] [30] [34]. Among the crucial factors affecting crop yields, planting date is one of the most important management variables that need to be tailored to the anticipated ENSO conditions. Under rainfed conditions, crop managers try to reduce the effect of drought by selecting a planting date that minimizes plant water deficit. The adjustment of planting dates based on climatic conditions can be useful for increasing crop yields and reducing interannual yield variability. Another fundamental factor that might influence the ENSO effect on crops is soil fertility. This hypothesis is plausible because, under dry conditions, a less fertile soil may produce proportionately lower yields relative to a more fertile soil because of fertility-limiting production conditions. The yield difference between less fertile and more fertile soils could be larger under wet conditions relative to dry conditions because under wet conditions more fertile soils might produce relatively more because of the increased efficiency of nutrient utilization.

The influences of planting date on the effect of ENSO on cotton and peanut yields in Georgia, US, were studied by references [24] and [25], respectively. The ENSO effect on cowpea and wheat yields as influenced by N application rate was studied by reference [32] for the humid region of the southern US. For the semi-arid region of the southern US, however, no study has examined the ENSO impacts on cowpea and wheat yields as influenced by planting date and N application rate. If these important management variables really influenced the ENSO impact, this information would be very helpful to cowpea and wheat growers in this region in maximizing production by tailoring planting dates to specific N application rates under each ENSO phase.

The objective of this study was to explore the effects of ENSO on the grain yields of mono-cropped cowpea, mono-cropped winter wheat, and double-cropped winter wheat under cowpea-wheat doubling systems in the semi-arid region of the southern US as influenced by 1) the planting dates of cowpea and winter wheat and 2) the N application rate to wheat, using the sequence analysis tool of Decision Support System for Agrotechnology Transfer (DSSAT), a widely-tested and used suite of crop models [35] [36]. We conducted simulation modeling because it provides considerable insight into the behavior of an agroecosystem and into ways for managing it to achieve specific goals [37]. Because the scientific study of an agroecosystem requires a system model of components and their interactions, models are necessary for understanding and predicting overall agroecosystem performance for specific purposes [38]. Moreover, "systems analysis and modeling" is the only interdisciplinary professional field that enables us to integrate and oversee our incomplete knowledge about a system [39]. Crop simulation models can predict plant growth and development as influenced by management and environment by using quantitative descriptions of ecophysiological processes [40].

2. Materials and Methods

2.1. DSSAT and Sequence Analysis

The DSSAT is a suite of more than 42 crop models. It can simulate crop growth and development processes as defined by the soil-plant-atmosphere dynamics, using various tools that manage databases on crop, soil, and weather and several applications that perform graphical display, seasonal analysis, rotational analysis, and genotype coefficient estimation [41]. The DSSAT suite has been used for various purposes such as precision crop management and studying agroecosystem sustainability, climate change impacts, and greenhouse gas emission [41]. Simulations are performed on a daily basis by integrating crop, soil, weather, and management data with crop models and application programs.

For rapid simulation, inspection, and analysis of results of long-term cropping sequences, DSSAT contains the Sequence Analysis tool [42]. As multiple cropping seasons are involved in a sequence analysis, this tool allows for the carryover of soil water and nutrients from the preceding crop to the following crop [43] [44].

2.2. Site and Data

Llano Estacado is a semi-arid region in the southern US and comprises parts of eastern New Mexico and northwestern Texas [45] [46]. The economy of this region is predominantly agricultural, with farming of various crops prevalent. The overuse in the past of the Ogallala Aquifer, the main freshwater source for the region, has persuaded some farmers to return to dryland crops. The Texas A&M AgriLife Research & Extension Center at Amarillo is situated in this region. At the Amarillo Center, numerous experiments have been conducted to investigate, discover, develop, evaluate, and apply technology to sustain livestock and crop production in the Texas Panhandle region and beyond. In this study, Amarillo (35.19˚N, 102.06˚W), Texas was used as a representative site for the Llano Estacado region [47].

To explore the effect of interannual climate variability on cowpea and winter wheat grain yields in the Llano Estacado region, a long-term weather dataset spanning 81 years (1942-2022) was used. Historical daily data on precipitation, temperature, and windspeed at Amarillo were obtained from the website of National Centers for Environmental Information [48]; whereas those on solar radiation were generated using a reliable irradiation model described by [49].

Pullman clay loam (*Torrertic paleustolls*) is a primary soil used for agricultural purposes in Llano Estacado. Thus, this soil was used as a representative soil for the study region [50]. The soil data (**Table 1**) were obtained from the Gridded Soil Survey Geographic (GSSURGO) database of the USDA NRCS [51] [52]. The run-off curve number and the drainage coefficient of the soil were 81 and 0.60, respectively.

2.3. The Simulation Study Design

The grain yields of cowpea and winter wheat in the three cropping systems, namely fallow-cowpea, fallow-wheat, and cowpea-wheat under double cropping, were simulated using the DSSAT Sequence Analysis tool. The cowpea or wheat crop that followed fallow, known as the mono-cropped cowpea or mono-cropped wheat, hereafter, will be referred to as ^{m}cowpea and ^{m}wheat, respectively, and the wheat crop that followed cowpea, known as the double-cropped wheat, as ^{d}wheat. A total of 94 scenarios were simulated that comprised four planting dates for cowpea (June 1, June 15, July 1, and July 15), six planting dates for wheat (September 15, September 30, October 15, October 30, November 15, and November 30), and three N application rates to wheat (0, 50, and 100 kg N ha^{-1}) (**Table 2**).

For simulations, Pullman clay loam was used as soil, and "Newton" and "Cal #5 MG4" were used as cultivars for winter wheat and cowpea, respectively. For Newton, the genetic coefficients already estimated for the study region by [53] were used. For Cal #5 MG4, the default genetic coefficients provided in the standard DSSAT release [36] that correspond to the coefficients upon which the

Table 1. Properties of Pullman clay loam soil in the Llano Estacado region of the southern US.

Layer (cm)	Soil properties							
	Clay (%)	Silt (%)	TN† (%)	OC (%)	FC	WP	WH	pH
0 - 13	29.50	31.30	0.11	1.16	0.34	0.21	0.13	7.00
13 - 46	38.50	29.20	0.10	0.73	0.38	0.27	0.11	7.60
46 - 84	43.50	32.50	0.08	0.39	0.38	0.24	0.14	7.80
84 - 132	42.50	22.40	0.05	0.36	0.37	0.23	0.14	8.20
132 - 168	37.50	31.40	0.05	0.13	0.36	0.23	0.13	8.20
168 - 200	36.50	21.70	0.04	0.20	0.34	0.23	0.11	8.20

†TN: Total N; OC: Organic Carbon; FC: Field Capacity; WP; Wilting Point; WH: Water Holding capacity.

Table 2. The simulation study scenarios comprising 3 cropping systems, 4 × 6 planting dates, and 3 N applications rates.

Cropping system	Factors and levels	Scenarios
Fallow-cowpea	4 cowpea planting dates	4
Fallow-wheat	6 wheat planting dates × 3 N rates	18
Cowpea-wheat	4 cowpea planting dates × 6 wheat planting dates × 3 N rates	72
Total scenarios		94
Total seasons		81
Total modal runs		7614

cowpea model was adapted were used. For each scenario, simulation started on April 1, two months before the earliest cowpea planting date of June 1 in 1942, and terminated on the harvest date associated with the latest planting date of wheat in 2022. For simulations, 30 plants m^{-2} for cowpea and 323 plants m^{-2} for wheat were assumed. Dry seeds were planted in rows at 3 cm depth using the conventional tillage.

Only wheat crops received N fertilizer. Of the total quantity of N set for application, one half was applied at planting and the other half on February 15 of the following year. To let the nutrients in stover residues transfer from the preceding crop to the following crop in cycles, the residues of each crop were assumed to be automatically incorporated into the soil on the harvest day of the crop. The "Century" method in the DSSAT system was assumed for organic matter estimation, with "Cultivated, good management, initial default SOM" as the five years' field history [54].

2.4. ENSO Classification

For ENSO analyses, the grain yields of ^{m}cowpea, ^{m}wheat, and ^{d}wheat each that were simulated for each of 81 seasons (1942-2022) were assigned to a specific ENSO phase as categorized by the Japan Meteorological Agency (JMA) index [55] [56] [57] [58]. The JMA index is a 5-month running average of the sea surface temperature anomalies over the tropical Pacific (4˚S - 4˚N, 150˚W - 90˚W). An ENSO year, which starts from October through the following September, is categorized as El Niño, La Niña, or Neutral if the index values are ≥0.5˚C, ≤−0.5˚C, or between −0.5˚C and 0.5˚C, respectively, for 6 consecutive months, including October, November, and December [56] [58]. The JMA index was chosen for ENSO characterization as it selects the known ENSO events better than other similar indices [58]. According to this index, the total number of years under El Niño, La Niña, and Neutral phases during the 1942-2022 period were 18, 21, and 42, respectively.

2.5. Data Analyses

Statistical significance tests were performed to examine yield differences across

ENSO phases as influenced by cowpea planting date for ^{m}cowpea, as influenced by wheat planting date × N application rate interactions for ^{m}wheat, and as influenced by cowpea planting date × wheat planting date × N application rate interactions for ^{d}wheat. The tests were carried out using the pairwise Wilcoxon rank sum test [59], a nonparametric alternative to the two-sample t-test, as the assumption of normality was not met for each Analysis of Variance (ANOVA) test. For statistical analyses, the R software environment (R version 4.1.1) was used (https://www.r-project.org/).

To assess the status of crop water stress during the cowpea and wheat growing seasons, Agricultural Reference Index for Drought (ARID), an agricultural drought index that is simple and sound [60], widely applicable [61], able to predict yield loss from drought for several field crops [62], and applicable to drought forecasting [63] was used. Using data on soil and weather, daily values of ARID during cowpea and wheat growing seasons were computed and used to associate drought with yields.

3. Results and Discussion

3.1. The ENSO Effect on Mono-Cropped Cowpea Yields

The simulated, detailed response of ^{m}cowpea yields to ENSO phases as influenced by planting date is presented in **Figure 1**. The results showed that the impact of ENSO on ^{m}cowpea yields in the Llano Estacado region was significant only for the planting date of July 15 (**Table 3**). For this planting date, the ^{m}cowpea yields under the El Niño phase were significantly greater than those under the La Niña phase. At all other planting dates, however, the ^{m}cowpea yields were about the same across all ENSO phases. These results were likely because the status of crop water stress during early June through the first week of October, the cowpea growing seasons associated with most planting dates, was about the same across all ENSO phases (**Figure 2**). This indicated that the amounts of water taken up by the crops associated with these planting dates were not significantly different across ENSO phases. The ^{m}cowpea crops associated with the July 15 planting date, on the other hand, received significantly more precipitation and thus had less water stress under El Niño than under La Niña especially during the first week of October through the end of this month (**Figure 2**).

Although the ENSO effect on ^{m}cowpea yields was significant only for the July 15 planting date, the El Niño years tended to produce more cowpea yields than did the La Niña years, especially for the crops planted in July (**Table 3**, **Figure 3**). The ^{m}cowpea yields associated with the crops planted in July were about 10% greater in the El Niño years compared with the normal yield, an average yield of the entire 81 seasons (**Figure 3(a)**). These yields in the La Niña years, on the other hand, were about 20% less than the normal yield. Under the El Niño phase, the yields of cowpea crops planted in July were about 30% greater than those produced under the La Niña phase (**Figure 3(b)**).

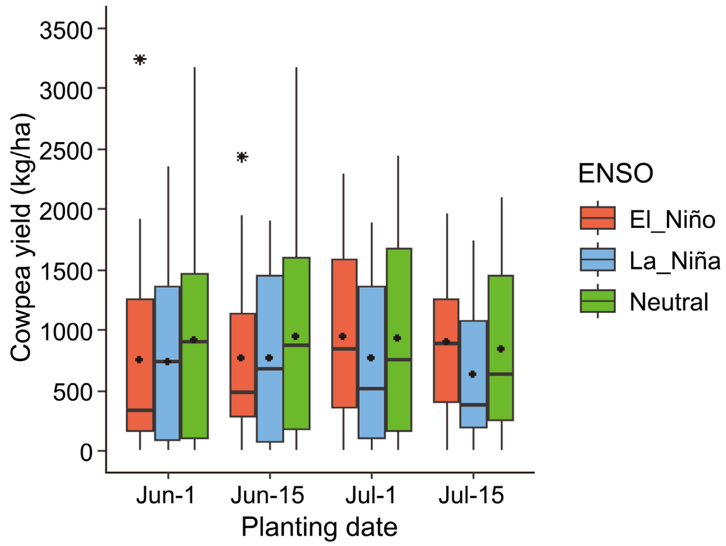

Figure 1. Boxplots showing cowpea yield response to ENSO × planting date in the Llano Estacado region of the southern US. In a boxplot, the lower and upper ends of whiskers indicate minimum and maximum values, respectively; the dot indicates the mean value; the colored region shows interquartile range, and stars indicate outliers.

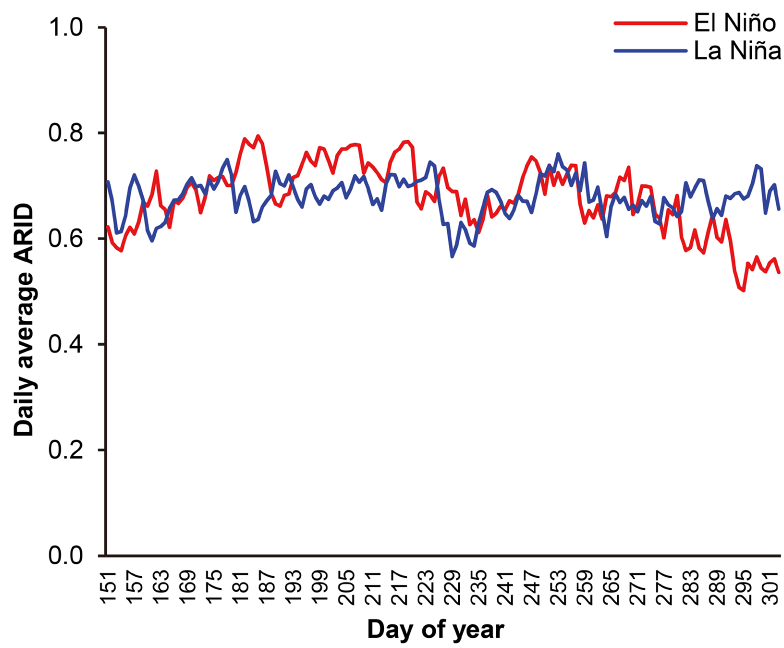

Figure 2. Daily average values of Agricultural Reference Index for Drought (ARID) during the cowpea growing season of June 1 through October 30 under El Niño and La Niña in the Llano Estacado region of the southern US.

These results were in agreement with those found for Piney Woods, a humid vegetational region in the southern US [32]. In that region, irrespective of soil type and N application rate to wheat, the cowpea yields under El Niño years were significantly greater than those under La Niña. However, a slight discrepancy between those results and the results from this study was that in the Piney

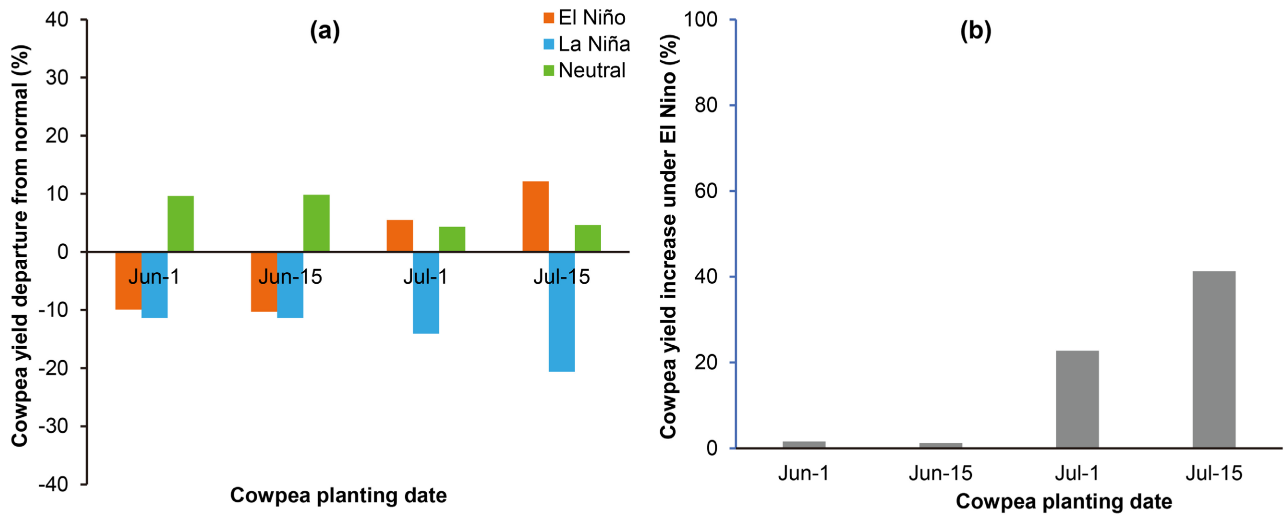

Figure 3. (a) Departure of cowpea grain yields produced under an El Niño-Southern Oscillation phase (El Niño, La Niña, or Neutral) from the normal (an 81-year average) yield for each cowpea planting date; and (b) increase in cowpea yields under El Niño relative to La Niña in the Llano Estacado region of the southern US.

Table 3. Simulated grain yields ($kg \cdot ha^{-1}$) of cowpea in the Llano Estacado region of southern US under the three El Niño-Southern Oscillation (ENSO) phases as affected by planting date.

Planting date	ENSO phase		
	El Niño	La Niña	Neutral
June 1	$753^{a\dagger}$	741^{a}	917^{a}
June 15	771^{a}	762^{a}	944^{a}
July 1	942^{a}	767^{a}	932^{a}
July 15	892^{a}	632^{b}	832^{ab}

†Means followed by the same letter across ENSO phases (horizontally) within a planting date are not significantly different at $\alpha = 0.1$.

Woods case the greater yields under El Niño relative to La Niña occurred even with the crops planted in June; whereas in the case of Llano Estacado, the greater yields under El Niño were associated only with the crops planted in July, not June. This difference indicated that the ENSO signal during the cowpea growing season in the Llano Estacado region was weaker than that in the Piney Woods region. In fact, the ENSO signal in the southeastern US is strongest in the southernmost part of the region and gradually weakens toward the north [28] [63]. Moreover, the northern parts of the region, especially those along the I-40 corridor, have been found to have very weak or no ENSO effects during the summer [24] [25].

3.2. The ENSO Effect on Mono-Cropped Wheat Yields

Figure 4 shows the simulated, detailed response of ^{m}wheat yields in the Llano Estacado region to ENSO as influenced by planting date × N application rate.

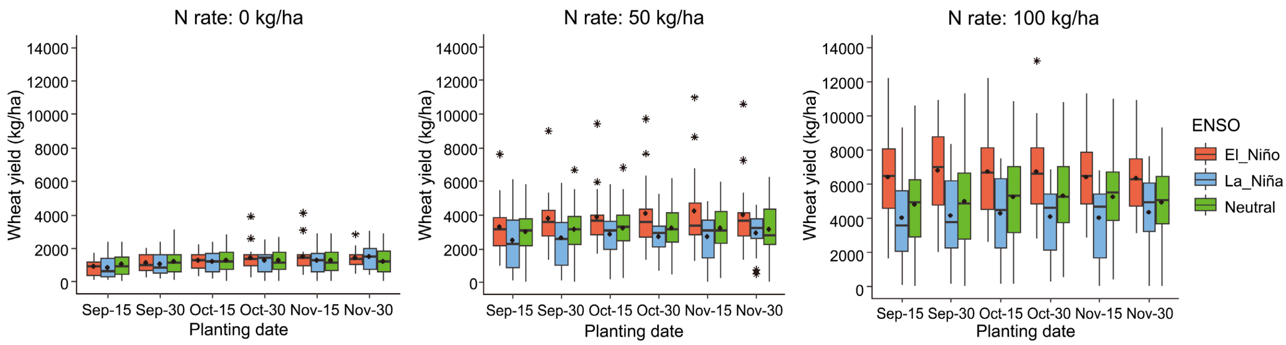

Figure 4. Response of wheat yields to El Niño-Southern Oscillation (ENSO) × planting date × N rate in the Llano Estacado region of the southern US. In a boxplot, the lower and upper ends of whiskers indicate minimum and maximum values, respectively; the dot indicates the mean value; the colored region shows interquartile range, and stars indicate outliers.

The results showed that at all planting dates the impact of ENSO on ^{m}wheat yields in this region was significant for the N rates of 50 and 100 kg·ha^{-1} (**Table 4**). For these N rates, the ^{m}wheat yields under the El Niño phase were significantly greater than those under the La Niña phase. At the zero N rate, however, the ^{m}wheat yields at any planting date were not significantly different across the three ENSO phases.

The greater yields under the El Niño phase at the N rates of 50 and 100 kg·ha^{-1} were likely because the amount of precipitation during October through May in the following year, the winter wheat growing season associated with the planting dates studied, was greater under El Niño than under La Niña (**Figure 5(a)**). That is, the crop water stress during this period was less under the El Niño phase (**Figure 5(b)**). The amount of precipitation during the growing season associated with each planting date was greater under the El Niño phase (**Figure 6(a)**). Accordingly, the crop water stress during the growing season for each planting date was lower during this phase (**Figure 6(b)**), indicating that the amount of water taken up by the crops at each planting date was different across ENSO phases.

Even with significantly different amounts of precipitation across ENSO phases, similar yields in all ENSO phases at zero N rate were due to low inherent fertility level of the soil. As **Table 1** shows, the total N and organic C contents of the soil were 0.07% and 0.67%, respectively. Since the plant production condition was N-limited under no N fertilizer application, the difference in precipitation across the ENSO phases could not lead to significantly different yields. The results indicated that under N-limited conditions the water use efficiency would be low, and thus the ENSO effect would not be evident. Indeed, when soil N level is low, it is the supply of N, not of water, that determines the grain yields; and, conversely, when soil N level is not low, it is the supply of water that determines the grain yields [64]. A higher N rate under high soil moisture condition increases biomass and grain yield by enhancing leaf area index and photosynthetic rate; that is, N fertilization enhances the amount of water extracted by a crop, and thus the water use efficiency [65]. Water and N are two vital factors influencing N uptake and utilization. While the former increases yields mainly through N

Table 4. Simulated grain yields (kg·ha^{-1}) of mono-cropped winter wheat in the Llano Estacado region of the southern US under the three El Niño-Southern Oscillation (ENSO) phases as affected by planting date × N application rate.

WPD†	N rate: 0 kg·ha^{-1} ENSO phase			N rate: 50 kg·ha^{-1} ENSO phase			N rate: 100 kg·ha^{-1} ENSO phase		
	E	L	N	E	L	N	E	L	N
Sep-15	$874^{a‡}$	851^{a}	1037^{a}	3269^{a}	2469^{b}	3013^{ab}	6404^{a}	4010^{b}	4776^{b}
Sep-30	1120^{a}	1074^{a}	1219^{a}	3781^{a}	2593^{b}	3101^{ab}	6778^{a}	4162^{c}	4975^{b}
Oct-15	1243^{a}	1175^{a}	1296^{a}	3826^{a}	2847^{b}	3237^{ab}	6719^{a}	4277^{c}	5236^{b}
Oct-30	1434^{a}	1263^{a}	1284^{a}	4081^{a}	2711^{b}	3237^{b}	6690^{a}	4051^{c}	5281^{b}
Nov-15	1502^{a}	1289^{a}	1261^{a}	4213^{a}	2689^{b}	3221^{b}	6379^{a}	3990^{c}	5255^{b}
Nov-30	1462^{a}	1383^{a}	1216^{a}	4022^{a}	2948^{b}	3129^{b}	6329^{a}	4311^{b}	4924^{b}

†WPD: Wheat Planting Date; E: El Niño; L: La Niña; N: Neutral. ‡Means followed by the same letter across ENSO phases (horizontally) within an N rate-planting date combination are not significantly different at $\alpha = 0.1$.

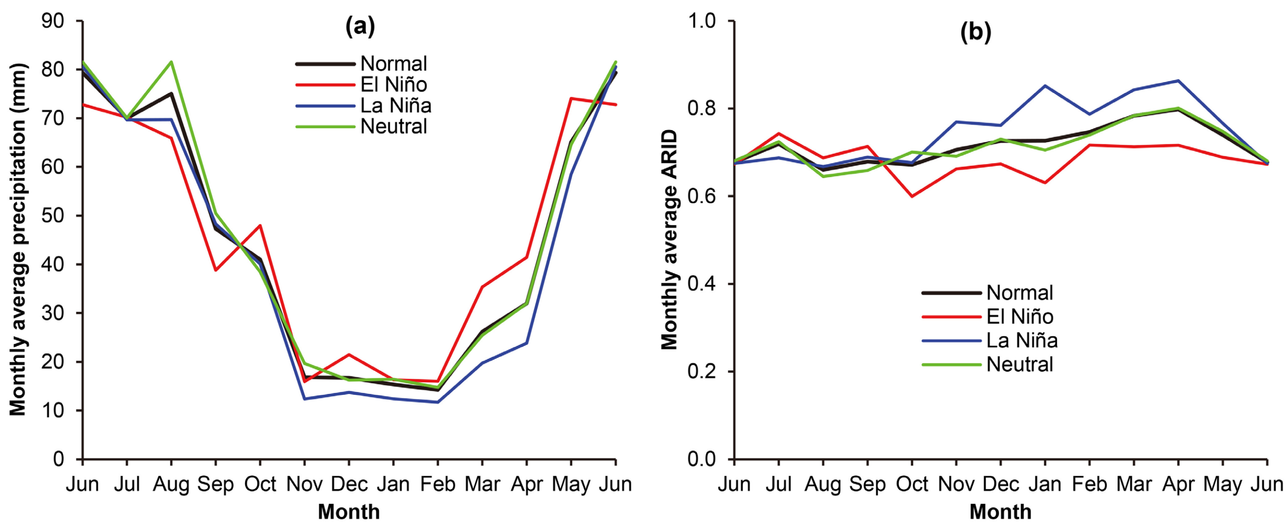

Figure 5. Average monthly values of (a) precipitation and (b) Agricultural Reference Index for Drought (ARID) during El Niño, La Niña, Neutral, and normal (all 81) years in the Llano Estacado region of the southern US.

productivity, the latter enhances yields through water productivity [66]. There is a significant synergistic relationship between crop water productivity and N use efficiency [67]. At the N rate of 50 kg·ha^{-1} or higher, however, N was not limiting. Thus, water use efficiency at these N rates was not restricted. The El Niño phase received more precipitation during the winter wheat growing season compared with the La Niña phase (**Figure 5**, **Figure 6**), thus leading to a higher soil water content, which in turn led to a higher N use efficiency. A higher soil N content, on the other hand, led to a higher water use efficiency. Because of these higher efficiencies, wheat yields under the El Niño phase at 50 kg N ha^{-1} or

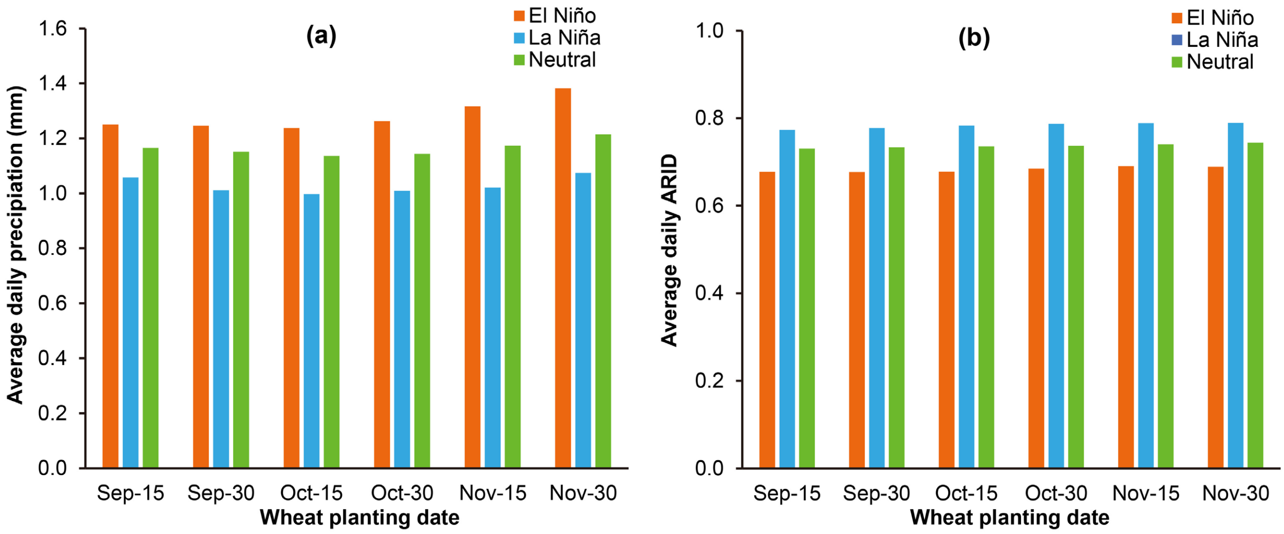

Figure 6. Average daily values of (a) precipitation and (b) Agricultural Reference Index for Drought (ARID) during wheat growing seasons associated with various planting dates under El Niño, La Niña, and Neutral phases in the Llano Estacado region of the southern US.

higher were significantly greater than those under the La Niña phase.

Although the ENSO effect on ^{m}wheat yields was significant only for the N application rates of 50 and 100 kg·ha^{-1}, the El Niño years tended to produce higher yields relative to the La Niña years for all systems comprising all the six planting dates x three N rates (**Table 4**, **Figure 7**). Irrespective of the planting date, the ^{m}wheat yields associated with the N rates of 0, 50, and 100 kg·ha^{-1} were approximately 5%, 20%, and 27% greater, respectively, in the El Niño years compared with the normal yield, an average yield of the entire 81 seasons (**Figures 7(a)-(c)**).

In the La Niña years, on the other hand, the ^{m}wheat yields at 0, 50, and 100 kg N ha^{-1} were about 5%, 15%, and 20% less than the normal yield, respectively, regardless of the planting date. Compared with the La Niña phase, the ^{m}wheat grain yields under the El Niño phase were greater by about 8%, 40%, and 60% at the N rates of 0, 50, and 100 kg·ha^{-1}, respectively, irrespective of the planting date (**Figure 7(d)**). These results demonstrated that the ENSO impact on ^{m}wheat yields in the Llano Estacado region would be greater with an increase in N application rate from 0 to 100 kg·ha^{-1} due to an increase in water use efficiency.

Statistically, the ENSO difference across planting dates in terms of yield departure from the normal yield was not significant (**Figure 7**). However, the difference tended to be greatest for November 15 planting date, especially at 50 kg N ha^{-1} or less. This was probably because the growing season associated with this planting date fell in peak winter when ENSO signal in the southern US is the strongest of all seasons.

The results regarding the greater wheat yields during the El Niño phase relative to La Niña in the Llano Estacado region were in agreement with those observed by reference [33]. They [33] evaluated ENSO effects on wheat yields in the Texas High Plains, which lies in the Llano Estacado region, using about 19

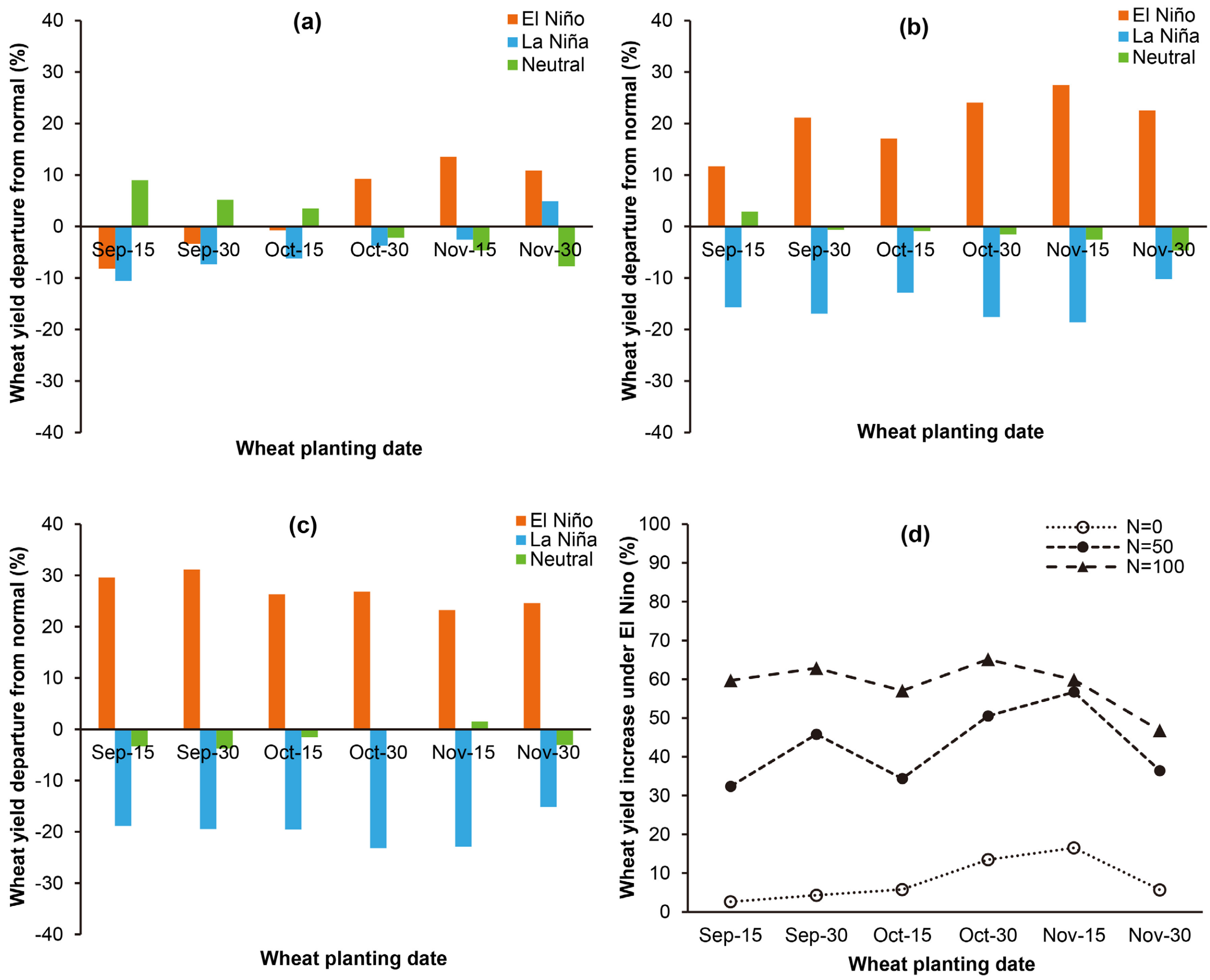

Figure 7. Departure of mono-cropped wheat grain yields produced under an El Niño, La Niña, or Neutral phase from the 81-year average normal yield for each planting date at the N application rate of: (a) 0, (b) 50, and (c) 100 kg·ha^{-1}; and (d) increase in wheat yields under El Niño relative to La Niña for each planting date-N rate combination in the Llano Estacado region of the southern US.

years' field-observed wheat yield data and found that the yields under the El Niño phase were about 55% greater than those under the La Niña phase. The greater yields under El Niño, relative to La Niña, that reference [33] as well as this study found in the Llano Estacado region were mainly due to precipitation and temperature, key weather variables determining growth, development, and yields of wheat. The precipitation difference during wheat seasons across ENSO phases and its effects on yields have been previously discussed (**Figure 5**, **Figure 6**). Regarding the temperature effects, due to lower temperatures during wheat growing seasons, the El Niño phase years generally resulted in greater yields. The La Niña phase years, in contrast, had lower yields due to higher temperatures during the growing seasons. Higher temperatures led to a shorter growing season, a shorter grain-filling period, lack of vernalization, and increased leaf senescence [26].

Our finding of the greater yields under El Niño for the semi-arid region of

Llano Estacado, however, did not agree with those found for the humid region of Piney Woods [32]. In the Piney Woods case, the grain yields of winter wheat were greatest under the La Niña phase. The likely reasons for this inconsistency were as follows. Llano Estacado is a semi-arid region that received an 81-year average precipitation of about 29 mm, roughly one-fourth of that received by the humid region of Piney Woods (116 mm), during the winter wheat growing season of October through May. As a dryland, therefore, Llano Estacado had water-limited growing conditions. Accordingly, wheat crops in this region were more sensitive to water than those in Piney Woods. Thus, an El Niño year in Llano Estacado, relative to a La Niña year, produced proportionately more yields than did an El Niño year in the Piney Woods region. Moreover, the ENSO signal in the northern part of the southern US is weaker than that in the southern part [28] [63]. Wheat shows a strong yield enhancement during weak-to-moderate El Niño events as it normally benefits from enhanced winter precipitation during El Niño; however, strong El Niño events, which bring excessive winter precipitation, suppress wheat yields [34]. Thus, the lesser wheat yields during El Niño, relative to La Niña, in the Piney Woods region caused by proportionately more or excessive winter precipitation were likely due to the following conditions. The relatively excessive precipitation during El Niño led to more losses of N through leaching. The excessively cooler conditions caused by excessive precipitation under El Nino possibly provided fewer wheat tillers per unit area [68] and more freeze injury to wheat crops, especially during jointing to flowering [69].

3.3. The ENSO Effect on Double-Cropped Wheat Yields

The simulated, average responses of ^{d}wheat yields in the Llano Estacado region to ENSO phases as influenced by cowpea planting date, wheat planting date, and N application rate are presented in **Table 5**. As the results showed, the impact of ENSO on ^{d}wheat yields in this region was significant especially for the scenarios comprising the wheat crops that were planted on October 15 or later following the cowpea crops planted in June and the wheat crops that were planted on October 30 or later following the cowpea crops planted in July. For these scenarios, the ^{d}wheat yields under the El Niño phase were significantly greater than those under the La Niña phase. The greater yields under El Niño were likely because the amounts of precipitation and crop water uptake during the wheat growing seasons associated with the significant scenarios were greater under this phase (**Figure 5**, **Figure 6**).

For the scenarios comprising wheat planted before October 15 or October 30 following cowpea planted in June or July, respectively, either the ENSO comparison was not possible because of no feasibility of cowpea-wheat doubling cropping in the study region [70], or, in the cases of feasible scenarios, the ^{d}wheat yields were not significantly different across ENSO phases. With a long-term simulation study conducted for the Llano Estacado region using 80 years' (1942-2021) weather data, reference [70] found that the number of feasible years

Table 5. Simulated grain yields (kg·ha^{-1}) of double-cropped winter wheat in the Llano Estacado region of the southern US under three El Niño-Southern Oscillation (ENSO) phases as affected by cowpea planting date × wheat planting date × N application rate.

CPD†	WPD	N rate: 0 kg·ha^{-1} ENSO phase			N rate: 50 kg·ha^{-1} ENSO phase			N rate: 100 kg·ha^{-1} ENSO phase		
		E	L	N	E	L	N	E	L	N
June-1	Sep-15	NA§	NA	NA	NA	NA	NA	NA	NA	NA
	Sep-30	422^{a‡}	228^{a}	567^{a}	760^{a}	364^{a}	847^{a}	1033^{a}	406^{a}	1082^{a}
	Oct-15	1129^{a}	552^{b}	749^{ab}	1954^{a}	749^{b}	1062^{b}	2537^{a}	747^{b}	1204^{b}
	Oct-30	1220^{a}	794^{b}	1056^{ab}	2049^{a}	1053^{b}	1445^{b}	2490^{a}	1096^{b}	1650^{b}
	Nov-15	1573^{a}	941^{b}	1079^{b}	2427^{a}	1197^{b}	1453^{b}	2803^{a}	1239^{b}	1607^{b}
	Nov-30	1626^{a}	936^{b}	1066^{b}	2368^{a}	1143^{b}	1386^{b}	2652^{a}	1177^{b}	1483^{b}
June-15	Sep-15	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Sep-30	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Oct-15	855^{a}	291^{b}	674^{ab}	1450^{a}	413^{b}	1029^{ab}	1832^{a}	524^{b}	1294^{ab}
	Oct-30	1009^{a}	614^{b}	982^{ab}	1504^{a}	797^{b}	1383^{ab}	2008^{a}	953^{b}	1599^{ab}
	Nov-15	1549^{a}	913^{b}	1144^{ab}	2381^{a}	1182^{b}	1629^{ab}	2797^{a}	1356^{b}	1889^{b}
	Nov-30	1410^{a}	1025^{b}	1040^{ab}	2145^{a}	1447^{b}	1488^{b}	2523^{a}	1682^{b}	1697^{b}
July-1	Sep-15	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Sep-30	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Oct-15	150^{a}	NA	15^{a}	319^{a}	NA	23^{a}	476^{a}	NA	35^{a}
	Oct-30	780^{a}	281^{b}	564^{ab}	1190^{a}	389^{b}	981^{ab}	1446^{a}	393^{b}	1243^{a}
	Nov-15	1191^{a}	605^{b}	997^{ab}	2001^{a}	881^{b}	1485^{a}	2491^{a}	966^{b}	1840^{a}
	Nov-30	1173^{a}	802^{b}	964^{ab}	1884^{a}	1154^{b}	1440^{ab}	2316^{a}	1324^{b}	1687^{ab}
July-15	Sep-15	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Sep-30	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Oct-15	228	NA	NA	394	NA	NA	618	NA	NA
	Oct-30	494^{a}	119^{a}	296^{a}	956^{a}	238^{b}	539^{ab}	1207^{a}	256^{b}	695^{ab}
	Nov-15	1338^{a}	271^{c}	727^{b}	2569^{a}	433^{c}	1279^{b}	3419^{a}	493^{c}	1818^{b}
	Nov-30	1398^{a}	347^{b}	1194^{a}	2623^{a}	518^{c}	1924^{b}	3371^{a}	529^{c}	2493^{b}

†CPD: Cowpea Planting Date; WPD: Wheat Planting Date; E: El Niño; L: La Niña; N: Neutral. §NA: Not Available. For this scenario, cowpea-wheat double cropping system was not possible. ‡Means followed by the same letter across ENSO phases (horizontally) within an N rate-planting date combination are not significantly different at $\alpha = 0.1$.

for cowpea-wheat double-cropping in the Llano Estacado region ranged from 0 to 52, depending on the double-cropping scenario comprising the planting dates of cowpea and wheat (**Figure 8**). As they demonstrated, the feasibility was highest, about 65%, with July 15 and November 30 as the planting dates of cowpea and wheat, respectively. They further observed that the feasibility of double-cropping

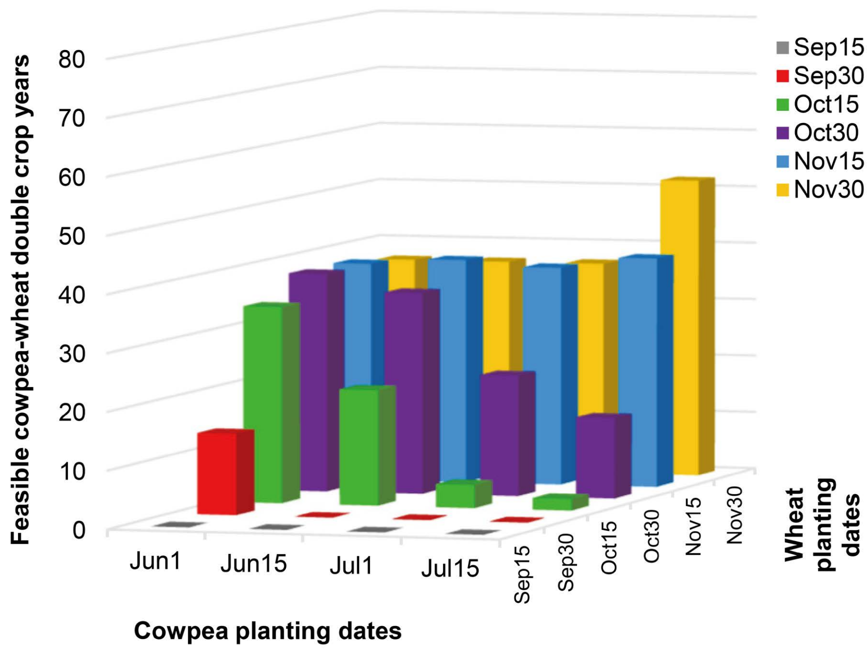

Figure 8. The total number of years that were feasible for cowpea-wheat double-cropping in the Llano Estacado region of the southern US as impacted by the planting dates of cowpea and wheat.

was primarily determined by the number of days available for and required by the preceding cowpea crop and the total number of days needed by the double crops of cowpea and wheat, which decreased with delays in cowpea and wheat planting.

Even with a higher soil N level, the generally lesser yields of ^{d}wheat (Table 5), relative to ^{m}wheat (Table 4), were because of the number of feasible years for double-cropping (Figure 8). As the number of feasible years for any double-cropping scenario was not 80 (out of total 80 years available), the ^{d}wheat yields for the unfeasible years (80 minus feasible years) were assumed to be zero. The averaging of ^{d}wheat yields associated with both feasible and unfeasible years, therefore, led to the smaller values compared with the yields of ^{m}wheat that were associated with the years that were all feasible.

Unlike ^{m}wheat yields, which were impacted by ENSO only at the N rate of 50 kg·ha^{-1} or higher (Table 4), the ^{d}wheat yields were impacted by ENSO also at the zero N rate (Table 5). As explained above, the insignificant impact of ENSO on ^{m}wheat yields at the zero N rate was due to low inherent fertility level of the soil. With the inclusion of cowpea, a legume crop, just before wheat crops, a significant amount of N (about 100 kg ha^{-1} season^{-1}) was incorporated into the soil through symbiotic N fixation and cowpea stover residues application. Thus, under double-cropping systems containing cowpea under dryland conditions, wheat production was not N-limited but water-limited. As soil N level was not low even at the zero N rate, the ^{d}wheat grain yields were determined by the water supply [64] that was associated with ENSO conditions and the water use efficiency that was enhanced by high N level [65] [66] [67]. Thus, the [d]wheat yields under El Niño were significantly greater than those under La Niña even when no N fertilizer was applied.

4. Conclusions

Simulated results showed that in Llano Estacado, a semi-arid region of the southern US, the El Niño phase of ENSO produced about 30% higher yields of mono-cropped cowpea than those produced under the La Niña phase, especially for the crops planted in July. The cowpea yields in El Niño years were about 10% more than the normal yield, whereas those in La Niña years were about 20% less than the normal yield. At the N rates of 0, 50, and 100 kg·ha^{-1}, El Niño years produced, respectively, about 8%, 40%, and 60% higher yields of mono-cropped wheat than those produced in La Niña years and about 5%, 20%, and 27% more than the normal yield. In La Niña years, the wheat yields at 0, 50, and 100 kg N ha^{-1} were, respectively, about 5%, 15%, and 20% less than the normal yield. The impact of ENSO on wheat yields under cowpea-wheat double-cropping systems was significant only for the wheat crops planted in October or later following the cowpea crops planted in June or later. Unlike mono-cropped wheat yields, double-cropped wheat yields were impacted by ENSO also at zero N due to high soil N level caused by N transfer from cowpea residues and roots.

In Llano Estacado, this study suggested more successful cowpea production with mid-July planting dates during El Niño. The avoidance of planting cowpeas during La Niña would also substantially reduce risk and losses. Most commercial wheat operations in this region do not apply N fertilizer; thus, attention to the ENSO phase may not be deemed as an important management strategy. However, the recognition of El Niño would provide an incentive to add N fertilizer to substantially increase grain yields by 40% to 60%. For a double-cropping cowpea-wheat system for cover crop and/or grain production, the transfer of cowpea-origin N for wheat provided a significant productivity enhancement during El Niño. Management strategies should be attentive to probabilities for rainfall events and recognize the ENSO phase that will coincide with potential planting dates to avert the risk of crop failure and economic loss.

Acknowledgements

Funding for this work was provided by Texas A&M AgriLife Research at Overton, TX.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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