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Exploring the Potential of Cowpea-Wheat Double Cropping in the Semi-Arid Region of the Southern United States Using the DSSAT Crop Model

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Abstract

Information is limited on the potential of double-cropping cowpea (*Vigna unguiculata* L.) and wheat (*Triticum aestivum* L.) in the semiarid region of the southern United States. Using the Decision Support System for Agrotechnology Transfer (DSSAT) crop model and weather data of 80 years, we assessed the possibility of cowpea-wheat double-cropping in this region for grain purpose as affected by planting date and N application rate. Results showed that the possibility of double-cropping varied from 0% to 65%, depending on the cropping system. The possibility was less with systems comprising earlier planting dates of wheat and later planting dates of cowpea. Results indicated that cowpea-wheat double-cropping could be beneficial only when no N was applied, with wheat planted on October 15 or later. At zero N, the double-crops of cowpea planted on July 15 and wheat planted on November 30 were the most beneficial of all the 72 double-cropping systems studied. With a delay in planting cowpea, the percentage of beneficial double-cropping systems decreased. At N rates other than zero, fallow-wheat monocropping systems were more beneficial than cowpea-wheat double-cropping systems, and the benefit was greater at a higher N rate. At 100 kg N ha^{-1}, the monocrop of wheat planted on October 15 was the most beneficial of all the 94 systems studied. Results further showed that fallow-wheat yields increased almost linearly with an increase in N rate from 0 to 100 kg·ha^{-1}. Fallow-wheat grain yields were quadratically associated with planting dates. With an increase in N rate, wheat yields reached the peak with an earlier planting date. Wheat yields produced under monocropping systems were greater than those produced under double-cropping systems for any cowpea planting date. Cowpea yields produced under monocropping systems were greater than those produced under any double-cropping system. The relationship between cowpea grain yields and planting dates was quadratic, with July 1 planting date associated with the maximum yields.

Keywords

Cover-Crop, Cowpea-Wheat, DSSAT, Double-Crop, Model, Semi-Arid

1. Introduction

Double cropping in the southern region of the United States is an agronomic practice that has potential to improve efficiency of land use and provide a continuous soil cover to prevent soil erosion and nutrient loss due to wind, leaching and surface run off. In practice, using winter wheat (*Triticum aestivum* L.) as the cool season component of double cropping, total agricultural production varies according to warm season crop choice, rainfall, soil type, and specific agronomic techniques. A twelve-year study in eastern Oklahoma, US, indicated that double cropping using wheat-soybean (*Glycine max* (L.) Merr.) or wheat-grain sorghum (*Sorghum bicolor* (L.) Moench) was both sustainable and resulted in higher total grain yields compared with monocropping [1]. In Argentina, wheat-soybean double crops outyielded monocrops by 58% to 82% [2].

Results from a five-year study conducted in North Carolina, US, varied with the choice of warm season crop [3]. Production of corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), and soybean in monoculture outyielded the same crops in double cropping with wheat in all years. Grain sorghum and peanut (*Arachis hypogaea* L.) yields were higher in monoculture in two and four years, respectively, compared with double cropping with wheat. In this five-year study, no economic advantage for double cropping was noted for 80% of the crop-year combinations evaluated.

Cowpea (*Vigna unguiculata* (L.) Walp.) is a drought and heat tolerant legume crop grown worldwide as a vegetable, forage, and pulse crop [4]. Dry pulse crop production of cowpea in the United States is limited to California and Texas and ranged from 2000 to 6000 ha from 2005 to 2015 [5]. Cowpea is grown on 1.4 million ha in Brazil and is used successfully as a double crop with wheat [6].

More information is needed regarding the total crop production potential and limitations of cowpea-wheat double cropping in the southern United States to help increase productivity while enhancing soil health. Reference [7] conducted a simulation modeling study to examine the effects of cowpea-wheat crop sequence, soil type, N application rate, El Niño-Southern Oscillation (ENSO), and their interactions on the grain yields of cowpea and winter wheat in the humid region of the southern United States. However, no study has assessed the relationships among cowpea-winter wheat double-cropping, N application rate, and planting date for the semi-arid region of the southern United States. An understanding of such relationships could assist cowpea-winter wheat farmers in this region in adopting alternative management strategies for grain or cover-crop purposes.

The objectives of this study were to investigate the feasibility of growing cowpea-wheat double crops for grain purposes in the semi-arid region of the Southern United States and to assess the effects of cowpea and wheat planting dates and N application rate to wheat on the grain yields of these crops using the sequence analysis tool of Decision Support System for Agrotechnology Transfer (DSSAT), which is a widely-tested and used suite of crop models that can be used to effectively study such cropping systems [8] [9]. We conducted this simulation study because systems analysis is a valuable approach to solving real-world problems safely and efficiently by providing clear comprehensions of complex systems [10] [11]. In addition, crop simulation models can be valuable tools for studying various scenarios comprising a number of variables in the soil-plant-atmosphere continuum as they predict plant growth and development as influenced by crop management and environment by using quantitative descriptions of ecophysiological processes [12].

2. Materials and Methods

2.1. The DSSAT Suite and Sequence Analysis

The DSSAT is a software application program consisting of various crop models that predict growth, development, and yield as defined by the soil-plant-atmosphere dynamics and several tools that manage database on crop, soil, experiment, and weather and include applications for graphical display, seasonal analysis, rotational analysis, and genotype coefficient estimation [13]. The DSSAT suite of crop models has been used for various applications such as precision crop management, agroecosystem sustainability, climate change impacts, and greenhouse gas emission studies [13]. Model simulations are carried out mainly on a daily basis using weather, soil, and crop management data. By integrating crop, soil, weather, and management options with crop models and application programs, the DSSAT suite simulates multi-year outcomes of crop management strategies.

Sequence Analysis, an important DSSAT tool, allows for rapid simulation, inspection, and analysis of results of long-term cropping sequences [14]. With this tool, a series of statistics can be calculated, and various graphics showing relationships between trends and variability can be created. Since simulation studies are conducted across multiple cropping seasons, this tool allows for the carryover of soil water and nutrients from the preceding crop to the following crop [15] [16].

2.2. Site and Data

The Texas A&M AgriLife Research & Extension Center at Amarillo (35.19˚N, 102.06˚W) is situated in the Llano Estacado region of the southern United States (https://familypedia.fandom.com/wiki/Llano_Estacado). This region, where agriculture is a major economic activity, comprises parts of eastern New Mexico and northwestern Texas. 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, Texas was used as a representative site for the Llano Estacado region [17].

To explore the interannual climate variability effects on the feasibility of growing cowpea-wheat double crops as well as on the yields of cowpea and wheat in the Llano Estacado region, a long-term weather dataset spanning 80 years (1942-2021) was used. The historical daily data on precipitation, temperature, and windspeed in the Amarillo region were obtained from the website of National Centers for Environmental Information (https://www.ncei.noaa.gov/access/search/data-search/daily-summaries); whereas those on solar radiation were generated using a reliable irradiation model described by [18].

Pullman clay loam (*Torrertic paleustolls*) was used as a representative soil for the study because it is one of the major soils used for agricultural purposes in the Llano Estacado region [19]. The soil data (**Table 1**) were obtained from the Gridded Soil Survey Geographic (gSSURGO) database of the USDA NRCS [20] [21]. The drainage coefficient of the soil was 0.60, whereas the run-off curve number was 81.

2.3. The Simulation Study Design

The DSSAT Sequence Analysis tool was used to simulate grain yields for cowpea and winter wheat in three cropping systems: cowpea-wheat, fallow-wheat, and

Table 1. Properties of Pullman clay loam, a major soil in the Llano Estacado region of the US.

Layer	MH[a]	Soil properties									
		WP	FC	SA	WH	HC	Clay	Silt	TN	OC	pH
(cm)	-	-	-	-	-	cm/h	%	%	%	%	-
0 - 13	At	0.21	0.34	0.46	0.13	0.97	29.50	31.30	0.11	1.16	7.00
13 - 46	Bt1	0.27	0.38	0.43	0.11	0.36	38.50	29.20	0.10	0.73	7.60
46 - 84	Bt2	0.24	0.38	0.45	0.14	0.36	43.50	32.50	0.08	0.39	7.80
84 - 132	Btk1	0.23	0.37	0.42	0.14	0.36	42.50	22.40	0.05	0.36	8.20
132 - 168	Btk2	0.23	0.36	0.40	0.13	0.36	37.50	31.40	0.05	0.13	8.20
168 - 203	Btk3	0.23	0.34	0.38	0.11	0.36	36.50	21.70	0.04	0.20	8.20

[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.

fallow-cowpea. The wheat crop that followed cowpea or fallow, hereafter, will be referred to as ^{c}wheat and ^{f}wheat, respectively, and the cowpea crop that followed fallow as ^{f}cowpea. Simulations were made for a total of 94 scenarios comprising three N application rates to wheat, namely 0, 50, and 100 kg N ha^{-1}; four planting dates for cowpea, namely June 1, June 15, July 1, and July 15; and six planting dates for wheat, namely September 15, September 30, October 15, October 30, November 15, and November 30 (**Table 2**).

For simulations, the following management and environmental inputs were assumed. For soil, we used Pullman clay loam. For cultivars, we used "Newton" for winter wheat and "Cal #5 MG4" for cowpea. Because the genetic coefficients for this wheat cultivar were already estimated by [22] for the Texas Panhandle region, 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 [9] and correspond to the cultivar coefficients upon which the cowpea model was adapted (K. J. Boote, personal communication, 11 February 2022). 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, the plant populations assumed were 30 plants m^{-2} (about 40 kg·ha^{-1}) for cowpea and 323 plants m^{-2} (about 100 kg·ha^{-1}) for wheat. Using the conventional tillage, dry seeds were planted on rows at 3 cm depth. Inorganic N fertilizer was applied only to wheat, not cowpea.

Of the total amount of N set for application to wheat, 50% was applied at the time of planting and the remainder on February 15 of the following year. For organic amendments, the stover residues of each crop were assumed to be automatically incorporated into the soil on the harvest day of the crop so that the

Table 2. The simulation study scenarios comprising 3 cropping systems, 4 × 6 planting dates, and 3 N applications rates (kg N ha^{-1}).

System	Factors and levels	Number of scenarios	Example of a scenario
cowpea-wheat[†]	4 cowpea planting dates × 6 wheat planting dates × 3 N application rates	72	Cowpea_Jul 15-Wheat_Nov 30 (100 N)
fallow-wheat	6 wheat planting dates × 3 N application rates	18	Wheat_Sep 15 (50 N)
fallow-cowpea	4 cowpea planting dates	4	Cowpea_Jul 15
Total scenarios		94	
Total years (seasons)		80	
Total modal runs		7520	

[†]Double crop.

nutrients in the residues would transfer from the preceding crop to the following crop in cycles. For soil organic matter estimation, Century was used as the method, with the five years' field history of "Cultivated, good management, initial default SOM" [23].

2.4. Data Analyses

For ^{f}wheat, regression analyses were carried out to explore relationships between grain yields and planting dates as influenced by N application rate. For ^{f}cowpea, however, since there was no N rate involved, the grain yields were regressed only against the planting dates in general.

In the case of ^{c}wheat double-cropping, however, our objective was to assess the potential success and yields of cowpea-wheat double cropping in the study region as affected by the planting dates of both crops and N application rate to wheat. For this assessment, we ran the DSSAT crop model with sequential analysis for 80 years, starting from the earliest cowpea planting date in 1942 through the latest wheat planting date in 2021, for each of the 72 double-cropping scenarios presented in **Table 2**.

For a given scenario—denoted as $C_i W_{j.k}$; where C_i is cowpea with the *i*-th planting date of Jun 1, Jun 15, Jul 1, or Jul 15; and $W_{j.k}$ is wheat with the *j*-th planting date of Sep 15, Sep 30, Oct 15, Oct 30, Nov 15, or Nov 30 and the *k*-th N application rate of 0, 50, or 100 kg N ha^{-1}—we calculated the feasibility of a successful cowpea-wheat double-crop in the study region and the associated average yields of both cowpea and wheat crops.

The feasibility of a successful double-crop for the $C_i W_{j.k}$ scenario was obtained by counting the number of successful cowpea-wheat double-cropped seasons, that is, the number of events with wheat following cowpea successively and then dividing that number by the total 80 seasons.

The average yield of each crop involved in double-cropping for the $C_i W_{j.k}$ scenario was obtained by summing up yields in the successful double-crop years and then dividing the sum by 80. For unsuccessful (failed) double-crop years, the yields of each crop were assumed to be zero.

Each scenario, a cropping *system*, comprised two different crops: cowpea and wheat. To compare total crop yields (*benefits*) across systems, one would need to combine the yields of both crops. Since the yields of two different crops could not be added together in terms of absolute yields, we combined them in terms of the *system benefit index* (*SBI*), defined as follows. A greater value of SBI would be an indication of a more benefitted system in terms of cowpea-wheat double-cropping.

$$^{c-w}SBI_{i,j,k} = C_i / C_s + W_{j,k} / W_s \quad (1)$$

where $^{c-w}SBI_{i,j,k}$ is the system benefit index for the double-crop cowpea-wheat scenario associated with the *i*-th planting date of cowpea, the *j*-th planting date of wheat, and the *k*-th N rate to wheat; C_i is cowpea yield with the *i*-th planting date; C_s is the standard yield of cowpea in the study region; $W_{j,k}$ is wheat yield with the *j*-th planting date and the *k*-th N rate; and W_s is the standard yield of wheat in the study region. The crop yields are in kg·ha^{-1}. The C_s and W_s, in turn, were estimated as follows.

$$C_s = \frac{\sum_{i=1}^{n} {}^{f}C_i}{n} \tag{2}$$

where ${}^{f}C_i$ is the yield of cowpea following fallow for the *i*-th planting date, where $n = 4$ and $i = 1$ (Jun 1), …, n (Jul 15).

$$W_s = \frac{\sum_{j=1}^{m} {}^{f}W_j}{m} \tag{3}$$

where ${}^{f}W_j$ is the yield of wheat following fallow for the zero N rate and the *j*-th planting date, where $m = 6$ and $j = 1$ (Sep 15), …, m (Nov 30).

Similarly, the SBIs for fallow-cowpea and fallow-wheat cropping systems were computed as:

$${}^{f-c}SBI_i = C_i / C_s \tag{4}$$

$${}^{f-w}SBI_{j,k} = W_{j,k} / W_s \tag{5}$$

where ${}^{f-c}SBI_i$ and ${}^{f-w}SBI_{j,k}$ are the system benefit indices for the fallow-cowpea and fallow-wheat scenarios, respectively. The other variables are already defined above.

Once the 72 values of ${}^{c-w}SBI_{i,j,k}$, 18 values of ${}^{f-w}SBI_{j,k}$, and 4 values of ${}^{f-c}SBI_i$ were computed, the ${}^{c-w}SBI_{i,j,k}$ value of a system in question was then compared with the corresponding values of ${}^{f-c}SBI_i$ and ${}^{f-w}SBI_{j,k}$ (associated with the 0 N rate) to find out if the double-crop system being compared would be more beneficial than the corresponding fallow-cowpea or fallow-wheat systems. The double-crop system would be more beneficial than either of the fallow-cowpea or fallow-wheat system if:

$${}^{c-w}SBI_{i,j,k} > {}^{f-c}SBI_i \text{ and } {}^{f-w}SBI_{j,k} \tag{6}$$

The possibility of planting a wheat crop might depend on the length of the growing season of the preceding crop cowpea. The cowpea seasonal length, in turn, could be affected by drought, if any, during the season [24] [25]. Thus, to explore the effect of drought on cowpea growing season, an agricultural drought index—Agricultural Reference Index for Drought (ARID)—was used as it is computationally simple and physically and physiologically sound [26]; is applicable to a wide range of crops, soils, topographies, and management with fairly small uncertainties [27]; has potential to predict the yield loss from drought for several field crops that are more sensitive to water stress [28]; and, as a drought indicator, may be used in drought forecasting [29]. Using the weather data and soil parameters, the daily values of ARID during the cowpea growing seasons were computed, and these values were used to associate seasonal length with drought.

3. Results and Discussion

3.1. The Feasibility of Cowpea-Wheat Doubling-Cropping Systems

3.1.1. In Terms of Successful Double-Cropping Years

The simulation results showed that the possibility of growing the double crops of cowpea and winter wheat in the semi-arid region of Llano Estacado was generally low. Of the 80 years studied (1942-2021), the number of feasible years for cowpea-wheat double-cropping ranged from 0 to 52, depending on the double-cropping scenario comprising the planting dates of cowpea and wheat (Table 3).

Table 3. The feasibility of cowpea-wheat Double-Cropping (DC) in the Llano Estacado region as influenced by the planting dates of cowpea and wheat.

DC system	Planting date†		Feasible DC years‡		DAC$	DNC	DNW	DNDC
	Cowpea	Wheat	No.	%				
Cowpea$_{Jun01}$-Wheat$_{Sep15}$	151	258	0	0	107	125	289	**414**
Cowpea$_{Jun01}$-Wheat$_{Sep30}$	151	273	14	18	122	125	274	**399**
Cowpea$_{Jun01}$-Wheat$_{Oct15}$	151	288	34	43	137	125	260	**385**
Cowpea$_{Jun01}$-Wheat$_{Oct30}$	151	303	38	48	152	125	242	367
Cowpea$_{Jun01}$-Wheat$_{Nov15}$	151	318	38	48	167	125	222	347
Cowpea$_{Jun01}$-Wheat$_{Nov30}$	151	333	37	46	182	125	202	327
Cowpea$_{Jun15}$-Wheat$_{Sep15}$	166	258	0	0	92	119	289	**408**
Cowpea$_{Jun15}$-Wheat$_{Sep30}$	166	273	0	0	107	119	274	**393**
Cowpea$_{Jun15}$-Wheat$_{Oct15}$	166	288	20	25	122	119	260	**379**
Cowpea$_{Jun15}$-Wheat$_{Oct30}$	166	303	35	44	137	119	242	361
Cowpea$_{Jun15}$-Wheat$_{Nov15}$	166	318	39	49	152	119	222	341
Cowpea$_{Jun15}$-Wheat$_{Nov30}$	166	333	37	46	167	119	202	321
Cowpea$_{Jul01}$-Wheat$_{Sep15}$	181	258	0	0	77	115	289	**404**
Cowpea$_{Jul01}$-Wheat$_{Sep30}$	181	273	0	0	92	115	274	**389**
Cowpea$_{Jul01}$-Wheat$_{Oct15}$	181	288	4	5	107	115	260	**375**
Cowpea$_{Jul01}$-Wheat$_{Oct30}$	181	303	21	26	122	115	242	357
Cowpea$_{Jul01}$-Wheat$_{Nov15}$	181	318	38	48	137	115	222	337
Cowpea$_{Jul01}$-Wheat$_{Nov30}$	181	333	37	46	152	115	202	317
Cowpea$_{Jul15}$-Wheat$_{Sep15}$	196	258	0	0	62	110	289	**399**
Cowpea$_{Jul15}$-Wheat$_{Sep30}$	196	273	0	0	77	110	274	**384**
Cowpea$_{Jul15}$-Wheat$_{Oct15}$	196	288	2	3	92	110	260	**370**
Cowpea$_{Jul15}$-Wheat$_{Oct30}$	196	303	14	18	107	110	242	352
Cowpea$_{Jul15}$-Wheat$_{Nov15}$	196	318	40	50	122	110	222	332
Cowpea$_{Jul15}$-Wheat$_{Nov30}$	196	333	52	65	137	110	202	312

†In day number (day of year); ‡Out of 80 years (1942-2021); $DAC, days available for cowpea season; DNC, days needed for cowpea season; DNW, days needed for wheat season; DNDC, days needed for double-cropping.

The feasibility was highest (65%) with the latest planting dates of both crops, July 15 of cowpea and November 30 of wheat (**Figure 1**). But for a given planting date of cowpea, the feasibility, in general, kept decreasing with a shift in wheat planting toward the earlier part of the season. Accordingly, when wheat was planted on September 30, cowpea-wheat double-cropping was possible only with the cowpea planting date of June 1. But the double-cropping possibility decreased to zero with any cowpea planting date when wheat was planted on September 15 due to too short a season for cowpea to set grains.

For a given planting date of wheat, especially the earlier ones, the possibility of double cropping was generally highest with the earliest planting date of cowpea (June 1) and decreased thereafter with a delay in cowpea planting. The rate of decrease (slope) in possibility, however, diminished with a delay in wheat planting such that it even became negative, that is, the possibility increased for the later planting dates of wheat.

The feasibility of double-cropping cowpea and wheat was primarily determined by the length of growing season of the preceding crop cowpea and the number of days available for the cowpea season. For any wheat planting date, the number of days available for cowpea crops decreased with a delay in cowpea planting (**Figure 2(a)**). For any cowpea planting date, on the other hand, the number of days available for cowpea crops decreased with advancement in wheat planting. Thus, the growing window available for cowpea crops was shortest with the latest planting date of cowpea and the earliest planting date of wheat, whereas longest with the earliest planting date of cowpea and the latest planting date of wheat.

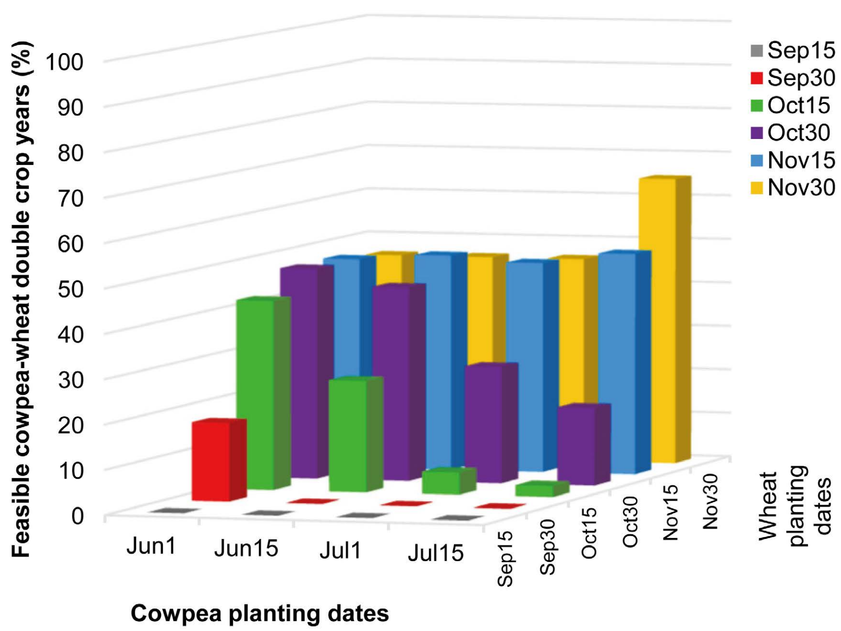

Figure 1. Feasible cowpea-wheat double-cropping years as affected by planting dates in the Llano Estacado region.

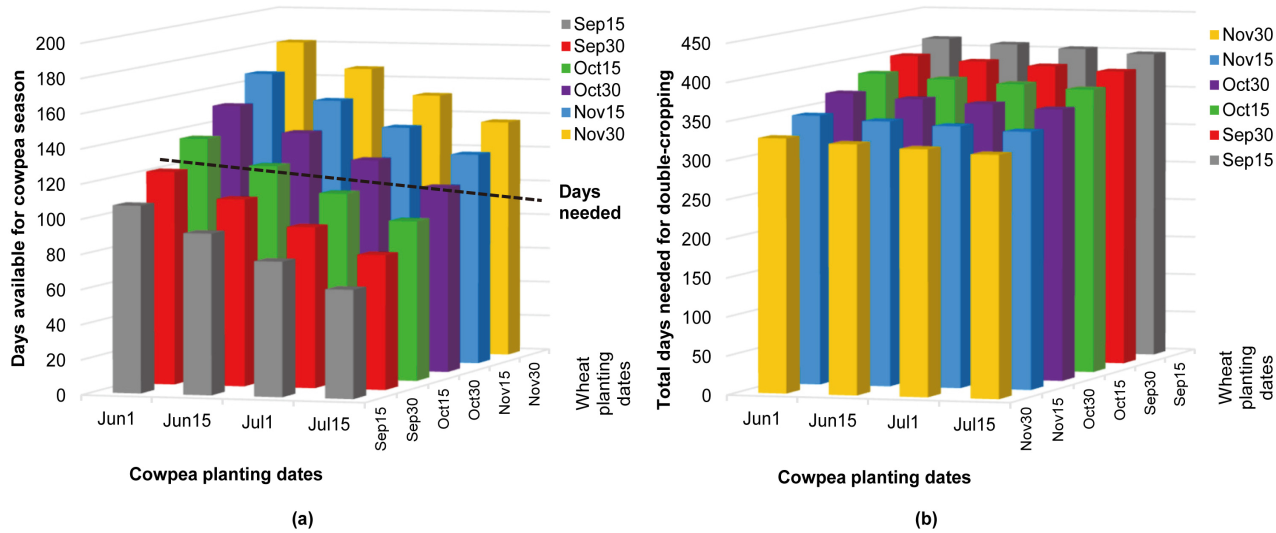

Figure 2. For various combinations of cowpea and wheat planting dates, the number of days available for (a) cowpea season, and (b) cowpea-wheat double-cropping seasons in the Llano Estacado region.

The average number of days required by the cowpea crop seasons with the planting dates of June 1, June 15, July 1, and July 15 were 125, 119, 115, and 110, respectively, which have been approximately represented by the dotted line in Figure 2(a). For the scenarios (cropping systems) whose available seasonal lengths roughly fell below this line, the possibility of double-cropping was either zero or very low. The days available and needed for cowpea seasons in these scenarios are underlined in Table 3.

The number of days available for and required by cowpea crops was one of the factors defining the feasibility of double-cropping. Another factor was the total number of days needed by the double crops cowpea and wheat to complete their lifecycles. The total days needed for double-cropping decreased with delays in cowpea and wheat planting (Figure 2(b)). Thus, the double-cropping feasibility for the July 15-November 30 scenario was the highest of all scenarios (Figure 1). Since the maximum number of days available for double-cropping was assumed to be 365 or 366 days (one year), the possibility of double-cropping was zero for the scenarios that needed more than a year to complete their lifecycles. The total days needed for cowpea-wheat double cropping in these scenarios are bold in Table 3 (the last column).

The decrease in total days needed for double-cropping with delays in planting was due to a decrease in the seasonal length of each crop with a delay in planting (Figure 3). Irrespective of wheat planting date, the seasonal length of cowpea decreased with a delay in planting. Similarly, regardless of cowpea planting date, the seasonal length of wheat decreased with a delay in planting.

In the case of cowpea, a decrease in seasonal length with delayed planting was due to strong associations among planting date, daylength, and seasonal length. Daylength decreased linearly with a delay in cowpea planting (Figure 4(a)), and

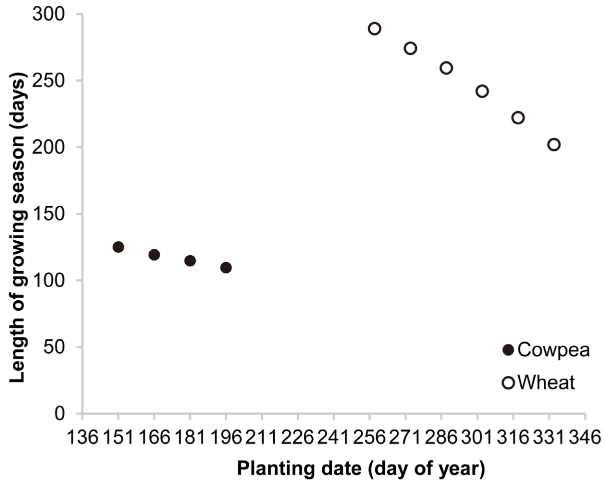

Figure 3. The lengths of cowpea and wheat growing seasons as affected by planting dates ranging from Jun 1 through Nov 30 (day of year 151 - 333) in the Llano Estacado region.

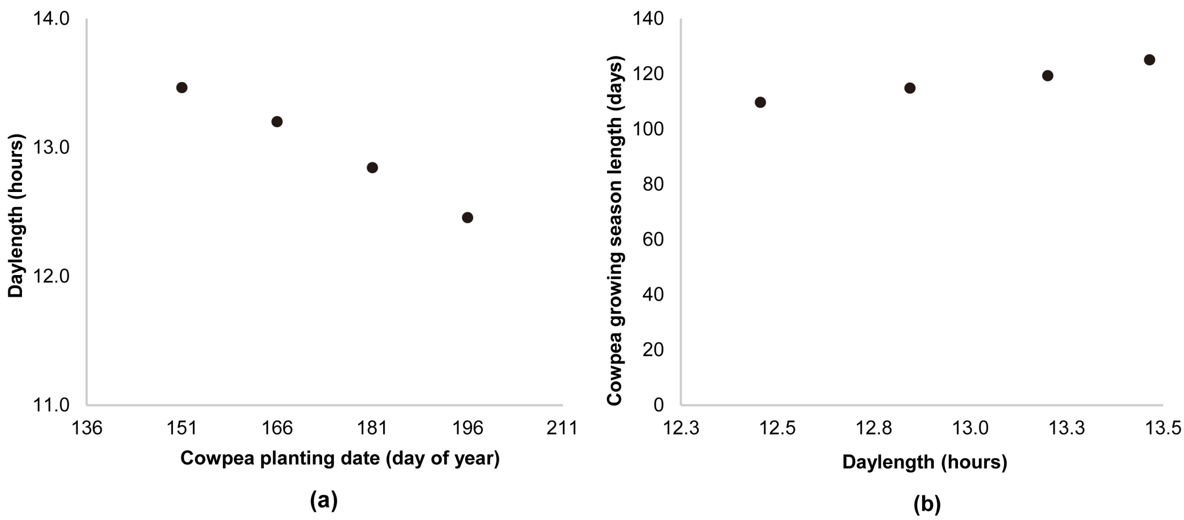

Figure 4. (a) Relationship between daylength and cowpea planting date and (b) the length of cowpea growing season as affected by daylength in the Llano Estacado region.

cowpea seasonal length decreased linearly with a decrease in daylength (**Figure 4(b)**). Thus, daylength was one of the factors that defined the length of cowpea growing season.

Another factor was drought that occurred especially during the reproductive phase of cowpea. The scenarios with low feasibility in **Table 3**, such as $\text{Cowpea}_{\text{Jun01}}$-$\text{Wheat}_{\text{Sep30}}$, $\text{Cowpea}_{\text{Jul01}}$-$\text{Wheat}_{\text{Oct15}}$, $\text{Cowpea}_{\text{Jul15}}$-$\text{Wheat}_{\text{Oct15}}$, and $\text{Cowpea}_{\text{Jul15}}$-$\text{Wheat}_{\text{Oct30}}$, were particularly affected by drought. In these scenarios, the double-cropped years were drier than the other years, especially during the terminal parts of the growing seasons (**Figure 5**). The drier conditions during this time of the season led to shorter seasonal lengths. Reference [25] found that drought stress reduced the length of cowpea season to reach physiological maturity by about 18%. The reduction in days to flowering was also observed by

[30]. Reference [31] also found that the cowpea growth period was significantly shortened by drought. The shortening of growing season is associated with drought escape mechanism of the cowpea plants [32]. Because of shorter seasonal lengths, the scenarios with higher droughted conditions were more feasible for double-cropping relative to the ones with lower droughted conditions.

In the case of wheat, a decrease in seasonal length with a delay in planting was due to the constant association between its maturity and planting dates. Regardless of planting date, wheat crops matured at about the same time in growing seasons (**Figure 6**). For instance, the wheat crops planted on September 15 and November 15 matured on July 4 and July 9, respectively. Reference [33] also observed that wheat crops planted at different dates reached maturity at about the

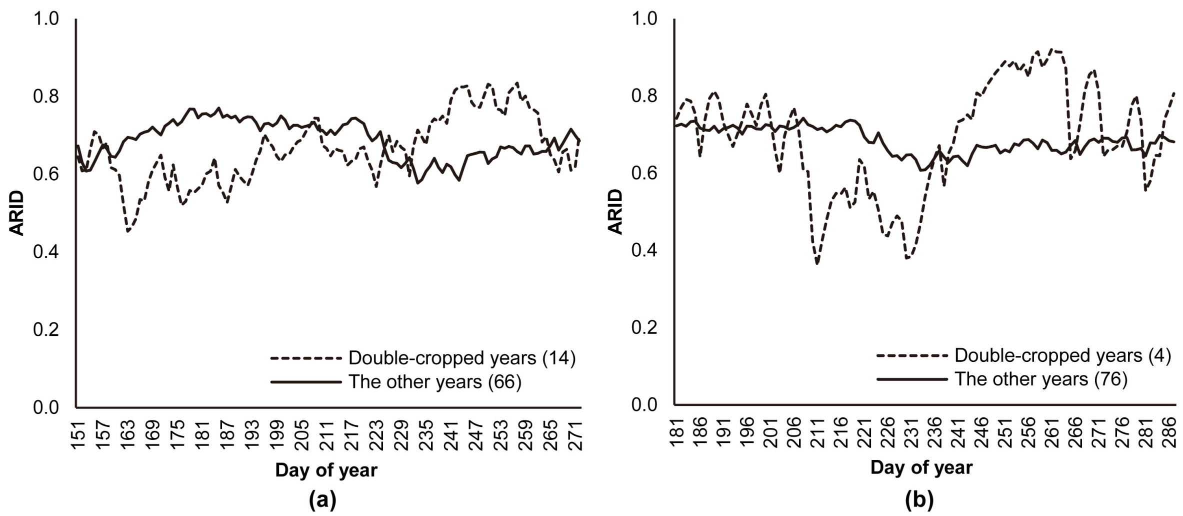

Figure 5. Values of the Agricultural Reference Index for Drought (ARID) for double-cropped years and the other years in the Llano Estacado region: (a) during the cowpea planting date of Jun 1 through the wheat planting date of Sep 30, and (b) during the cowpea planting date of Jul 1 through the wheat planting date of Oct 15.

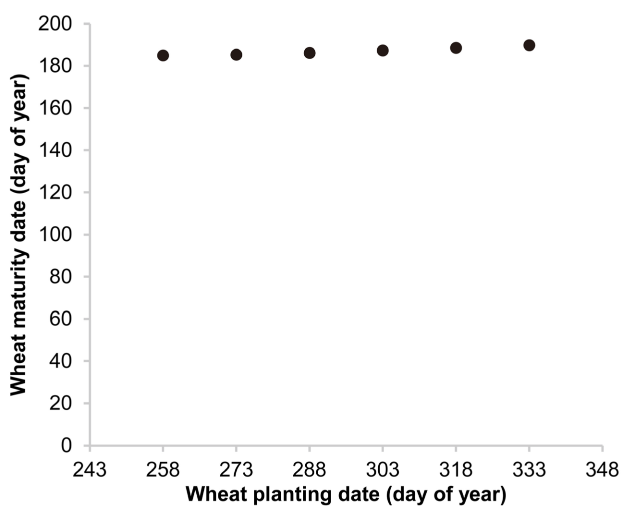

Figure 6. Relationship between the planting and maturity dates of wheat in the Llano Estacado region.

same time. Similarly, [34] found that the crop duration of late-planted wheat was shortened significantly due to accelerated grain-filling rate. The likely reason for this phenomenon is that high temperatures in late spring accelerate wheat growth and development rates and enable the plant to initiate anthesis and maturation [34] [35] [36] [37].

3.1.2. In Terms of Yield Benefit

The 80-year average grain yields of cowpea and wheat under various cropping systems and N rates to wheat are presented in **Table 4**. A cropping system comprises a sequence of fallow-cowpea or fallow-wheat monocrop or cowpea-wheat double-crops. In the case of double-crops, a system consists of a cowpea crop planted at a specific date followed by a wheat crop planted at a specific date.

Table 4. The average† yields ($kg{\cdot}ha^{-1}$) of cowpea and wheat grains under various N rates ($kg{\cdot}ha^{-1}$) and cropping systems in the Llano Estacado region.

N rate	System‡	Fallow-	$Wheat_{Sep15}$	$Wheat_{Sep30}$	$Wheat_{Oct15}$	$Wheat_{Oct30}$	$Wheat_{Nov15}$	$Wheat_{Nov30}$
				Cowpea grain yields				
	Fallow-	-	-	-	-	-	-	-
	$Cowpea_{Jun01}$-	**836**	0	140	349	395	380	366
0	$Cowpea_{Jun15}$-	**860**	0	0	166	324	386	372
	$Cowpea_{Jul01}$-	**<u>893</u>**	0	0	50	247	408	396
	$Cowpea_{Jul15}$-	**796**	0	0	32	141	365	513
				Wheat grain yields				
	Fallow-	-	**952**	**1158**	**1252**	**1327**	**1329**	**<u>1353</u>**
	$Cowpea_{Jun01}$-	-	0	445	783	1024	1154	1158
0	$Cowpea_{Jun15}$-	-	0	0	614	892	1175	1050
	$Cowpea_{Jul01}$-	-	0	0	50	539	938	968
	$Cowpea_{Jul15}$-	-	0	0	51	263	745	1020
	Fallow-	-	**2928**	**3121**	**3267**	**3289**	**<u>3304</u>**	**3283**
	$Cowpea_{Jun01}$-	-	0	701	1181	1478	1605	1543
50	$Cowpea_{Jun15}$-	-	0	0	962	1256	1681	1625
	$Cowpea_{Jul01}$-	-	0	0	92	820	1441	1465
	$Cowpea_{Jul15}$-	-	0	0	89	455	1347	1713
	Fallow-	-	**4942**	**5167**	**<u>5318</u>**	**5275**	**5176**	**5085**
	$Cowpea_{Jun01}$-	-	0	893	1384	1693	1780	1666
100	$Cowpea_{Jun15}$-	-	0	0	1184	1521	1953	1879
	$Cowpea_{Jul01}$-	-	0	0	125	1013	1780	1759
	$Cowpea_{Jul15}$-	-	0	0	139	643	1837	2173

†Out of 80 years (1942-2021); ‡A cropping system comprises a sequence of fallow-cowpea, fallow-wheat, or cowpea-wheat double-crops. For instance, the system comprising the combination of $Cowpea_{Jun01}$- and $Wheat_{Sep15}$ denotes the system of June 1-planted cowpea crop followed by September 15-planted wheat crop.

The simulation results showed that the cowpea yields produced under fallow-cowpea monocropping systems with any cowpea planting date would be greater than those produced under any cowpea-wheat double-cropping system. Of all the systems compared, the cowpea crops planted on July 1 produced the greatest cowpea yields.

In the case of wheat, the grain yields produced under the fallow-wheat system with a given N rate and a given wheat planting date were greater than those produced under cowpea-wheat systems with those N rate and wheat planting date and any cowpea planting date. The same phenomenon occurred with all N rates and wheat planting dates. At the N rates of 0, 50, and 100 $kg \cdot ha^{-1}$, the greatest wheat yields of all the systems compared were associated with the fallow-wheat crops planted on November 30, November 15, and October 15, respectively. With an increase in N rate, thus, the most productive fallow-wheat system was associated with an earlier planting date of wheat.

The standard yield of cowpea in the study region was estimated to be 846 $kg \cdot ha^{-1}$, the average value of fallow-cowpea grain yields associated with the four planting dates (values in the third column of **Table 4**). Similarly, the standard yield of wheat, 1229 $kg \cdot ha^{-1}$, was obtained by averaging the fallow-wheat yields associated with the six planting dates and the zero N rate (values on the first row of **Table 4** under "Wheat grain yields"). The SBI values for cowpea and wheat presented in **Table 5** were obtained by dividing the yields of cowpea and wheat presented in **Table 4** by the standard yields of cowpea and wheat, respectively. The SBI table conveys the same information as the yield table with respect to yield benefit comparison among the systems within the cowpea or wheat crop. However, unlike the yield table where the yields of cowpea and wheat could not be combined, the SBI values of both cowpea and wheat under a given system in the SBI table could be combined to produce the total SBI values presented in **Table 6**, which could be used to compare the double-crop systems.

Using the total SBI values presented in **Table 6**, one could compare the relative importance of a given cropping system (scenario) in terms of total yield benefit with those of the other systems. For instance, the system of fallow followed by wheat planted on October 15 with the N rate of 100 $kg \cdot ha^{-1}$, denoted as Fallow-$Wheat_{Oct15,100N}$, was found to be the most productive (total SBI = 4.33) of all the total 94 systems compared. Within the systems that comprised the N rate of 50 $kg \cdot ha^{-1}$ only, the Fallow-$Wheat_{Nov15,50N}$ was the most productive (total SBI = 2.69), whereas the $Cowpea_{Jul15}$-$Wheat_{Nov30,0N}$ system was the most productive (total SBI = 1.44) of all the scenarios comprising the zero N rate. These most productive systems indicated that the fallow-wheat monocropping systems would be more beneficial than the cowpea-wheat double-cropping systems at N rates other than zero, and that the fallow-wheat systems would be more productive with a higher N rate (100 vs. 50 $kg \cdot ha^{-1}$). The SBI values indicated that, with an increase in N rate, the fallow-wheat system would be most productive with an earlier planting date.

Table 5. The system benefit index† (SBI) values for cowpea and wheat crops under various N rates (kg·ha^{-1}) and cropping systems in the Llano Estacado region.

N rate	System‡	Fallow-	Wheat$_{Sep15}$	Wheat$_{Sep30}$	Wheat$_{Oct15}$	Wheat$_{Oct30}$	Wheat$_{Nov15}$	Wheat$_{Nov30}$
				Cowpea SBIs				
	Fallow-	-	-	-	-	-	-	-
	Cowpea$_{Jun01}$-	**0.99**	0.00	0.17	0.41	0.47	0.45	0.43
0	Cowpea$_{Jun15}$-	**1.02**	0.00	0.00	0.20	0.38	0.46	0.44
	Cowpea$_{Jul01}$-	**1.06**	0.00	0.00	0.06	0.29	0.48	0.47
	Cowpea$_{Jul15}$-	**0.94**	0.00	0.00	0.04	0.17	0.43	0.61
				Wheat SBIs				
	Fallow-	-	**0.77**	**0.94**	**1.02**	**1.08**	**1.08**	**1.10**
	Cowpea$_{Jun01}$-	-	0.00	0.36	0.64	0.83	0.94	0.94
0	Cowpea$_{Jun15}$-	-	0.00	0.00	0.50	0.73	0.96	0.85
	Cowpea$_{Jul01}$-	-	0.00	0.00	0.04	0.44	0.76	0.79
	Cowpea$_{Jul15}$-	-	0.00	0.00	0.04	0.21	0.61	0.83
	Fallow-	-	**2.38**	**2.54**	**2.66**	**2.68**	**2.69**	**2.67**
	Cowpea$_{Jun01}$-	-	0.00	0.57	0.96	1.20	1.31	1.26
50	Cowpea$_{Jun15}$-	-	0.00	0.00	0.78	1.02	1.37	1.32
	Cowpea$_{Jul01}$-	-	0.00	0.00	0.07	0.67	1.17	1.19
	Cowpea$_{Jul15}$-	-	0.00	0.00	0.07	0.37	1.10	1.39
	Fallow-	-	**4.02**	**4.21**	**4.33**	**4.29**	**4.21**	**4.14**
	Cowpea$_{Jun01}$-	-	0.00	0.73	1.13	1.38	1.45	1.36
100	Cowpea$_{Jun15}$-	-	0.00	0.00	0.96	1.24	1.59	1.53
	Cowpea$_{Jul01}$-	-	0.00	0.00	0.10	0.82	1.45	1.43
	Cowpea$_{Jul15}$-	-	0.00	0.00	0.11	0.52	1.49	1.77

†For each crop, the SBI for a system in question was computed as a ratio of grain yield under the system to the grain yield under a standard condition. ‡A cropping system comprises a sequence of fallow-cowpea, fallow-wheat, or cowpea-wheat double-crops. For instance, the system comprising the combination of Cowpea$_{Jun01}$- and Wheat$_{Sep15}$ denotes the system of June 1-planted cowpea crop followed by September 15-planted wheat crop.

Table 6. The total system benefit index† (SBI) values for various cropping systems comprising cowpea and wheat crops planted on various dates and applied with several N rates (kg·ha^{-1}).

N rate	System‡	Fallow-	Wheat$_{Sep15}$	Wheat$_{Sep30}$	Wheat$_{Oct15}$	Wheat$_{Oct30}$	Wheat$_{Nov15}$	Wheat$_{Nov30}$
	Fallow-	-	**0.77**	**0.94**	1.02	1.08	1.08	1.10
	Cowpea$_{Jun01}$-	0.99	0.00	0.53	**1.05**	**1.30**	**1.39**	**1.38**
0	Cowpea$_{Jun15}$-	1.02	0.00	0.00	0.70	**1.11**	**1.41**	**1.29**
	Cowpea$_{Jul01}$-	1.06	0.00	0.00	0.10	0.73	**1.25**	**1.26**
	Cowpea$_{Jul15}$-	0.94	0.00	0.00	0.08	0.38	1.04	**1.44**

Continued

50	Fallow-	-	**2.38**	**2.54**	**2.66**	**2.68**	**2.69**	**2.67**
	$Cowpea_{Jun01}$-	-	0.00	0.74	1.37	1.67	1.75	1.69
	$Cowpea_{Jun15}$-	-	0.00	0.00	0.98	1.41	1.82	1.76
	$Cowpea_{Jul01}$-	-	0.00	0.00	0.13	0.96	1.65	1.66
	$Cowpea_{Jul15}$-	-	0.00	0.00	0.11	0.54	1.53	2.00
100	Fallow-	-	**4.02**	**4.21**	**4.33**	**4.29**	**4.21**	**4.14**
	$Cowpea_{Jun01}$-	-	0.00	0.89	1.54	1.84	1.90	1.79
	$Cowpea_{Jun15}$-	-	0.00	0.00	1.16	1.62	2.05	1.97
	$Cowpea_{Jul01}$-	-	0.00	0.00	0.16	1.12	1.93	1.90
	$Cowpea_{Jul15}$-	-	0.00	0.00	0.15	0.69	1.93	2.37

†The total SBI for a system in question was computed first by computing the ratio of grain yield under the system to the grain yield under a standard condition for cowpea and wheat each and then by combining the corresponding values of the two crops together. ‡A cropping system comprises a sequence of fallow-cowpea, fallow-wheat, or cowpea-wheat double-crops. For instance, the system comprising the combination of $Cowpea_{Jun01}$- and $Wheat_{Sep15}$ denotes the system of June 1-planted cowpea crop followed by September 15-planted wheat crop.

The total SBI values further showed that cowpea-wheat double-cropping could be beneficial only at the N rate of zero, especially with the wheat crops planted on October 15 or later. With cowpea planted on June 1, four double-cropping systems, namely $Cowpea_{Jun01}$-$Wheat_{Oct15,0N}$, $Cowpea_{Jun01}$-$Wheat_{Oct30,0N}$, $Cowpea_{Jun01}$-$Wheat_{Nov15,0N}$, and $Cowpea_{Jun01}$-$Wheat_{Nov30,0N}$, were more beneficial than the monocrops of cowpea and wheat planted on those specific dates. With a delay in planting cowpea, however, the number of advantageous double-cropping systems decreased linearly, with a constriction of the wheat planting window toward November 30. That is, for cowpea crops planted on June 1, June 15, July 1, and July 15, the beneficial double-cropping systems were 4, 3, 2, and 1, respectively. In other words, with an expansion of the cowpea planting window toward July 15, the number of beneficial double-cropping systems increased from 1 to 4 as the planting date of wheat was delayed from October 15 to November 30. The SBI values associated with these numbers are bolded in **Table 6**.

3.2. The Fallow-Wheat Monocropping Systems

As the SBI values in **Table 6** showed, except for certain systems with zero N rate (10 in total), the fallow-wheat monocropping systems were more beneficial than the cowpea-wheat double-cropping systems. Particularly, in all systems with N rate greater than zero, the fallow-wheat systems were the most beneficial.

The response of fallow-wheat grain yields to wheat planting date as affected by N rate is presented in **Figure 7**. Regardless of planting date, the effect of N rate on wheat yields was significant. With an increase in N rate from 0 through 100, wheat yields increased almost linearly. This indicated that the suggested N rate of 34 kg·ha^{-1} [38] [39], especially for the years with above average seasonal

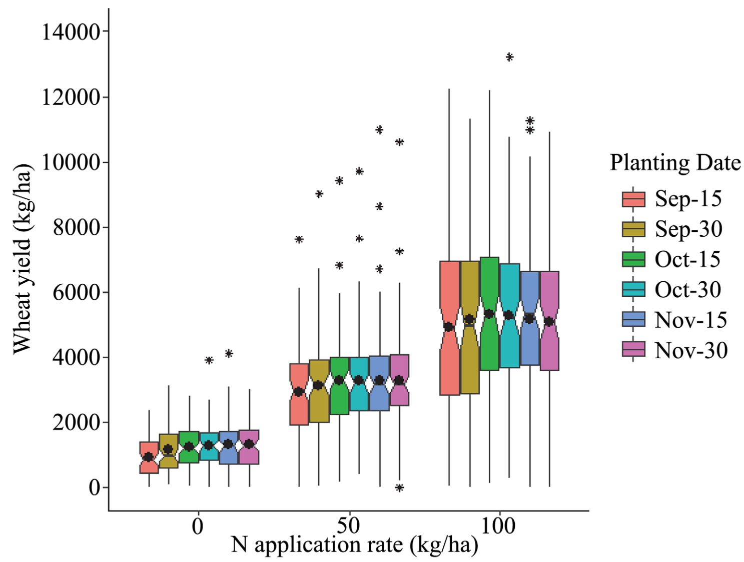

Figure 7. Boxplots showing wheat yield response to N rate × planting date. In a boxplot, the lower and upper ends of whiskers indicate minimum and maximum values, respectively; the dot indicates the mean value; the colored region shows interquartile range; and stars indicate outliers.

precipitation, might not be adequate to meet the yield potential of fallow-wheat systems in the study region under rainfed conditions.

For each N rate studied, the relationship between wheat grain yield and planting date was quadratic (**Figure 8**). When no fertilizer was applied, wheat yields increased, although at a diminishing rate, until the planting date of November 30 (day of year, DOA = 333). With an increase in N rate, however, wheat yields reached the peak and decreased thereafter with an earlier planting date. That is, the maximum yields of wheat at the N rates of 50 and 100 kg·ha^{-1} were associated with the planting dates of November 15 (DOY = 318) and October 15 (DOY = 288), respectively. This could be likely due to the weather conditions of cooler temperatures, optimal rainfall, and reduced drought.

Irrespective of planting dates, the grain yields of fallow-wheat at the N rates of 0, 50, and 100 kg N ha^{-1} were about 1200, 3200, and 5200 kg·ha^{-1}. Reference [38] found that, at the N rate of 34 kg·ha^{-1} in Bushland, Texas (the study region), the 77-year (1940-2016) average value of observed wheat grain yields associated with high yielding cultivars under dryland conditions was 2300 kg·ha^{-1}. In our study, the 80-year (1942-2021) average value of simulated wheat yields associated with the N rate of 50 kg·ha^{-1} was about 3200 kg·ha^{-1}. Because the yield of 2300 kg·ha^{-1} at 34 kg N was approximately equal to the yield of 3200 kg·ha^{-1} at 50 kg N, results indicated that the simulated yield values were reliable.

3.3. The Fallow-Cowpea Monocropping Systems

The SBI values in **Table 6** showed that within the fallow-cowpea monocropping systems considered the monocrop of cowpea planted on July 1 was the most beneficial of all systems, with the SBI of 1.06. However, no fallow-cowpea monocropping system was the best among the entire 94 systems studied or among the 34 systems associated with zero N. Nevertheless, certain fallow-cowpea monocropping systems were more beneficial than certain fallow-wheat or cowpea-wheat systems. The monocrop of cowpea planted on June 1 was better than the systems associated with the earlier planting dates of wheat (September 15 and 30). With a delay in cowpea planting, the cowpea monocropping system was better than an additional system associated with an additional planting date of wheat. Thus, when the monocrop of cowpea was planted on July 15, the number of better monocropping systems was the greatest.

The detailed response of fallow-cowpea grain yields to cowpea planting date is presented in Figure 9. The relationship between cowpea grain yield and planting date was quadratic (Figure 10). Of all the planting dates considered, the planting

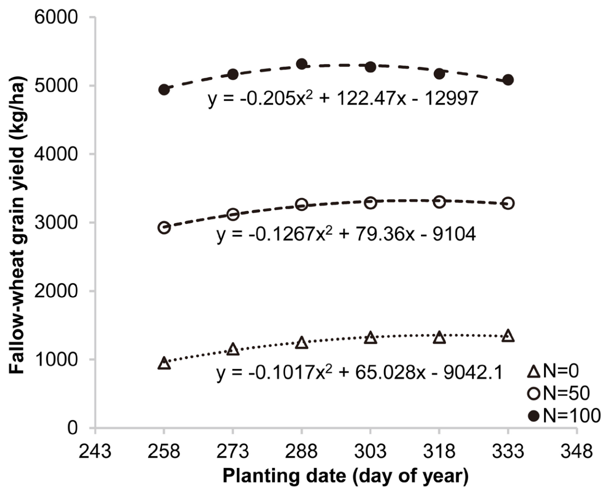

Figure 8. Associations between fallow-wheat grain yield and wheat planting date for the three N application rates of 0, 50, and 100 kg·ha^{-1} in the Llano Estacado region.

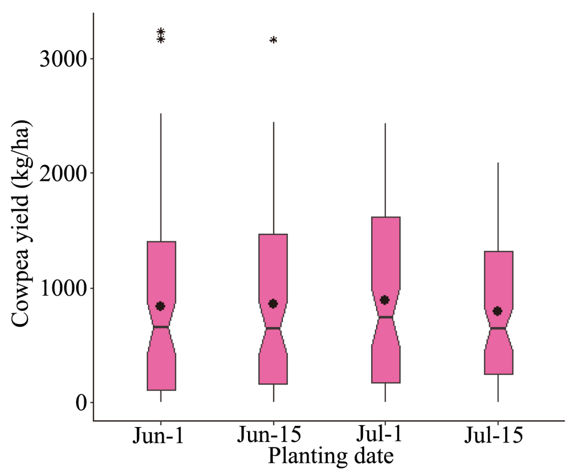

Figure 9. Boxplots showing cowpea yield response to planting date. In a boxplot, the lower and upper ends of whiskers indicate minimum and maximum values, respectively; the dot indicates the mean value; the colored region shows interquartile range; and the stars indicate outliers.

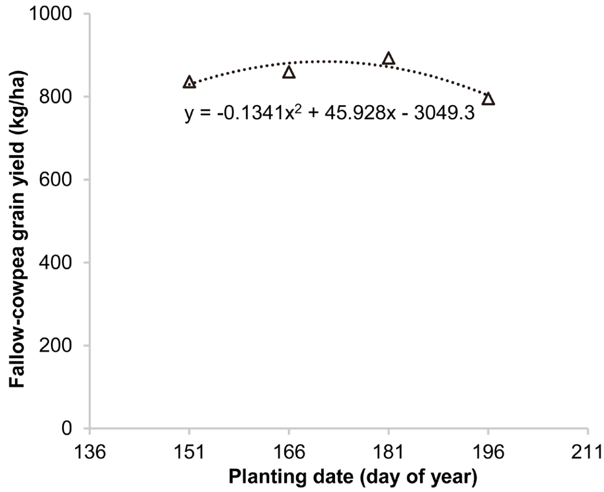

Figure 10. Association between fallow-cowpea grain yield and cowpea planting date in the Llano Estacado region.

date of July 1 (DOY = 181) was associated with the highest yields of cowpea. The cowpea crops planted before and after this date had lower yields. The reduction in yields with planting dates after July 1 was likely because there was not enough time for cowpea to flower and set seeds.

4. Conclusions

The study results showed that the possibility of growing cowpea-wheat double-crops in the semi-arid region of Llano Estacado varied from 0% to 65%, depending on the double-cropping scenario comprising the planting dates of these crops. The highest feasibility was associated with the cowpea planting date of July 15 and the wheat planting date of November 30. However, for a given cowpea planting date, the double-cropping feasibility decreased with an earlier planting date of wheat. Thus, the double-cropping possibility was zero when wheat was planted on September 15. For given wheat planting date, especially the earlier ones, the possibility of double-cropping was highest with the cowpea planting date of June 1 and decreased thereafter with a delay in cowpea planting.

The simulation results indicated that cowpea-wheat double-cropping could be beneficial only when no N was applied, and wheat crops were planted on October 15 or later. At zero N, the double-crops of cowpea planted on July 15 and wheat planted on November 30 were the most beneficial. With a delay in planting cowpea, however, the number of beneficial double-cropping systems would decrease. At N rates other than zero, however, fallow-wheat monocropping systems would be more beneficial than cowpea-wheat double-cropping systems, and the benefit would be more at a higher N rate. At 100 kg N ha^{-1}, the monocrop of wheat planted on October 15 was the most beneficial of all the 94 systems studied. With an increase in N rate, the most beneficial fallow-wheat system was associated with an earlier planting date. As the simulation results showed, fallow-wheat yields increased almost linearly with an increase in N rate from 0 through 100, indicating that the suggested N rate of 34 kg·ha^{-1} might not be enough to meet the yield potential of fallow-wheat production systems in the study region under rainfed conditions. Regardless of the N rate, the relationship between fallow-wheat grain yield and planting date was quadratic. With an increase in N rate, wheat yields reached the peak and decreased thereafter with an earlier planting date. That is, the maximum yields of wheat at the N rates of 0, 50, and 100 kg·ha^{-1} were associated with the planting dates of November 30, November 15, and October 15, respectively. Irrespective of N rate and planting date, the wheat yields produced under monocropping systems were greater than those produced under double-cropping systems with any cowpea planting date. The cowpea yields produced under monocropping systems with any planting date were greater than those produced under any double-cropping system. The relationship between cowpea grain yield and planting date was quadratic, with July 1 planting date associated with the maximum yields.

Environmental conditions in semi-arid regions of the United States impose limits on the physical production and economic success of cropping systems. This study has revealed some opportunities and potential obstacles for double-cropping a summer legume with the long-time, standard winter wheat crop under limited and restricted soil moisture. There is an increasing awareness and need for adopting and incorporating summer legume cover crops in long-time mono-cropped grain production regions for potential improvement of soil health and reduction of soil erosion. Simulated successes and constraints for double-cropping cowpea with wheat for grain crops could be extended to the use of cowpeas as only a cover crop without the expectation of a double grain crop.

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Conflicts of Interest

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

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