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Estimating the Drought-Induced Yield Loss for Winter Wheat in a Semi-Arid Region of the Southern United States Using a Drought Index

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Abstract

The economy of most rural locations in the semi-arid region of Llano Estacado in the southern United States is predominantly based on agriculture, primarily beef and wheat (*Triticum aestivum* L.) production. This region is prone to drought and is projected to experience a drier climate. Droughts that coincide with the critical phenological phases of a crop can be remarkably costly. Although drought cannot be prevented, its losses can be minimized through mitigation measures if it is predicted in advance. Predicting yield loss from an imminent drought is an important need of stakeholders. One way to fulfill this need is using an agricultural drought index, such as the Agricultural Reference Index for Drought (ARID). Being plant physiology-based, ARID can represent drought-yield relationships accurately. This study developed an ARID-based yield model for predicting the drought-induced yield loss for winter wheat in this region by accounting for its phenological phase-specific sensitivity to water stress. The reasonable values of the drought sensitivity coefficients of the yield model indicated that it could reflect the phenomenon of water stress decreasing the winter wheat yields in this region reasonably. The values of the various metrics used to evaluate the model, including Willmott Index (0.86), Nash-Sutcliffe Index (0.61), and percentage error (26), indicated that the yield model performed fairly well at predicting the drought-induced yield loss for winter wheat. The yield model may be useful for predicting the drought-induced yield loss for winter wheat in the study region and scheduling irrigation allocation based on phenological phase-specific drought sensitivity.

Keywords

ARID, Drought, Drought index, Growth-stage, Model, Phenological-Phase, Prediction, Semi-Arid, Wheat, Yield

1. Introduction

The Llano Estacado region in the southern United States comprises the semi-arid areas of northwestern Texas and eastern New Mexico [1]. This region is prone to various extreme weather events, including frequent and flash droughts. Drought may occur during any time of the year in this region. The drought conditions can develop rapidly when the shortage of rain is combined with high temperatures. Due likely to global warming and subsequent increase in the evapotranspiration losses of soil water, this region is projected to experience a drier climate in the future [2]. Studies have shown that with elevated temperatures the potential for more intense droughts in the region will be higher [3]-[5]. Under warmer conditions, rain tends to be concentrated into heavier events, with longer dry periods in between [6]. In this region, further stresses on water supply for agriculture are likely, as the region's urban areas continue to expand, with the largest impacts expected in heavily irrigated areas which have already been plagued by unsustainable water use [7].

The economy of most rural and regional locations in this region is predominantly based on agriculture, primarily beef and wheat (*Triticum aestivum* L.) production [8]. Cattle ranchers and crop growers across the region depend on rain for raising livestock and producing crops. Droughts, especially those that coincide with the critical phenological stages of a crop, can be remarkably costly [8]. Even after the termination of a drought episode, its economic impact usually lasts for several years. Many communities and local economies in the region continue to face significant challenges brought about by drought. In Texas alone, drought has cost as high as $50 billion over the last 40 years [8].

Drought cannot be prevented. However, the losses due to an impending drought can be minimized through adaptation or mitigation measures if it is predicted beforehand [9]. Predicting yield loss from an imminent drought is one of the most important needs of crop growers and farm managers. The drought-induced yield loss is influenced by several factors such as the onset, severity, and duration of a drought episode; plant species or crop type; crop growth stage; soil type; temperature; and crop management. The impact of drought depends on the sensitivity of a crop to drought stress, which varies by growth stage. Soil texture determines water retention capacity and thus the soil water balance. Higher temperatures increase crop evapotranspiration losses. Crop management decisions such as on planting date, crop variety, and irrigation, if any, also have significant influence on the impact of drought on crop yields. The ability to predict yield loss can help stakeholders with decisions regarding applying appropriate adaptation or mitigation measures such as diversifying cropping systems, changing species or varieties, manipulating planting dates, making irrigation efficient, shifting from irrigated to dryland farming, or leaving the field unplanted. The drought-induced yield losses may be predicted using various yield models that are based on classical statistical methods such as regressions; machine learning techniques such as artificial neural network, fuzzy-logic inference system, random forest, Gaussian processes, Kstar, sequential minimal optimization, and model trees; time series analysis; remote sensing-based vegetation indices; or drought indices [10]. Compared with other methods, the drought indices are simpler, usually represented by a number. However, they provide a comprehensible big picture on drought conditions by integrating all relevant agricultural, hydrological, and meteorological information into that number.

A number of drought indices exist that can monitor or predict an agricultural drought [11] [12], a temporary condition where the amount of plant available water in the soil due to precipitation falls short of the atmospheric demand for evapotranspiration [13]. However, as yield formation is a plant physiological process, only a plant physiology-based drought index is able to predict the yield loss due to drought more accurately [14]. One of such few indices is the Agricultural Reference Index for Drought (ARID) [14]. This drought index is computationally simple, biophysically sound, and generally applicable and can characterize an agricultural drought better than many similar indices can [15]. The ARID is computed on a daily basis as the ratio of plant water deficit to plant water need as:

$$\text{ARID}_i = 1 - \frac{T_i}{ET_{o,i}} \tag{1}$$

where the subscript i stands for the i-th day, T is transpiration (mm·d^{-1}), and ET_o is the reference grass evapotranspiration (mm·d^{-1}) [16] [17]. The ARID values range from 0, indicating no water stress, to 1, indicating full water stress.

Considering that (i) a crop yield model that takes into account a series of phenological phases during the crop growing season could reflect the effect of water stress on yield better than the one that considers the whole season as a single phase, given that a differential yield response to water stress occurs at each phenological phase; (ii) relative yields (water-stressed yields relative to non-water-stressed ones) could be more reliably estimated than absolute yields, as a crop yield is defined by many factors besides drought; (iii) the effect of water deficit on crop yield at different growth phases could be expressed using a multiplicative method, as crop yield is not linearly related to total water use when plants are stressed; and (iv) the determinate, flowering crops have several distinct growth phases with differing drought sensitivities, [18] developed the following model for estimating the relative yield (${}^{R}Y$) and, eventually, the fraction of yield loss due to drought, computed as 1 minus ${}^{R}Y$, for a determinate, flowering crop using the growth phase-specific values of ARID.

$${}^{R}Y = \prod_{p=1}^{P} \left(1 - \text{ARID}\right)_p^{\lambda_p} \tag{2}$$

where ${}^{R}Y$ is the relative yield of a crop, the symbol Π indicates a product, "*p*" is a growth phase, "*P*" is the total number of phases considered during the crop growing season, and λ_p is the relative sensitivity of the crop to drought stress during the *p*-th growth phase.

The general objective of this study was to develop an ARID-based relative yield model for predicting the drought-induced yield loss for winter wheat in the Llano Estacado region of the United States. The specific objective was to estimate the phase-specific drought sensitivity coefficient (λ_p) values for various phenological phases (*P*) of winter wheat to be used in the yield model (Equation (2)).

2. Materials and Methods

2.1. Obtaining the Yield Data

To calculate the relative yields of a winter wheat variety, its absolute yields ($kg \cdot ha^{-1}$) under both irrigated and dryland farming conditions would be needed. In the Llano Estacado region, such yields for a period sufficiently long for conducting modeling studies were available only for Bushland, Texas and Clovis, New Mexico. These data were obtained (**Table 1**) from the Hard Winter Wheat Regional Nursery Program of the USDA Agricultural Research Service agency (https://www.ars.usda.gov/plains-area/lincoln-ne/wheat-sorghum-and-forage-research/docs/hard-winter-wheat-regional-nursery-program/research/). In both locations, each trial season involved a number of cultivars, as many as 50. However, there was no cultivar that was grown under both dryland and irrigated conditions for a sufficiently long period. Thus, the yields of all the winter wheat varieties involved in the trials at each location in each year (season) under each farming regimen (dryland or irrigated) were averaged to calculate the dryland and irrigated yields of a general winter wheat variety for these locations and years. These average yields were used as the yields of winter wheat for further analyses.

Considering the irrigated yield as the non-water-limited yield, the relative yield for winter wheat in location *j* and year *k*, detonated as (${}^{R}Y_{j,k}$), was calculated from the observed values of the dryland yield (${}^{D}Y_{j,k}$) and the irrigated yield (${}^{I}Y_{j,k}$) using Equation (3).

Table 1. The number of seasons and years for which both dryland and irrigated winter wheat grain yield data were available in two locations in the Llano Estacado region of the USA.

Location	Lat., Lon.	Seasons	Years
Bushland, TX	35.21°N, 101.91°W	49	1947, 1953, 1954, 1958-1960, 1962, 1964, 1966, 1968, 1970, 1972, 1973, 1975, 1977, 1979-1982, 1985-1988, 1990-1992, 1994-2002, 2004, 2006-2012, 2016-2021
Clovis, NM	34.60°N, 103.21°W	47	1962-1964,1968-1973, 1975-2001, 2005-2008, 2010-2011, 2015-2019

$$^{R}Y_{j,k} = \frac{^{D}Y_{j,k}}{^{I}Y_{j,k}} \quad (3)$$

2.2. Obtaining the Weather Data

For calculating thermal time to estimate durations for various phenological phases, the daily data on ambient maximum temperature (˚C) and minimum temperature (˚C) would be needed. For computing ARID, the daily data on additional meteorological variables, namely precipitation (mm), dewpoint temperature (˚C), average windspeed ($m \cdot s^{-1}$), and solar radiation ($MJ \cdot m^{-2}$), would be necessary. The daily precipitation, temperature, and windspeed data spanning several years (**Table 1**) for the two locations were obtained from National Centers for Environmental Information (NCEI; https://www.ncei.noaa.gov/access/search/data-search/daily-summaries). The dewpoint temperatures were obtained from various sources or estimated from minimum temperatures. Due to the lack of observed data, the daily solar radiation values for these locations and years were generated using a reliable global solar radiation model for the southeastern United States [19].

2.3. Estimating Phase Durations

For drought sensitivity analyses and other purposes, the winter wheat growing season has been divided by previous research into multiple phenological phases ranging from three [20] to ten [21]. While the sensitivity of wheat yields to drought represented by just three phases might be too general to reflect the effects of drought at various critical times during the season, assessing the drought sensitivity using ten phases is not practical from the viewpoint of getting relevant data and estimating the phase durations accurately. Thus, reference [22] grouped the ten various phases into four groups: germination-emergence; emergence-double ridge, double ridge-anthesis, and anthesis-maturity. Taking into account the availability of phase duration data and assuming the double ridge-anthesis phase to be too wide from the practical standpoint and thus splitting this group further into two groups, we considered the following consolidated five phases for this study: 1) planting to emergence, 2) emergence to tillering, 3) tillering to booting, 4) booting to anthesis, and 5) anthesis to physiological maturity.

To split a wheat growing season into multiple phenological phases mentioned above, wheat planting dates would be needed. However, the planting dates associated with the yield trials were not available. Thus, a representative planting date for the Bushland area was estimated from the planting date data available at the Texas A&M AgriLife Research and Extension Center at Amarillo (https://amarillo.tamu.edu/), and that for the Clovis area was estimated from the data available at the Clovis Agriculture Center of New Mexico State University (https://clovissc.nmsu.edu/research/trails.html). The estimated representative planting dates for Bushland and Clovis were 21 October and 15 October, respectively.

Another requirement for splitting the season into several phases would be estimating the total number of days required to complete each phase. As temperature is another key factor defining the time-span of a development phase, a logical approach to this estimation could be using the thermal time, also known as growing degree-days, approach. Based on this approach and using the total thermal time (TTT; ˚C d) needed for each phase under dryland conditions (**Table 2**), the number of days taken to complete each of the five phenological phases considered above was estimated using Equation (4).

Table 2. Total thermal time (TTT) needed to complete each phenological phase of winter wheat under dryland farming conditions in the Llano Estacado region of the USA.

Phenological phase (*p*)	*p*	TTT (˚C d)
Planting to emergence	1	150
Emergence to tillering	2	200
Tillering to booting	3	1152
Booting to anthesis	4	261
Anthesis to maturity	5	640

$$D_p = \sum_{i_p = SD_p}^{n_p,\ \text{when}\ \sum_{i_p=SD_p}^{n_p} TT_{i_p} = TTT_p} 1 \tag{4}$$

where the subscript "*p*" stands for a given phenological phase during the wheat growing season (p = 1, 2, …, 5); D_p is the number of days taken by the p-th phase; i_p is the i-th day of the p-th phase; SD_p is the start day of the p-th phage; n_p is the n-th day of the p-th phase; TTT_p is the total thermal time needed to complete the p-th phase (**Table 2**); and TT_{i_p} is the thermal time (˚C d) on the i-th day of the p-th phase, which was computed as [20]:

$$TT_{i_p} = \begin{cases} T_{base} & \text{if } T_{av_{i,p}} < T_{base} \\ T_{UL} & \text{if } T_{av_{i,p}} > T_{UL} \\ T_{av_{i,p}} & \text{else} \end{cases} \tag{5}$$

where T_{base} is the base temperature at which development stops, assumed to be 0˚C for winter wheat [23]; T_{UL} is the upper limit temperature at which the rate of development plateaus, assumed to be 25˚C for winter wheat [24]; and $T_{av_{i,p}}$ is the average temperature on the i-th day of the p-th phase, which in turn, was calculated as follows.

$$T_{av_{i,p}} = \frac{T_{max_{i,p}} + T_{min_{i,p}}}{2} \tag{6}$$

where $T_{max_{i,p}}$ and $T_{min_{i,p}}$ are the maximum and minimum temperatures on the

i-th day of the p-th phase, respectively.

Using the procedures described above (Equations (4), (5) and (6)), thus, 245 D_p values (involving 49 years × 5 phases) were estimated for Bushland, TX and 235 D_p values (involving 47 years × 5 phases) for Clovis, NM. Once the planting date for each location and the D_p value for each year in each location were estimated, each wheat growing season in each location (**Table 1**) was split into the five phenological phases stated above. The thermal time required to complete each growth phase could be significantly influenced by the soil moisture condition [21] [25] [26]. Thus, the TTT value required to complete each of these phenological phases under dryland farming conditions in the Llano Estacado region (**Table 2**) was obtained from the literature [21] [25]-[28].

2.4. Computing ARID Values

For each location, the daily values of ARID for each wheat growing season (year) that had yield data (**Table 1**) were computed from the daily values of its input variables stated above, using the ARID equations described by [14] and the computational procedure (the MATLAB program) provided by [13]. Once the daily values of ARID were computed for each year in each location, they were averaged by phase. Consequently, there were 245 phasic values of ARID for Bushland, TX and 235 phasic values of ARID for Clovis, NM. In the yield model (Equation (2)), the (1 − ARID) values are needed as inputs. Accordingly, the phasic values of ARID were converted into the corresponding phasic values of (1 − ARID) by subtracting an ARID value from one.

2.5. Estimating Drought Sensitivity Coefficients

Once the relative yield values of winter wheat were calculated using Equation (3) and the phasic values of (1 − ARID) were calculated as explained above for each year in each location, a matrix of dataset comprising 49 rows (years) and 6 columns was prepared for Bushland and that comprising 47 rows and 6 columns for Clovis. For developing the yield model for the region, these two matrices were combined to produce a single matrix of 96 rows and 6 columns. The first column in the matrix contained the relative yields (the dependent or output variable), and the remaining columns contained the corresponding phasic values of (1 − ARID) for the five phases (the independent or input variables).

For estimating the drought-sensitivity coefficient for winter wheat during the phenological phase p, denoted as λ_p, regressing the linearized form (Equation (7)) of the yield model (Equation (2)) would be necessary. Accordingly, all the values in the matrix prepared for the region as explained above were converted into the natural logarithmic (ln) values. These transformed matrices, in turn, were used in the R-project software (https://www.r-project.org/) to estimate the λ_p values through multiple linear regressions. The linearized form of the yield model is as follows (Equation (7)).

$$\ln\left({}^{R}Y_{j,k}\right)=\sum_{p=1}^{5}\left\{\lambda_p\times\ln\left(1-\mathrm{ARID}_{j,k,p}\right)\right\} \tag{7}$$

where ${}^{R}Y$ is the relative yield; and the subscripts *j*, *k*, and *p* stand for the *j*-th location, the *k*-th year, and the *p*-th phenological phase, respectively.

2.6. Evaluating the Yield Model

For evaluating the performance of the winter wheat yield model, a dataset independent of the one used for model development (parameterization) would be necessary to avoid overfitting the data. This would necessitate splitting the limited available data into two independent subsets: one for parameterization and the other for model evaluation. This process would reduce the size of the parameterization set, which in turn would lead to a less robust model. To evaluate the yield model without reducing the size of the parameterization set, thus, the leave-one-out technique of cross-validation was used. Following this technique, the available dataset (the transformed matrix discussed above) for the region was divided into two parts: one for parameterization and the other for evaluation. That is, of the total 96 input-output combinations for the region, the first 95 combinations (rows) were used as the parameterization set for estimating the λ_p values through the regression of Equation (7) and the last one combination (row) as the evaluation set for yield estimation through the use of the just estimated λ_p values in the yield model (Equation (2)). Leaving one combination out and adding one combination in, both the window of the parameterization set and the evaluation set were moved forward 95 times. Each movement created a new parameterization set and a new evaluation set, which, in turn, produced a set of new λ_p values through regressions (using Equation (7)) and, finally, a yield estimate (using Equation (2)). This process, consequently, provided 96 relative yield estimates for the region. Finally, using the modelling efficiency index, also known as the Nash-Sutcliffe Index [29], the mean absolute error, the root mean square error (RMSE), and the Willmott Index [30] as the measures of fit, the estimated relative yields (using Equation (2)) for the years for which the observed yields were available in each location were compared with the corresponding calculated relative yields (using Equation (3)) to evaluate the performance of the winter wheat yield model developed for the region.

3. Results and Discussion

3.1. Drought Sensitivity Coefficients

Table 3 shows the phenological phase-specific drought sensitivity coefficients estimated for the winter wheat yield model for the Llano Estacado region of the United States. Using these coefficients in Equation (2) resulted in the following relative yield model for winter wheat.

$$\begin{aligned}{}^{R}Y=0.97&\times\left(1-\mathrm{ARID}\right)_{PE}^{0.068}\times\left(1-\mathrm{ARID}\right)_{ET}^{0.086}\times\left(1-\mathrm{ARID}\right)_{TB}^{0.279}\\&\times\left(1-\mathrm{ARID}\right)_{BA}^{0.07}\times\left(1-\mathrm{ARID}\right)_{AM}^{0.042},\end{aligned} \tag{8}$$

where ^{R}Y is the relative yield of winter wheat; and the subscript PE stands for the planting-emergence phase, ET the emergence-tillering phase, TB the tillering-booting phase, BA the booting-anthesis phase, and AM the anthesis-maturity phase.

Table 3. The phenological phase-specific drought sensitivity coefficient (λ_p) values for the winter wheat relative yield model for the Llano Estacado region of the USA.

Phenological phase (p)	λ_p	Value
	intercept	0.970
Planting-emergence ($p = 1$)	λ_1	0.068
Emergence-tillering ($p = 2$)	λ_2	0.086
Tillering-booting ($p = 3$)	λ_3	0.279
Booting-anthesis ($p = 4$)	λ_4	0.070
Anthesis-maturity ($p = 5$)	λ_5	0.042

The values of all the sensitivity coefficients were positive, indicating that the water stress during any phase of the wheat growing season would have negative impacts on yields. This result was in agreement with the findings of several previous studies. Reference [31] in an experiment conducted in Arizona, USA, observed that water stress at any growth stage of wheat reduced grain yields. Reference [22] in a review study also found that water stress could occur during any phenological phase of wheat, depending on the environment in which the crop was grown. In a review paper, [32] also demonstrated that wheat is vulnerable to drought stress, which can occur at any growth stage. While water stress involving the entire growing season results in crop failure, the deficit at any particular stage results only in high losses, not crop failure [33].

Of all the phases of winter wheat considered, the tillering-booting phase had the largest values for the drought sensitivity coefficients, indicating this phase as the most sensitive to water stress. This implication was consistent with the findings of various studies. Reference [22] concluded that the most critical phase of winter wheat for water deficit was tillering-booting, and that a mild to moderate water stress during this period could reduce cell growth and leaf area significantly, consequently reducing photosynthesis per unit area. If the stress is more intense, net photosynthesis is decreased even more due to the partial closure of stomata [34]. The tillering-booting phase of wheat comprises several growth stages such as double ridge or floral initiation, beginning of leaf sheaths lengthening (pseudo-stem erecting), terminal spikelet, jointing, visibility of second stem node, beginning of flag-leaf emergence, visibility of flag-leaf ligule, and booting. In a study conducted in the North China Plain, [20] found that winter wheat was most vulnerable to moderate and severe drought during the period between spring greenup (which occurs around the beginning of leaf sheaths lengthening) and anthesis, and that the yield loss due to drought increased with the aggravation of drought. In a modeling study performed in the Po River Basin of Northern Italy, [33] found that, of all the phases they studied, the double ridge-anthesis phase was the most sensitive to water stress, followed by the anthesis-maturity (yield formation) phase. In an experiment carried out in Arizona, [31] observed that water stress during jointing was the most critical of all growth stages to wheat yield. The likely reasons for the greatest drought sensitivity during the tillering-booting phase were as follows. During the tillering-booting phase, especially during the period between 30 days before and 10 days after anthesis, which coincides with the active growth of peduncle and spike, the kernel number is determined [22]. At the terminal spikelet stage, the potential number of spikelets per head is determined. At terminal spikelet, booting, and flag-leaf emergence stages, crop water demand is high, which is about 2.5, 6.4, and 7.6 mm per day, respectively [35]. The water stress during jointing to late booting, the rapid spring growth period prior to heading, reduces yields by reducing the number of stems and heads through increasing the senescence of tillers and stems and by reducing the number of grains through fewer spikelets per head, fewer grains per spikelet, or both [36]. Reference [31] found that the water stress during jointing would decrease the number of grains per head, and that a seven-day stress during this stage could reduce the number of heads per unit area by 25% and grains per head by 16%. They also found that wheat experiencing water stress at jointing caused shorter planting-flowering duration, shorter plants, more lodging, and reduced grain yields due to fewer heads per unit area and fewer seeds per head.

In drought sensitivity, the tillering-booting phase was followed by the emergence-tillering and the booting-anthesis phases. During the booting-anthesis phase, spike continues growing and emerges (heading). The number of kernels decreases sharply when water stress occurs during the spike growth period [37]. The yield is decreased at a maximum rate when water stress starts about 10 days before spike emergence [22]. Water stress during this phase reduces the availability of carbon and nitrogen, both of which are critical for spike growth. Wheat yield during this period is highly vulnerable to drought due to insufficient assimilates [38]. Water deficit at the heading stage increases the number of sterile spikelets and florets and that at the anthesis stage affects pollination and fertilization, thus reducing the seed setting rate and ultimately the grain yield [39]. In a study conducted in the Wei River Basin of Northwest China, [39] found that greening-anthesis was a highly sensitive phase to drought.

Another highly sensitive phase was emergence-tillering [39], during which leaf expansion and tillering occur. Both of these growth stages are very sensitive to water stress [40]-[42]. Plant water stress during this phase limits leaf and tiller development [36]. Water stress immediately before floral initiation decreases the number of spikelet primordia [43]. At low leaf moisture contents during the emergence-tillering phase, leaf growth can be drastically reduced [44]. If conditions are dry enough, tillering may decrease by about 50% [41] [42]. Consequently, the leaf area index (LAI) development is severely hampered by drought during this phase [22]. Through causing seedling death, drought during this phase may lead to a plummet in yields if no effective measures are followed. However, relative to other phases, the drought impact on wheat yields is less severe during this phase [20].

The sensitivity coefficients showed that the planting-emergence phase was less sensitive to drought relative to emergence-tillering, tillering-booting, and booting-anthesis phases but more so than the anthesis-maturity phase. This result was in line with the finding of [33], who demonstrated that water deficit during the planting-emergence phase was less critical to wheat yields than those during other phases. The drought sensitivity during this phase was likely because an early drought in the growing season may have affected wheat germination and crop establishment [45]. High water deficits during the planting-emergence and the emergence-tillering phases prevent crop development [22].

As the smallest value of the sensitivity coefficients indicated, winter wheat yields were the least sensitive to water stress that occurred during the anthesis-maturity phase, compared with the ones that occurred during the other phases considered. Literature also shows that water stress during the anthesis-maturity phase is the least detrimental of all phases. Reference [31] observed in Arizona that water stress during the grain-filling or dough stage was less critical to wheat yields than that during the tillering-anthesis period. Reference [20] found in the North China Plain region that, of all the phases they studied, drought during the anthesis-maturity period had the smallest yield impacts, and with no heavy losses. This result is supported by the finding of [46] that wheat roots, especially in subsoil, increased rapidly during the late grain-filling period under some drought conditions, with the total root mass density peaking at the milky ripe stage. This indicated that a mild to moderate drought in the late growth period could be beneficial for root growth and distribution, which, consequently, might lead to an increase in yield to some extent or, at least, would not allow yields to decrease drastically. Reference [47] also found that greater root mass and root length density in the subsoil layers might contribute to yields during the period of some water deficit by enhancing access to the subsoil water after anthesis.

Although there is some possibility that the drought-induced root mass increase in subsoil during the terminal growth period might compensate the water deficit experienced by the crop due to drought to some extent by extracting some water from the subsoil layers, as indicated by the studies cited, this extracted water may not fully meet the crop water demand. As a result, wheat is vulnerable to drought even during this phase and may suffer some losses [32] [33]. The likely reasons for the negative effects of drought on grain yields during this phase are as follows. The water stress around anthesis accelerates development [48] and thus decreases the accumulation of soluble carbohydrates in the stem [49]. The water stress during grain-filling reduces grain weight by shortening the period of grain-filling through accelerated senescence [37] [50]. The latter part of the grain-filling period in Llano Estacado is usually hot, dry, and somewhat windy, which tend to cause early grain-filling termination and senescence. Under these conditions, more grains (large grain number), obtained through more spikes per unit area, more spikelets per spike, more grains per spikelet, or all, may be more important than the high grain-filling rate (large grain size) during the anthesis-maturity phase for high yields [36]. This phenomenon was well reflected by the values of the sensitivity coefficients, which were larger for tillering-booting and booting-anthesis phases than for the anthesis-maturity phase (**Table 3**). The reasonable values of the sensitivity coefficients indicated that Equation (8) expressed the ARID-winter wheat yield relationship for the Llano Estacado region accurately.

3.2. The Yield Model Performance

Table 4 shows the values of the various metrics that were used to evaluate the performance of the winter wheat relative yield model for the Llano Estacado region of the United States. The RMSE value was 0.11 (dryland yield per unit of irrigated yield). The overall percentage error of the yield model, computed as the ratio of RMSE to the mean observed relative yield, was about 26. The Willmott Index value for the region was 0.86, whereas the Nash-Sutcliffe Index value was 0.61.

Table 4. Values of the various metrics used to evaluate the performance of the winter wheat yield model developed for the Llano Estacado region of the USA.

Metric	Value
Mean observed relative yield	0.40
Mean predicted relative yield	0.41
Willmott Index	0.86
Nash-Sutcliffe Index	0.61
Mean absolute error	0.09
Root mean square error	0.11
Percentage error	26.15

The various metrics values indicated that the winter wheat yield model for the Llano Estacado region performed fairly well at predicting the relative yields and thus the drought-induced yield losses. The mean absolute error and the percentage error values of the ARID-based yield model were relatively low. The value of the Willmott Index, which measured the degree to which the measured values were approached by the model-predicted values, indicated that the relative yields of winter wheat estimated by the yield model agreed fairly closely with the relative yields calculated from the observed data. The value of the Nash-Sutcliffe Index, which compared the residual variance of the model-predicted values to the variance of the measured data, also indicated that the agreement between the model-estimated and observed values were satisfactory for the winter wheat yield model, and thus the predictive power of the model was relatively good. The positive values of the Nash-Sutcliffe Index showed that model predictions were more accurate than the means of the observed data. The mean predicted relative yield of winter wheat for the region was 0.40, whereas the mean observed relative yield was 0.41. If the percentage error of the model were computed as the absolute difference between the predicted and the observed values relative to the observed value, the mean error value would be about 2.9%, an indication for a small error. The range of the predicted yields was 0.16 to 0.69 and that of the observed yields was 0.13 to 0.78. That is, the width of the range of the predicted yields (0.53) relative to that of the observed yields (0.65) was about 0.81, which indicated that the modeling error based on this statistic was about 19%, a relatively small value. To sum up, the yield model was able to reflect the phenomenon of water stress decreasing the yields of winter wheat in the Llano Estacado region reasonably well (**Figure 1**).

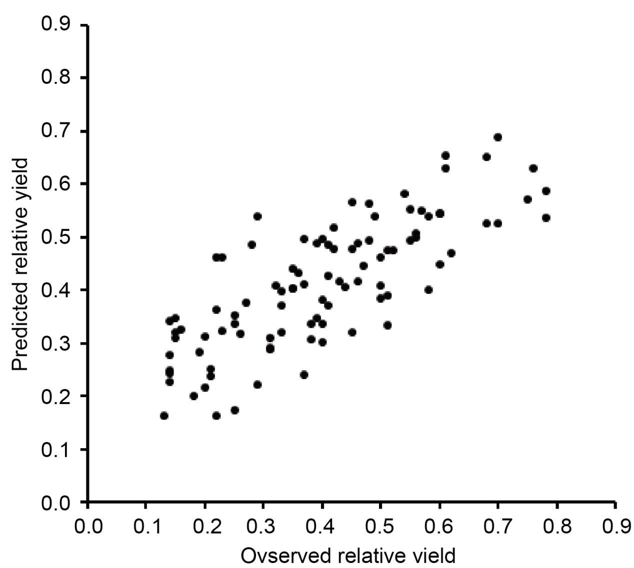

Figure 1. The model-predicted vs. observed values of the relative yield (dryland yield per unit of irrigated yield) of winter wheat in the Llano Estacado region of the USA (1947-2021).

It is important to note that the severity and impact of drought could vary depending on many factors such as specific wheat variety, management, environmental conditions, and the duration and intensity of the drought event. In spite of large uncertainties associated with the data on crop management, cultivars, dates of planting and harvesting, soil, and weather, the ARID-based yield model of wheat was able to estimate the overall effect of drought on the relative yield of winter wheat in the Llano Estacado region reasonably well, indicating that ARID has potential to predict the drought-induced yield losses for the field crops that are sensitive to water stress and grown under dryland farming conditions.

4. Conclusion

This study developed an Agricultural Reference Index for Drought (ARID)-based yield model for predicting the drought-induced yield loss for winter wheat in the Llano Estacado region of the United States by estimating the phase-specific drought sensitivity coefficient values for various phenological phases of this crop. The reasonable values of the sensitivity coefficients indicated that the yield model was able to express the relationship between ARID and the relative yields of winter wheat accurately. The yield model reflected the phenomenon of water stress decreasing the yields of winter wheat in this region and estimated the drought-induced yield losses reasonably well. The winter wheat yield model, which can predict the yield loss from drought by taking into account the differential sensitivity of various phenological phases to drought, might be useful for minimizing the effects of drought on yields through the adoption of necessary mitigation strategies and scheduling irrigation allocation based on the phenological phase to ensure water access to the phases that are more sensitive to water stress.

Conflicts of Interest

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

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