Agricultural Sciences, 2022, 13, 758-775
https://www.scirp.org/journal/as
ISSN Online: 2156-8561
ISSN Print: 2156-8553

Assessing Cowpea-Wheat Double Cropping Strategies in the Southern United States Using the DSSAT Crop Model

Prem Woli*, Gerald Ray Smith, Charles Long, Francis Monte Rouquette Jr.

Texas A&M AgriLife Research Center, Overton, Texas, USA
Email: *prem.woli@agnet.tamu.edu

How to cite this paper: Woli, P., Smith, G.R., Long, C. and Rouquette Jr., F.M. (2022) Assessing Cowpea-Wheat Double Cropping Strategies in the Southern United States Using the DSSAT Crop Model. *Agricultural Sciences*, **13**, 758-775.
https://doi.org/10.4236/as.2022.136049

Received: May 26, 2022
Accepted: June 27, 2022
Published: June 30, 2022

Abstract

Information is limited on the potential of cowpea-wheat double cropping in the southern United States to enhance soil health and increase net returns. Using the Decision Support System for Agrotechnology Transfer (DSSAT) crop model and weather data spanning 80 years, we assessed the effects of soil type (Darco: *Grossarenic Paleudults* and Lilbert: *Arenic Plinthic Paleudults*), N application rate (0, 100, and 200 kg·ha^{-1}), and El Niño-Southern Oscillation (ENSO) on the grain yields of double-cropped cowpea (*Vigna unguiculata* L.) and wheat (*Triticum aestivum* L.) in this region. Yield differences were tested using the pairwise Wilcoxon rank sum test. Results showed that yields of wheat that followed cowpea (^{c}wheat) were greater than those that followed fallow (^{f}wheat). The soil type effects on ^{c}wheat and ^{f}wheat yields decreased with an increase in N rate. The soil type effect on cowpea yields was greater during La Niña. The ENSO impact on cowpea yields was greater on the less fertile soil Darco. Yields of ^{c}wheat and ^{f}wheat increased with an increase in N rate up to 100 and 200 kg·ha^{-1}, respectively. The yield response of ^{c}wheat to N rate was less than that of ^{f}wheat. The N rate effects on ^{c}wheat and ^{f}wheat yields were greater on Darco and under El Niño. Yields of cowpea were greatest under El Niño, whereas those of wheat were greatest under La Niña. The ENSO effect on cowpea yields was greater on Darco. With an increase in N rate, the effect of ENSO was diminished.

Keywords

Cowpea-Wheat, DSSAT, Double-Cropping, ENSO, Model

1. Introduction

Improvements in agricultural practices are needed to enhance sustainability and efficient use of soil, water, and other cropping resources with attention to profitability and increased food production. Double cropping is a system of warm season-cool season cropping that produces two harvested crops in one 12-month period. Soybean (*Glycine max* [L.] Merr.) and wheat (*Triticum aestivum* L.) double cropping in the lower Mississippi River Valley of the United States is a common example of this type of intensive agriculture grain production [1]. In this region of the southern United States, soybean-wheat double cropping has been adopted to improve the sustainability of row-crop agriculture and to eliminate or decrease N fertilizer applied to the wheat crop. Multiple studies indicated that soybean-wheat double cropping improves profitability and resource efficiency compared to monocultures [1] [2]. Besides increased profits from soybean-wheat double cropping, this planting system decreases erosion and reduces soil-water losses by runoff and evaporation [3]. Using loamy sand and fine sandy loam soils for wheat-soybeans, reference [4] showed that double-cropped soybeans had improved growth and yield compared to the fallow-soybean mono-cropping system. They attributed the increased soybean growth to wheat serving as a cover crop during the winter months and the residual nutrients from the winter wheat. In addition, reference [5] showed that wheat-soybean double cropping improved the capture and efficiency of use of rainfall and photosynthetically active radiation compared to monocropping wheat or soybeans.

Cowpea (*Vigna unguiculata* [L.] Walp.) is important in world agriculture as a pulse, forage, and vegetable crop in tropical, semi-tropical, and arid regions. Cowpea is generally drought and heat tolerant compared to other grain legumes but will have production losses if daytime maximum temperatures are above 40˚C [6]. The estimated world production of dry pulse cowpea was 7 million metric tons in 2011 [6]. Dry pulse cowpea production in the United States was centered in California with some Texas production between the years 2005 and 2015 and has ranged from 2000 to 6000 ha yr^{-1} with yields at 2200 kg ha^{-1} [7]. In Brazil, about 1.4 million ha of cowpea are grown annually with average grain yields of 526 kg ha^{-1}. A cowpea-wheat double cropping system in Brazil produced 1900 kg ha^{-1} of cowpea grain and 5593 kg ha^{-1} of wheat grain with the 0 kg N ha^{-1} fertilizer treatment [8]. More field research information is needed to determine the potential for cowpea-wheat double cropping in other Texas regions and the humid southeastern United States to enhance soil health properties and increase net returns.

Climate is a major factor defining interannual variability in crop production. The yearly fluctuation of climate in the southern United States has been linked to a set of coupled ocean-atmosphere phenomena occurring across the tropical Pacific, collectively known as El Niño-Southern Oscillation (ENSO) [9] [10]. For the southern United States, an ENSO phase may be skillfully forecasted up to a year in advance because of the strong connection between weather patterns in this region and ENSO [11]. Thus, cowpea and wheat production in this region may potentially be benefitted from ENSO forecasts. A number of studies have been conducted on connections between ENSO and various specific crops in this region [12]-[22]. However, no study has assessed the relationships among cowpea-winter wheat double-cropping, soil type, N application rate, and ENSO for the southern United States. An understanding of such relationships could assist cowpea-winter wheat grain producers in this region in adopting alternative management strategies.

For solving real-world problems safely and efficiently by providing clear comprehensions of complex systems, the systems analysis approach is valuable [23] [24]. Since crop simulation models predict plant growth and development as influenced by crop management and the environment by using quantitative descriptions of ecophysiological processes [25], they can be valuable tools for studying various scenarios comprising a number of variables in the soil-plant-atmosphere continuum. One of the widely-tested and used suite of crop models that can be used to effectively study these scenarios is Decision Support System for Agrotechnology Transfer (DSSAT: [26] [27]).

The objectives of this study were to assess the effects of cowpea-wheat crop sequence, soil type, N application rate, ENSO, and their interactions on the grain yields of cowpea and winter wheat in southern United States using the sequence analysis tool of the DSSAT crop model.

2. Materials and Methods

2.1. DSSAT and Its Sequence Analysis Tool

The DSSAT crop model is a software application program comprising simulation models for many crops and tools to facilitate the effective use of the models [28]. The crop models simulate growth, development, and yield as a function of the soil-plant-atmosphere continuum. The model tools include database management programs for applications, crop data, soil, utilities, and weather. The DSSAT suite of crop models has been used for various applications at different spatial and temporal scales such as on-farm and precision management, climate variability and climate change impacts, breeding and gene-based modeling, water use, greenhouse gas emissions, and agroecosystem sustainability [28]. The inputs for the crop models include data on daily weather, soil surface and profile, and crop production-management details. The simulations are conducted primarily on a daily basis. At the end of each day, the balances of soil-plant water, nitrogen, phosphorus, and carbon, as well as development states are updated. To simulate multi-year outcomes of crop management strategies, DSSAT integrates the effects of soil, crop phenotype, weather, and management options by combining crop, soil, and weather databases with crop models and application programs.

The Sequence Analysis tool allows the user to conduct rapid inspection and analysis of results of long-term cropping sequences [29]. The model tool allows the user to calculate a series of statistics and create various graphics that examine relationships between trends and variability. The main aspect of the sequence analysis is that simulation studies are conducted across multiple cropping seasons; thus, status of soil water and nutrient is carried over from one cropping season to the subsequent one [30] [31].

2.2. Site and Data

The Texas A&M AgriLife Research & Extension Center at Overton (32.29˚N, 94.97˚W) is situated in the Pineywoods region of the southern United States. This region, where agriculture is a major economic activity, comprises eastern Texas, western Louisiana, and southern Arkansas. At the Overton Center, numerous soil fertility and cultivar trials and grazing experiments have been conducted by various scientists since 1967. In this study, Overton, Texas was used as a representative site for the Pineywoods region and the humid Southeastern United States [21] [22].

To explore the interannual climate variability effects on the yields of cowpea and wheat in the Pineywoods region, a long-term weather dataset spanning 80 years (1942-2021) was used. The historical daily data on temperature and precipitation were obtained from https://www.ncei.noaa.gov/access/search/data-search/daily-summaries (National Centers for Environmental Information) and the reports and publications from the Texas A&M AgriLife Research and Extension Center at Overton, whereas those on solar radiation were generated using a reliable irradiation model described by [32].

Darco (*Grossarenic Paleudults*) and Lilbert (*Arenic Plinthic Paleudults*) were used as representative soils for the study because they are some of the major soils used for agricultural purposes in the Pineywoods region [33] [34]. The soil data were obtained from the Gridded Soil Survey Geographic (gSSURGO) database of the USDA NRCS [35] [36]. These soils are distinct in various aspects, including texture and inherent fertility level. Compared with Lilbert, Darco had less clay and silt contents, greater saturated hydraulic conductivity, deeper A and E horizons (122 cm vs. 58 cm), less organic C and inorganic N contents, and smaller values of field capacity and wilting point (**Table 1**). However, the water holding capacities of both soils were about the same.

2.3. The Simulation Study Design

The DSSAT Sequence Analysis tool was used to simulate grain yields for cowpea and winter wheat in two sequences: cowpea-wheat double crop and fallow-wheat. The wheat crop that followed cowpea or fallow, hereafter, will be referred to as ^{c}wheat and ^{f}wheat, respectively. Simulations were made using two soils, Darco and Lilbert, and three N application rates only to wheat at 0, 100, and 200 kg N ha^{-1}. Thus, a total of 12 scenarios were assessed, which comprised 2 sequences × 2 soils × 3 N rates (**Table 2**).

For simulations, the following management and environmental inputs were assumed. For cultivars, we used "Hyfowet" for winter wheat and "Cal #5 MG4"

Table 1. Properties of two representative soils in the Pineywoods region of the southern US.

Soil	Layer	MH[a]	WP	FC	SA	WH	HC	Clay	Silt	TN	OC	pH
	(cm)	-	-	-	-	-	cm/h	%	%	%	%	-
Darco (drainage coefficient = 0.75; run-off curve number = 64):												
	0 - 10	A	0.07	0.17	0.42	0.10	33.12	9.0	9.2	3.48	0.35	5.5
	10 - 122	E	0.08	0.18	0.32	0.10	33.12	9.0	9.2	0.99	0.10	5.5
	122 - 203	Bt	0.16	0.24	0.40	0.08	3.24	23.5	17.8	0.58	0.06	5.5
	Weighted avg.		0.11	0.20	0.36	0.09	21.20	14.79	12.63	0.95	0.10	5.5
Lilbert (drainage coefficient = 0.60; run-off curve number = 35):												
	0 - 23	A	0.08	0.18	0.37	0.10	33.03	9.0	9.2	7.35	0.73	5.3
	23 - 58	E	0.07	0.18	0.36	0.10	33.03	9.0	9.2	3.48	0.35	5.3
	58 - 109	Bt	0.18	0.27	0.35	0.09	3.30	25.5	18.0	3.48	0.35	4.6
	109 - 203	Btv	0.18	0.27	0.32	0.09	1.02	27.0	17.6	3.48	0.35	4.6
	Weighted avg.		0.15	0.24	0.34	0.09	10.74	21.48	15.30	3.91	0.39	4.8

a. MH = master horizon, WP = wilting point, FC = field capacity, SA = saturation, WH = water holding capacity, HC = saturated hydraulic conductivity, TN = total N, OC = organic carbon.

Table 2. The simulation study scenarios comprising two crop sequences, two soil types, and three N applications rates (kg N ha^{-1}).

Sr. no.	Crop sequence	Soil type	N rate to wheat	Scenario
1	cowpea-wheat[a]	Darco	0	[cowpea-wheat (0N)]: Darco
2			100	[cowpea-wheat (100N)]: Darco
3			200	[cowpea-wheat (200N)]: Darco
4		Lilbert	0	[cowpea-wheat (0N)]: Lilbert
5			100	[cowpea-wheat (100N)]: Lilbert
6			200	[cowpea-wheat (200N)]: Lilbert
7	fallow-wheat	Darco	0	[fallow-wheat (0N)]: Darco
8			100	[fallow-wheat (100N)]: Darco
9			200	[fallow-wheat (200N)]: Darco
10		Lilbert	0	[fallow-wheat (0N)]: Lilbert
11			100	[fallow-wheat (100N)]: Lilbert
12			200	[fallow-wheat (200N)]: Lilbert

a. Double crop.

for cowpea. The Hyfowet cultivar was the highest-yielding wheat cultivar in east Texas as identified by [21]. Because the genetic coefficients for this cultivar were already estimated by [21], there was no need to further calibrate and evaluate the wheat model for this cultivar. For the Cal #5 MG4 cultivar, the default genetic coefficients for this cowpea cultivar are those in the standard DSSAT release [27] and correspond to the cultivar coefficients upon which the cowpea model was adapted (K. J. Boote, personal communication, 11 February 2022). The simulation start date was assumed to be June 20, 1942, and simulation would terminate on the harvest date of cowpea in 2021. On the simulation start day, soil moisture was assumed to be at field capacity and soil N content 25 kg ha^{-1}. For planting dates, we assumed June 20 for cowpea and October 20 for wheat. The plant populations used were 30 plants m^{-2} (about 40 kg seed ha^{-1}) for cowpea and 323 plants m^{-2} (about 100 kg seed ha^{-1}) for wheat. Using the conventional tillage, dry seeds were planted on rows at 3 cm depth. Inorganic N fertilizer was given only to wheat, not cowpea.

Of the total amount of N applied to wheat, 50% was applied at the planting time and the remainder on February 15 of the following year. For organic amendments, the cowpea stover residue of 2125 kg DM ha^{-1}, with the N content of 1.5%, was incorporated into the soil on the planting date of wheat, and the wheat residue of 500 kg DM ha^{-1}, with the N content of 1%, was incorporated in the soil on the planting date of cowpea. For soil organic matter, Century was used as the method, with the five years' field history of "Cultivated, good management, initial default SOM" [37].

2.4. ENSO Classification

For ENSO analyses, the yields of cowpea, ^{c}wheat, and ^{f}wheat that were simulated for each of the 80 years (1942-2021) were assigned to an ENSO phase – El Niño, La Niña, or Neutral – as categorized by the Japan Meteorological Agency (JMA) index [38] [39] [40] [41]. For ENSO characterization, the JMA index was chosen because it best selects the known ENSO events [41]. Accordingly, the total numbers of El Niño, La Niña, and Neutral years analyzed were 18, 20, and 42, respectively. The JMA index is a 5-month moving average of the sea surface temperature anomalies over the tropical Pacific (4˚S - 4˚N, 150˚W - 90˚W). The ENSO year of 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 [39] [41].

2.5. Data Analyses

For cowpea, ^{c}wheat, and ^{f}wheat each significance tests were carried out to assess grain yield differences across soil types as influenced by N rate and ENSO interactions, across N rates as influenced by soil type and ENSO interactions, and across ENSO phases as influenced by soil type and N rate interactions. The tests were done using a nonparametric alternative to the two-sample t-test, known as the pairwise Wilcoxon rank sum test [42]. The reason for using the Wilcoxon test was that 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/).

3. Results and Discussion

The grain yields of ^{c}wheat were greater than those of ^{f}wheat on both Darco and Lilbert soils at all the three N rates considered (0, 100, and 200 kg ha^{-1}) and under the three ENSO phases—El Niño, La Niña, and Neutral (Table 3). These results were likely because ^{c}wheat received more nutrients than did ^{f}wheat mainly through two processes: the symbiotic N fixation of cowpea (about 117 kg N ha^{-1} season^{-1}) and N transfer from the cowpea crop residue applied (about 32 kg N ha^{-1} season^{-1} from the residue of 2125 kg DM).

3.1. Soil Type Effects on Cowpea and Wheat Yields

3.1.1. Influence of N Rate

Under all ENSO phases, the soil type effect on ^{f}wheat yields was significant at all N rates considered (0, 100, and 200 kg ha^{-1}) and that on ^{c}wheat yields was significant only at 0 kg N ha^{-1} (Table 3). In all these cropping cases, the yields of both ^{c}wheat and ^{f}wheat on the Lilbert soil were greater than those on the Darco

Table 3. The soil type effects on the grain yields of cowpea and wheat as influenced by N rate x ENSO phase interactions over 80 years long-term weather at Overton, TX.

			Yield (kg ha^{-1})		
N rate	ENSO	Soil	Cowpea	^{c}Wheat†	^{f}Wheat
0	El Niño	Darco	980^{a‡}	3422^{b}	793^{b}
		Lilbert	1094^{a}	4104^{a}	1886^{a}
	La Niña	Darco	687^{b}	3915^{b}	1060^{b}
		Lilbert	842^{a}	4711^{a}	2662^{a}
	Neutral	Darco	922^{a}	3812^{b}	979^{b}
		Lilbert	1055^{a}	4587^{a}	2492^{a}
100	El Niño	Darco	983^{a}	4578^{a}	2504^{b}
		Lilbert	1095^{a}	4867^{a}	3498^{a}
	La Niña	Darco	700^{b}	4957^{a}	3013^{b}
		Lilbert	878^{a}	5119^{a}	4212^{a}
	Neutral	Darco	959^{a}	4692^{a}	2898^{b}
		Lilbert	1078^{a}	4886^{a}	4026^{a}
200	El Niño	Darco	981^{a}	4850^{a}	4428^{b}
		Lilbert	1105^{a}	4939^{a}	4904^{a}
	La Niña	Darco	715^{b}	5110^{a}	4899^{b}
		Lilbert	892^{a}	5129^{a}	5158^{a}
	Neutral	Darco	988^{a}	4871^{a}	4542^{b}
		Lilbert	1092^{a}	4908^{a}	4858^{a}

^{†,c}wheat = wheat preceded by cowpea, ^{f}wheat = wheat preceded by fallow, ‡Means followed by the same letter between soils (vertically) within a N rate-ENSO-crop combination are not significantly different at $\alpha = 0.1$.

soil. The greater yields produced on Lilbert, compared with Darco, were likely due to the following reasons. Lilbert was a heavier soil, containing larger proportions of clay and silt (**Table 1**); thus, it was less prone to percolation losses. Lilbert was more productive because its inherent inorganic N and organic C contents were greater. The eluviation zone of Lilbert, which consisted of the master horizons of A and E, was much shallower (58 cm) than that of Darco (122 cm). A shallower zone of eluviation, which contained more nutrients for plant growth, represented a smaller volume where small colloidal-sized materials had been removed through the movement of water [43]. Compared with the ^{c}wheat yields, the ^{f}wheat yields were associated with less fertile soils due to the absence of N fixed by cowpea and N transferred from cowpea residue. Because of lower soil fertility levels, the ^{f}wheat crops were more responsive to the applied N than were the ^{c}wheat crops. Thus, the ^{f}wheat yields on Lilbert were greater at all N rates. Since the productivity levels of soils associated with ^{c}wheat crops were already higher than associated with ^{f}wheat crops, additional amounts of N contributed less. Thus, the ^{c}wheat crops started plateauing at about 100 kg N ha^{-1}. Regardless of the ENSO phase, soil type effects on the yields of ^{c}wheat and ^{f}wheat decreased with an increase in N rate. For instance, at the N rates of 0, 100, and 200 kg ha^{-1}, respectively, the ^{c}wheat yields were 20%, 4%, and 1% greater and the ^{f}wheat yields were 148%, 40%, and 8% greater on Lilbert than those on Darco. The decreasing soil type effect with an increase in N rate was likely because the inherent fertility level of Lilbert was higher than that of Darco. Thus, the yield difference between the two soils was very large at low N level. With an increase in N rate, however, the yield difference became less because additional amounts of N contributed less due to decrease in N efficiency.

3.1.2. Influence of ENSO

At all N rates, cowpea yields were impacted by soil type only under the La Niña phase of ENSO. Irrespective of N rate, the soil type effect on cowpea yields was greater during La Niña. Under this phase, the cowpea yields on Lilbert were 25% greater than those on Darco, whereas the greater yields on Lilbert were only 12% during the El Niño phase (**Table 3**). Regardless of soil type and N rate, cowpea yields under La Niña were the least of all ENSO phases. This was likely because La Niña received the smallest amounts of precipitation during the growing season (June-October) (313 mm under La Niña vs. 362 mm under El Niño), the establishment phase (June-July), the peak summertime (August), and the flowering and pod formation stages (mid-Sept to mid-Oct), the critical stages of water requirement for cowpeas [44] (**Figure 1**). This scenario was confirmed by the amount of water transpired by the cowpea crops that was the least under this phase (197 mm vs. 220 mm under El Niño). Because the impact of weather on crop yields was stronger on a less productive soil as higher soil fertility could mask the weather effect, the La Niña impact on Darco, a less productive soil than Lilbert (Darco: 0.95% total N, 0.10% organic C vs. Lilbert: 3.91% total N, 0.39%

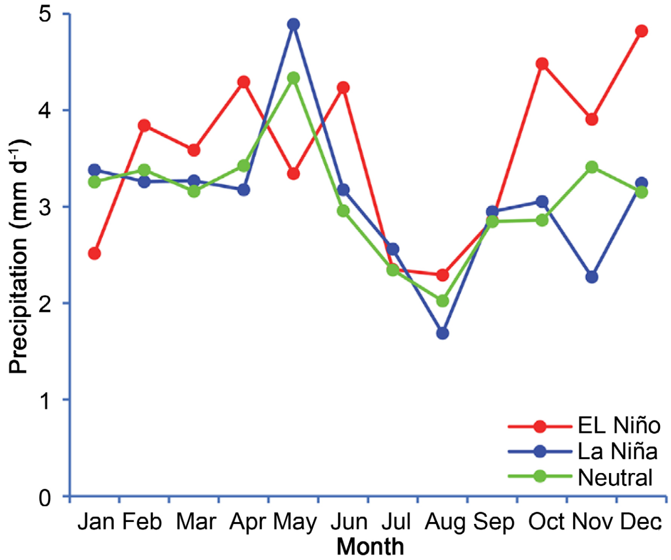

Figure 1. Daily average precipitation distribution in different months during the year under the three ENSO phases (El Niño, La Niña, and Neutral) at Overton, Texas.

organic C), was greater than that on Lilbert. This phenomenon led to further decrease in cowpea yields on Darco relative to Lilbert under La Niña. The greater yields of cowpea on Lilbert relative to Darco during La Niña were also likely due to the textural differences of these soils. The larger amount of water that the Lilbert soil, which was heavier than Darco, was able to conserve in a drier year of La Niña played more important role in producing cowpea yields than that conserved in a wetter year of El Niño. For ^{c}wheat and ^{f}wheat yields, the soil type effect was not influenced by ENSO because rainfall was not restrictive during this period of wheat growth.

3.2. The N Rate Effects on Cowpea and Wheat Yields

The yields of ^{c}wheat and ^{f}wheat were both impacted by the N application rate, regardless of soil type or ENSO phase (**Table 4**). On both soils under all ENSO phases, the yields of both ^{c}wheat and ^{f}wheat increased with an increase in N rate from 0 to 100 and 200 kg ha^{-1}, respectively. However, with an increase in N rate from 100 to 200 kg ha^{-1}, ^{c}wheat yields did not increase. The yield responses of ^{c}wheat to N rate were lower than those of ^{f}wheat because ^{c}wheat yields were associated with a higher soil fertility level from cowpea residue (about 32 kg N ha^{-1} season^{-1}) and N transfer through N fixation (about 117 kg N ha^{-1} season^{-1}). Since the inherent fertility level of the soil associated with ^{c}wheat was relatively high, additional amounts of N contributed less; thus, the ^{c}wheat yields started plateauing at 100 kg N ha^{-1}. The ^{f}wheat yields, however, did not level off at this N rate due to a lower soil fertility level.

For cowpea yields, however, no N application rate effect was observed on either soil under all ENSO phases. These results were expected because cowpea is a

Table 4. The N application rate effects on the grain yields of cowpea and wheat as influenced by soil type x ENSO phase interactions over 80 years long-term weather at Overton, TX.

			Yield (kg ha^{-1})		
Soil	ENSO	N rate	Cowpea	^{c}Wheat†	^{f}Wheat
Darco	El Niño	0	980^{a‡}	3422^{b}	793^{c}
		100	983^{a}	4578^{a}	2504^{b}
		200	981^{a}	4850^{a}	4428^{a}
	La Niña	0	687^{a}	3915^{b}	1060^{c}
		100	700^{a}	4957^{a}	3013^{b}
		200	715^{a}	5110^{a}	4899^{a}
	Neutral	0	922^{a}	3812^{b}	979^{c}
		100	959^{a}	4692^{a}	2898^{b}
		200	988^{a}	4871^{a}	4542^{a}
Lilbert	El Niño	0	1094^{a}	4104^{b}	1886^{c}
		100	1095^{a}	4867^{a}	3498^{b}
		200	1105^{a}	4939^{a}	4904^{a}
	La Niña	0	842^{a}	4711^{b}	2662^{c}
		100	878^{a}	5119^{a}	4212^{b}
		200	892^{a}	5129^{a}	5158^{a}
	Neutral	0	1055^{a}	4587^{b}	2492^{c}
		100	1078^{a}	4886^{a}	4026^{b}
		200	1092^{a}	4908^{a}	4858^{a}

^{†,c}wheat = wheat preceded by cowpea, ^{f}wheat = wheat preceded by fallow, ‡Means followed by the same letter across N rates (vertically) within a soil-ENSO-crop combination are not significantly different at $\alpha = 0.1$.

legume, despite no N fertilizer, and wheat residues carry-over (5 kg N ha^{-1} season^{-1} from the residue of 500 kg DM) did not enhance cowpea yields. The N applications were made only for ^{c}wheat and ^{f}wheat crops. These N applications did not have any significant residual effects on the yields of cowpea which followed wheat.

3.2.1. Influence of Soil Type

Regardless of the ENSO phase, the N rate effect on both ^{c}wheat and ^{f}wheat yields was greater on Darco, relative to Lilbert. For instance, ^{c}wheat yields on Darco and Lilbert increased by about 28% and 12%, respectively, when N rate was increased from 0 to 100 kg ha^{-1}. Likewise, ^{f}wheat yields at the N rate of 100 kg ha^{-1} on Darco and Lilbert, respectively, were 199% and 69% greater than those associated with 0 N rates. Reference [22] exhibited that the response of biomass production to N rate was influenced and controlled by soil water holding capacity and inherent fertility level.

As the water holding capacities of Darco and Lilbert were about the same (0.09; **Table 1**), the greater N rate effect on Darco was due to its lower inherent fertility level. Because the plant production conditions on Darco were more N-limiting compared with that on Lilbert, there was a greater yield response to external N application on Darco. The greater N response was also due to its lower clay and silt contents. The lighter texture of Darco provided better environment for soil aeration and root development. The yields associated with Lilbert were greater than those associated with Darco because the inherent fertility level of the former was higher than that of the latter.

3.2.2. Influence of ENSO

Irrespective of soil type, N rate effect was greater under an El Niño phase for both ^{c}wheat and ^{f}wheat yields. For instance, ^{c}wheat yields at the N rate of 100 kg ha^{-1} under El Niño and La Niña phases, respectively, were 27% and 18% greater than those associated with 0 N applications. Similarly, ^{f}wheat yields under El Niño and La Niña phases increased by about 151% and 121%, respectively, when N rate was increased from 0 to 100 kg ha^{-1}. The greater rates of increase in ^{c}wheat yields with increases in N rate under El Niño were likely due to the following reasons. With more precipitation during the wheat growing season in El Niño years, the available soil water relative to N was more; thus, plant N uptake became less water-dependent. However, with smaller amounts of soil water during La Niña, the water-limited production conditions increased, and the increase in grain yields with a higher N rate became smaller. These results agreed with the findings that increases in potato (*Solanum tuberosum* L.) [45] and bermudagrass [*Cynodon dactylon* (L.) Pers.] [22] biomass yields with an increase in N rate were small when the amounts of water in the soil were small.

3.3. The ENSO Effects on Cowpea and Wheat Yields

The yields of cowpea were impacted by ENSO on both soils and at all N rates considered. Regardless of soil type and N rate, cowpea yields in El Niño years were greater than those in La Niña years (**Table 5**).

The greater yields under El Niño conditions were likely due to the greater amounts of precipitation this ENSO phase delivered during the establishment phase, the growing season, the peak summertime, and the flowering and pod formation stages (**Figure 1**).

Although the ENSO impacts on ^{c}wheat and ^{f}wheat yields were statistically evident only at 0 kg N ha^{-1} and at 0 and 100 kg N ha^{-1}, respectively (**Table 5**), the general trend was that, regardless of soil type and N rate, yields of both ^{c}wheat and ^{f}wheat in La Niña years were greater than those in El Niño years (**Figure 2**). These results are in agreement with the findings of [19] [46] [47] and [48]. The likely reasons for the greater yields of both ^{c}wheat and ^{f}wheat under the La Niña phase, in general, were as follows. First, due to warmer conditions at

Table 5. The effects of ENSO on cowpea and wheat grain yields as influenced by soil type x N rate interactions over 80 years long-term weather at Overton, TX.

			Yield (kg ha^{-1})		
Soil	N rate	ENSO	Cowpea	^{c}Wheat†	^{f}Wheat
Darco	0	El Niño	980^{a‡}	3422^{b}	793^{b}
		La Niña	687^{b}	3915^{a}	1060^{a}
		Neutral	922^{ab}	3812^{a}	979^{ab}
	100	El Niño	983^{a}	4578^{a}	2504^{b}
		La Niña	700^{b}	4957^{a}	3013^{a}
		Neutral	959^{ab}	4692^{a}	2898^{a}
	200	El Niño	981^{a}	4850^{a}	4428^{a}
		La Niña	715^{b}	5110^{a}	4899^{a}
		Neutral	988^{ab}	4871^{a}	4542^{a}
Lilbert	0	El Niño	1094^{a}	4104^{b}	1886^{b}
		La Niña	842^{b}	4711^{a}	2662^{a}
		Neutral	1055^{ab}	4587^{a}	2492^{a}
	100	El Niño	1095^{a}	4867^{a}	3498^{b}
		La Niña	878^{b}	5119^{a}	4212^{a}
		Neutral	1078^{ab}	4886^{a}	4026^{a}
	200	El Niño	1105^{a}	4939^{a}	4904^{a}
		La Niña	892^{b}	5158^{a}	5129^{a}
		Neutral	1092^{ab}	4908^{a}	4858^{a}

^{†,c}wheat = wheat preceded by cowpea, ^{f}wheat = wheat preceded by fallow, ‡Means followed by the same letter across ENSO phases (vertically) within a soil-N rate-crop combination are not significantly different at $\alpha = 0.1$.

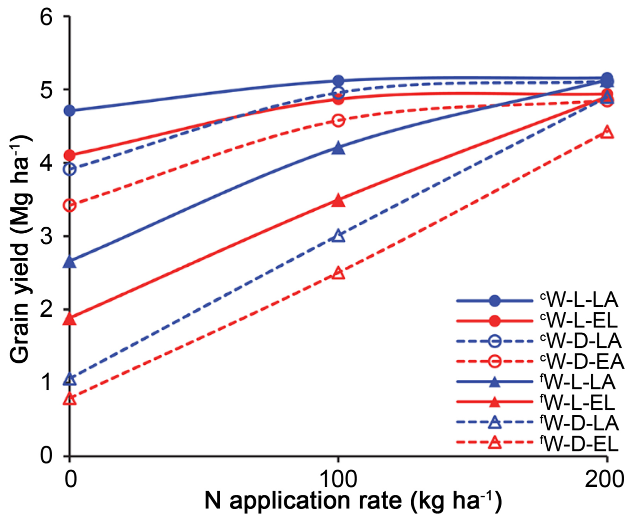

Figure 2. Grain yields of wheat preceded by cowpea (^{c}W) or fallow (^{f}W) as influenced by soil type [Darco (D) vs. Lilbert (L)] and ENSO [La Niña (LA) vs. El Niño (EL)] at Overton, TX. The legend ^{c}W-L-LA, for instance, corresponds to the yields of wheat following cowpea on the Lilbert soil during the La Niña phase.

the planting time under La Niña than under the other ENSO phases, wheat had better germination. For good germination and growth of wheat, 12˚C to 25˚C is the optimum temperature range [49]. Second, during germination and early vegetative stages, no significant harmful effect of drier conditions under La Niña was likely because the total amount of water required for these stages was small (<1.5 cm·d^{-1}) relative to the ones that occurred later in the season [50]. Third, due to warmer conditions under La Niña, more wheat tillers per area would be likely due to warmer temperatures [51], with the optimum temperature for tiller development being 13˚C [52]. Fourth, under the La Niña phase, more photosynthetic assimilates would be expected as this phase has been generally associated with clearer skies and more solar irradiation. Fifth, the La Niña phase had less likelihood of the occurrence of various insect pests and diseases due to drier and warmer conditions [17] [53]. Finally, La Niña was less likely to provide freeze injury to wheat crops, particularly during jointing to flowering [54].

3.3.1. Influence of Soil Type

The effect of ENSO on cowpea yields was greater on the Darco soil at all N rates. For instance, irrespective of N rate, the cowpea yields in El Nino years, compared with La Nina years, increased by about 40% on Darco and by about 26% on Lilbert. The stronger ENSO effect on cowpea yields on Darco relative to Lilbert was likely due to fertility and textural differences of these soils. On Darco, a less fertile soil compared with Lilbert, the effect of weather was more pronounced. As a lighter soil, the less amount of water Darco conserved, relative to Lilbert, in a drier year of La Niña resulted in less yields, whereas the yield difference between the soils in a wetter year of El Niño was less. Thus, the yield difference between the two ENSO phases (El Niño yields minus La Niña yields) was larger on Darco relative to Lilbert. However, the role of soil water holding capacity—another principal factor determining the influence of soil on the ENSO impact [16], was not significant as both soils had about the same capacity for water retention. The effects of ENSO on the yields of both ^{c}wheat and ^{f}wheat were not significantly influenced by the soils considered in this study.

3.3.2. Influence of N Rate

The effect of ENSO on the yields of all crops considered decreased with an increase in N rate on both soils. For instance, irrespective of soil type, cowpea yields in El Nino years, compared with La Nina years, increased by about 37%, 33%, and 31% at the N rates of 0, 100, and 200 kg ha^{-1}, respectively. Similarly, the yield increases in La Nina years compared with El Nino years at the N rates of 0, 100, and 200 kg ha^{-1}, respectively, were, about 15%, 7%, and 5% for ^{c}wheat and about 38%, 20%, and 8% for ^{f}wheat. The smaller ENSO impact on crop yields at a higher N rate was due to the masking effects of soil fertility on weather effects.

When 0 N was applied or at low soil fertility, the ENSO impacts on ^{c}wheat and ^{f}wheat yields were the greatest (**Table 5**). With an increase in N rate, however, the ENSO impacts diminished (**Figure 2**). Accordingly, no ENSO impact was significant at N rates greater than or equal to 100 kg N ha^{-1} for ^{c}wheat, and at 200 kg N ha^{-1} for ^{f}wheat. The results demonstrated that weather was the driving variable for wheat production on impoverished soils, and thus the ENSO had impacts only at low soil fertility. High soil fertility levels masked the impacts of the ENSO on wheat yields. Unlike ^{c}wheat, which received more nutrients through N fixation and N transfer from cowpea residues, the ENSO impact on ^{f}wheat, which received no residue nutrients, was significant also at 100 kg N ha^{-1} because the soil fertility level even at this N rate was still too low to conceal the effect of ENSO.

4. Conclusions

The simulation results showed that grain yields of wheat preceded by cowpea (^{c}wheat) were greater than those preceded by fallow (^{f}wheat) on all soils, at all N rates, and under all ENSO phases. Yields of both ^{c}wheat and ^{f}wheat were greater on Lilbert, the more fertile soil. The soil type effects on ^{c}wheat and ^{f}wheat yields decreased with an increase in N rate. The soil type effect on cowpea yields was greater during La Niña. Cowpea yields under La Niña were the least of all ENSO phases regardless of soil type and N rate. The La Niña impact on cowpea was greater on the less fertile soil Darco. Yields of ^{c}wheat and ^{f}wheat increased with an increase in N rate from 0 to 100 and 200 kg ha^{-1}, respectively. The yield response of ^{c}wheat to N rate was less than that of ^{f}wheat. For ^{c}wheat and ^{f}wheat yields, the N rate effects were greater on Darco and under El Niño. The grain yields of cowpea were the greatest under El Niño, and those of ^{c}wheat and ^{f}wheat were the greatest under La Niña. The effect of ENSO on cowpea yields was greater on Darco. The effect of ENSO diminished with an increase in N rate.

Wheat grain production in a double-cropping system with cowpea illustrated the biological efficiency of the legume-preceding wheat compared to the fallow-wheat system, especially under zero N fertilization. With increased costs of inputs and current costs of N at $2.45 to $3.50 per kg N, cowpea-wheat double cropping using reduced N fertilizer inputs will improve the efficiency and profitability of the production system, compared to fallow-wheat.

Acknowledgements

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

Conflicts of Interest

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

References

[1] Tsiboe, F., Popp, J.S. and Brye, K.R. (2017) Profitability of Alternative Management

Practices in a Wheat-Soybean, Double-Crop Production System in Arkansas. *Agronomy Journal,* **109**, 2149-2162. https://doi.org/10.2134/agronj2017.03.0140

[2] Crabtree, R.J., Prather, J.D. and Mbolda, P. (1990) Long-Term Wheat, Soybean, and Grain Sorghum Double-Cropping Under Rainfed Conditions. *Agronomy Journal,* **82**, 683-686. https://doi.org/10.2134/agronj1990.00021962008200040007x

[3] Sanford, J.O. (1982) Straw and Tillage Practices in Soybean-Wheat Double Cropping. *Agronomy Journal,* **74**, 1032-1035. https://doi.org/10.2134/agronj1982.00021962007400060023x

[4] Lin, Y., Watts, D.B., Torbert, H.A. and Howe, J.A. (2019) Double-Crop Wheat and Soybean Yield Response to Poultry Litter Application. *Crop, Forage & Turfgrass Management,* **5**, 1-8. https://doi.org/10.2134/cftm2018.10.0082

[5] Caviglia, O.P., Sadras, V.O. and Andrade, F.H. (2004) Intensification of Agriculture in the South-Eastern Pampas: I. Capture and Efficiency in the Use of Water and Radiation in Double-Cropped Wheat-Soybean. *Field Crops Research*, **87**, 117-129. https://doi.org/10.1016/j.fcr.2003.10.002

[6] Singh, B.B. (2014) Cowpea, the Food Legume of the 21st Century. Crop Science Society of America, Madison.

[7] Lazicki, P., Geisseler, D. and Horwath, W.R. (2016) Dry Bean Production in California. California Department of Food and Agriculture, Sacramento. https://apps1.cdfa.ca.gov/FertilizerResearch/docs/Bean_Production_CA.pdf

[8] Galindo, F.S., da Silva, E.C., Pagliari, P.H., Fernandes, G.C., Rodrigues, W.L., Biagini, A.L.C., Baratella, E.B., da Silva, Jr., C.A., Neto, M.J.M., Silva, V.M., Muraoka, T. and Filho, M.C.M.T. (2021) Nitrogen Recovery from Fertilizer and Use Efficiency Response to *Bradyrhizobium* sp. and *Azospirillum brasilense* Combined with N Rates in Cowpea-Wheat Crop Sequence. *Applied Soil Ecology*, **157**, Article ID: 103764. https://doi.org/10.1016/j.apsoil.2020.103764

[9] Philander, S.G. (1990) El Niño, La Niña, and the Southern Oscillation. Academic Press, New York.

[10] Hansen, J.W., Jones, J.W., Kiker, C.F. and Hodges, A.W. (1999) El Niño: Southern Oscillation Impacts on Winter Vegetable Production in Florida. *Journal of Climate*, **12**, 92-102. https://doi.org/10.1175/1520-0442(1999)012<0092:ENOSOI>2.0.CO;2

[11] Steinemann, A.C. (2006) Using Climate Forecasts for Drought Management. *Journal of Applied Meteorology and Climatology*, **45**, 1353-1361. https://doi.org/10.1175/JAM2401.1

[12] Alexandrov, V. and Hoogenboom, G. (2001) Climate Variation and Crop Production in Georgia, USA, during the Twentieth Century. *Climate Research*, **17**, 33-43. https://doi.org/10.3354/cr017033

[13] Persson, T., Garcia y Garcia, A., Paz, J.O., Jones, J.W. and Hoogenboom, G. (2009). Maize Ethanol Feedstock Production and Net Energy Value as Affected by Climate Variability and Crop Management Practices. *Agricultural Systems*, **100**, 11-21. https://doi.org/10.1016/j.agsy.2008.11.004

[14] Olatinwo, R.O., Paz, J.O., Kemerait, Jr., R.C., Culbreath, A.K. and Hoogenboom, G. (2010) El Niño-Southern Oscillation (ENSO): Impact on Tomato Spotted Wilt Intensity in Peanut and the Implication on Yield. *Crop Protection*, **29**, 448-453. https://doi.org/10.1016/j.cropro.2009.10.014

[15] Paz, J.O., Woli, P., Garcia y Garcia, A. and Hoogenboom, G. (2012) Cotton Yields as Influenced by ENSO at Different Planting Dates and Spatial Aggregation Levels. *Agricultural Systems*, **111**, 45-52. https://doi.org/10.1016/j.agsy.2012.05.004

[16] Woli, P., Paz, J.O., Hoogenboom, G., Garcia y Garcia, A. and Fraisse, C.W. (2013) The ENSO Effect on Peanut Yield as Influenced by Planting Date and Soil Type. *Agricultural Systems*, **121**, 1-8. https://doi.org/10.1016/j.agsy.2013.06.005

[17] Woli, P., Ortiz, B.V., Flanders, K., Hagan, A., Kemerait, B. and Wright, D. (2013) Adapting Wheat Production to Climate in Alabama. ANR-2046. Alabama Cooperative Extension System, Auburn. https://ssl.acesag.auburn.edu/pubs/docs/A/ANR-2046/ANR-2046-archive.pdf

[18] Woli, P., Ortiz, B.V., Buntin, D. and Flanders, K. (2014) El Niño-Southern Oscillation (ENSO) Effects on Hessian Fly (Diptera: Cecidomyiidae) Infestation in the Southeastern United States. *Environmental Entomology*, **43**, 1641-1649. https://doi.org/10.1603/EN14032

[19] Woli, P., Ortiz, B.V., Johnson, J. and Hoogenboom, G. (2015) El Niño-Southern Oscillation Effects on Winter Wheat in the Southeastern United States. *Agronomy Journal,* **107**, 2193-2204. https://doi.org/10.2134/agronj14.0651

[20] Woli, P., Rouquette, Jr., F.M., Long, C.R., Gowda, P. and Pequeno, D.N.L. (2017) Coastal Bermudagrass Dry Matter Yield and Nitrogen Leaching Responses to Clipping Frequency. *Agronomy Journal*, **109**, 2649-2661. https://doi.org/10.2134/agronj2017.05.0268

[21] Woli, P., Rouquette, Jr., F.M., Smith, G.R., Long, C.R. and Nelson, L.R. (2019) Simulating Winter Wheat Forage Production in the Southern United States Using a Forage Wheat Model. *Agronomy Journal*, **111**, 1141-1154. https://doi.org/10.2134/agronj2018.06.0369

[22] Woli, P., Rouquette Jr., F.M. and Long, C.R. (2019) Investigating DSSAT: Bermudagrass Response to Nitrogen as Influenced by Soil and Climate. *Agronomy Journal*, **111**, 1741-1751. https://doi.org/10.2134/agronj2018.12.0783

[23] Tsuji, G.Y., Hoogenboom, G. and Thornton, P.K., Eds. (1998) Understanding Options for Agricultural Production. Kluwer Academic Publishers, Dordrecht, the Netherlands.

[24] Wallach, D., Makowski, D., Jones, J.W. and Brun, F. (2019) Working with Dynamic Crop Models, 3rd Edition, Academic Press, San Diego. https://doi.org/10.1016/C2016-0-01552-8

[25] Hodson, D. and White, J. (2010) GIS and Crop Simulation Modelling Applications in Climate Change Research. In: Reynolds, M.P., Ed., *Climate Change and Crop Production*, CABI, Oxfordshire, 245-262. https://doi.org/10.1079/9781845936334.0245

[26] Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D., Hunt, L.A., Wilkens, P.W., Singh, U., Gijsman, A.J. and Ritchie, J.T. (2003) DSSAT Cropping System Model. *European Journal of Agronomy*, **18**, 235-265. https://doi.org/10.1016/S1161-0301(02)00107-7

[27] Hoogenboom, G., Porter, C.H., Shelia, V., Boote, K.J., Singh, U., White, J.W., Hunt, L.A., Ogoshi, R., Lizaso, J.I., Koo, J., Asseng, S., Singels, A., Moreno, L.P. and Jones, J.W. (2019) Decision Support System for Agrotechnology Transfer (DSSAT), Version 4.7.5. DSSAT Foundation, Gainesville. https://DSSAT.net

[28] DSSAT (2022) DSSAT Overview. DSSAT Foundation, Inc. https://dssat.net/about/

[29] DSSAT (2022) Tools. DSSAT Foundation, Inc. https://dssat.net/tools/

[30] Thornton, P.K., Wilkens, P.W., Hoogenboom, G. and Jones, J.W. (1994) Sequence Analysis. In: Tsuji, G.Y., et al., Ed., *DSSAT Version 3*, Vol. 3-2, University of Hawaii, Honolulu.

[31] Bowen, W.T., Thornton, P.K. and Hoogenboom, G. (1998) The Simulation of Cropping Sequences Using DSSAT. In: Tsuji, G.Y., Hoogenboom, G. and Thornton, P.K., Eds., *Understanding Options for Agricultural Production*, Kluwer Academic Publishers, Dordrecht, 313-328. https://doi.org/10.1007/978-94-017-3624-4_15

[32] Woli, P. and Paz, J.O. (2012) Evaluation of Various Methods for Estimating Global Solar Radiation in the Southeastern United States. *Journal of Applied Meteorology and Climatology*, **51**, 972-985. https://doi.org/10.1175/JAMC-D-11-0141.1

[33] Matocha, I.E. and Anderson, W.B. (1976) Fertilization of Forages. In: *Grasses and Legumes in Texas: Development, Production, and Utilization, Research Monograph* 6C, Texas Agricultural Experiment Station, Texas A&M University, College Station, 98-168.

[34] Mullenix, M.K. and Rouquette, Jr., F.M. (2018) Review: Cool-Season Annual Grasses or Grass-Clover Management Options for Extending the Fall-Winter-Early Spring Grazing Season for Beef Cattle. *Professional Animal Scientist*, **34**, 231-239. https://doi.org/10.15232/pas.2017-01714

[35] Waltman, S.W. and Vasilas, L. (2013) Wetland Mapping and the Gridded Soil Survey Geographic (gSSURGO) Database. *National Wetlands Newsletter*, **35**, 14-16.

[36] NRCS (Natural Resources Conservation Service) (2020) Gridded Soil Survey Geographic (gSSURGO) Database User Guide, Version 2.4. United States Department of Agriculture Natural Resources Conservation Service, Washington DC.

[37] Gijsman, A.J., Hoogenboom, G., Parton, W.J. and Kerridge, P.C. (2002) Modifying DSSAT Crop Models for Low-Input Agricultural Systems Using a Soil Organic Matter-Residue Module from CENTURY. *Agronomy Journal*, **94**, 462-474. https://doi.org/10.2134/agronj2002.4620

[38] JMA (Japan Meteorological Agency) (1991) Climate Charts of Sea Surface Temperatures of the Western North Pacific and the Global Ocean. Japan Meteorological Agency, Tokyo.

[39] JMA (Japan Meteorological Agency) (2022) Historical El Niño and La Niña Events. Japan Meteorological Agency, Tokyo. https://ds.data.jma.go.jp/tcc/tcc/products/elnino/ensoevents.html

[40] Bove, M.C., Elsner, J.B., Landsea, C.W., Niu, X. and O'Brien, J.J. (1998) Effect of El Niño on U.S. Landfalling Hurricanes, Revisited. *Bulletin of American Meteorological Society*, **79**, 2477-2482. https://doi.org/10.1175/1520-0477(1998)079<2477:EOENOO>2.0.CO;2

[41] COAPS (Center for Ocean-Atmospheric Prediction Studies) (2022) ENSO Index According to JMA SSTA (1868-2020). Center for Ocean-Atmospheric Prediction Studies (COAPS), The Florida State University, Tallahassee. https://www.coaps.fsu.edu/jma

[42] Wilcoxon, F. (1945) Individual Comparisons by Ranking Methods. *Biometrics Bulletin*, **1**, 80-83. https://doi.org/10.2307/3001968

[43] Bortman, M., Brimblecombe, P., Cunningham, M.N., Cunningham, W.P. and Freedman, W. (2003) Environmental Encyclopedia, Vol. 1, 3rd Edition, Thomson Gale, Farmington Hills.

[44] Davis, D.W., Oelke, E.A., Oplinger, E.S., Doll, J.D., Hanson, C.V. and Putnam, D.H. (1991) Cowpea. In: Alternative Field Crops Manual. University of Wisconsin Cooperative Extension Service, Madison, Wisconsin and University of Minnesota Center for Alternative Plant and Animal Products, St. Paul, Minnesota. https://doi.org/10.1016/j.agwat.2016.04.003

[45] Woli, P., Hoogenboom, G. and Alva, A. (2016) Simulation of Potato Yield, Nitrate Leaching, and Profit Margins as Influenced by Irrigation and Nitrogen Management in Different Soils and Production Regions. *Agricultural Water Management*, **171**, 120-130. https://doi.org/10.2134/agronj2015.0403

[46] Hansen, J.W., Jones, J.W., Irmak, A. and Royce, F. (2001) El Niño-Southern Oscillation Impacts on Crop Production in the Southeast United States. In: Rosenzweig, C., Ed., *Impacts of El Niño and Climate Variability on Agriculture*, American Society of Agronomy Special Publication No. 63, American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, Madison, 55-76.

[47] Tapley, M.W. (2012) The Impact of Climate Variability on Wheat Growth and Yield. M.S. Thesis, Auburn University, Auburn.

[48] Baumhardt, R.L., Mauget, S.A., Schwartz, R.C. and Jones, O.R. (2016) El Niño Southern Oscillation Effects on Dryland Crop Production in the Texas High Plains. *Agronomy Journal*, **108**, 736-744.

[49] Edwards, J. (2014) Factors Affecting Wheat Germination and Stand Establishment in Hot Soils. PSS 2256. Oklahoma Cooperative Extension Service, Stillwater. http://archive.pss.okstate.edu/publications/wheat/wheat-misc-publications/factors-affecting-wheat-germination.pdf

[50] Al-Kaisi, M.M. and Shanahan, J.F. (1999) Irrigation of Winter Wheat. Crop Series, University Cooperative Extension Bulletin No. 0.556. Colorado State University Cooperative Extension, Fort Collins.

[51] Hou, R., Ouyang, Z., Li, Y., Wilson, G.V. and Li, H. (2012) Is the Change of Winter Wheat Yield Under Warming Caused by Shortened Reproductive Period? *Ecology and Evolution*, **2**, 2999-3008. https://doi.org/10.1002/ece3.403

[52] Hollis, P. (2014) It's All About the Tillers When Maximizing Wheat Profits, Yields. Southeast Farm Press, St. Charles. https://www.farmprogress.com/grains/it-s-all-about-tillers-when-maximizing-wheat-profits-yields

[53] Cunha, G.R., Dalmago, G.A. and Estefanel, V. (2001) El Niño—Southern Oscillation Influences on Wheat Crop in Brazil. In: Bedo, Z. and Lang, L., Eds., *Wheat in a Global Environment*, Kluwer Academic Publishers, Dordrecht, 445-450. https://doi.org/10.1007/978-94-017-3674-9_58

[54] Chapin, J.W. and Thomas, J.S. (2000) Cold Injury on Wheat. Small Grain 03. Clemson University Cooperative Extension Service, Clemson.