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Predicting the Yield Loss of Winter Wheat Due to Drought in the Llano Estacado Region of the United States Based on the Cultivar-Specific Sensitivity to Drought

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Abstract

In most agricultural areas in the semi-arid region of the southern United States, wheat (*Triticum aestivum* L.) production is a primary economic activity. This region is drought-prone and projected to have a drier climate in the future. Predicting the yield loss due to an anticipated drought is crucial for wheat growers. A reliable way for predicting the drought-induced yield loss is to use a plant physiology-based drought index, such as Agricultural Reference Index for Drought (ARID). Since different wheat cultivars exhibit varying levels of sensitivity to water stress, the impact of drought could be different on the cultivars belonging to different drought sensitivity groups. The objective of this study was to develop the cultivar drought sensitivity (CDS) group-specific, ARID-based models for predicting the drought-induced yield loss of winter wheat in the Llano Estacado region in the southern United States by accounting for the phenological phase-specific sensitivity to drought. For the study, the historical (1947-2021) winter wheat grain yield and daily weather data of two locations in the region (Bushland, TX and Clovis, NM) were used. The logical values of the drought sensitivity parameters of the yield models, especially for the moderately-sensitive and highly-sensitive CDS groups, indicated that the yield models reflected the phenomenon of water stress decreasing the winter wheat yields in this region satisfactorily. The reasonable values of the Nash-Sutcliffe Index (0.65 and 0.72), the Willmott Index (0.88 and 0.92), and the percentage error (23 and 22) for the moderately-sensitive and highly-sensitive CDS groups, respectively, indicated that the yield models for these groups performed reasonably well. These models could be useful for predicting the drought-induced yield losses and scheduling irrigation allocation based on the phenological phase-specific drought sensitivity as influenced by cultivar

genotype.

Keywords

ARID, Cultivar, Drought, Model, Phase, Prediction, Semi-Arid, Stage, Wheat, Yield

1. Introduction

A semi-arid region in the southern United States, Llano Estacado [1] is vulnerable to frequent and flash droughts, which may happen during any time of the year. Droughts can develop quickly especially when precipitation shortage is combined with high temperatures. Due to global warming, this region is projected to have a drier climate in the future [2]. The projected elevated temperatures will likely cause more intense droughts [3]-[5] and longer dry spells [6]. The continued urbanization in agricultural areas that are heavily irrigated will pose further stresses on water supply [7].

Wheat (*Triticum aestivum* L.) production is a primary economic activity in many agricultural areas in the region [8]. In the absence of irrigation options, the majority of wheat growers across the region pursue dryland farming. Droughts can be very costly for wheat production if they occur during the phenological phases of wheat that are more sensitive to drought [8].

Although drought cannot be avoided, its impact on crop yields can be reduced by applying appropriate mitigation measures if it is predicted in advance [9] [10]. Being able to predict crop yield loss due to an anticipated drought is a crucial need of crop growers. This ability allows them to make informed decisions regarding adopting proper mitigation measures. The yield losses due to drought could be predicted using various methods [9]-[11]. However, the simplest, yet viable, method is the drought index. The drought index, often represented by a number, provides a comprehensible big picture on drought by integrating all relevant agricultural, hydrological, and meteorological information into that number.

An agricultural drought is a temporary condition in which the amount of available water in the soil due to precipitation fails to meet the consumptive demand of crops [9] [10] [12]. To monitor or predict an agricultural drought, various drought indices exist. However, since yield formation is a plant physiological process, only a physiology-based drought index can predict the drought-induced yield loss more accurately [12]. The Agricultural Reference Index for Drought (ARID) is one of such few indices [10]. It can identify an agricultural drought better than many similar drought indices can [12] [13]. Moreover, simplicity, generality, daily resolution, and a soil-plant-atmosphere basis are some of the fundamental requirements of an agricultural drought index [9]. However, the available drought indices that are being applied to agricultural systems, except ARID, do not have all these agriculturally important features [12]. The ARID index is computationally simple, physically and physiologically sound, and generally applicable to characterize an agricultural drought [12]. Although ARID is a generic drought index, it is applicable to a wide range of crops, soils, topographies, and management and has fairly small uncertainties [13].

The sensitivity of a crop to water stress varies across various phenological phases during the crop growing season. While some phases are more sensitive, others are less [8]. Because a differential yield response to water stress occurs at each phenological phase, a crop yield model that takes into account the water stress sensitivity of various phenological phases during the growing season can reflect the effect of water stress on yield better than the one that considers the whole season as a single phase [14]. To estimate the yield loss due to drought for a determinate, flowering crop, [14] developed an ARID-based relative yield (Y_R) model (Equation (1)) by taking into account a series of phenological phases during the crop growing season. The relative yield is defined as the water-stressed yield relative to the non-water-stressed yield. Using Y_R, the fraction of drought-induced yield loss is computed as (1 − Y_R).

$$\mathrm{Y_R} = \prod_{\mathrm{p}=1}^{\mathrm{P}} \left(1-\mathrm{ARID}\right)_{\mathrm{p}}^{\lambda_{\mathrm{p}}}, \tag{1}$$

where Y_R is the relative yield of a crop, the symbol Π (pi) indicates a product, p is a phenological 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 during the p-th phenological phase.

Different wheat cultivars exhibit varying levels of sensitivity to water stress. That is, some cultivars can tolerate drought conditions much better than others, with key differences in their physiological responses such as root architecture, stomatal control, and osmotic adjustment [15]-[19]. These differences allow some cultivars to maintain yield even under water deficit situations while others suffer significant reductions in production.

This study developed the cultivar drought sensitivity (CDS) group-specific, ARID-based yield models to predict the drought-induced yield loss for winter wheat in the Llano Estacado region in the southern United States. Specifically, the study estimated the phenological phase-specific drought sensitivity coefficients for various phenological phases of winter wheat to be used in the CDS group-specific relative yield models (Equation (2)).

$$\mathrm{Y}_{\mathrm{R}_g} = \prod_{\mathrm{p}=1}^{\mathrm{P}} \left(1-\mathrm{ARID}\right)_{g,\mathrm{p}}^{\lambda_{g,\mathrm{p}}}, \tag{2}$$

where $\mathrm{Y}_{\mathrm{R}_g}$ is the CDS group-specific relative yield of winter wheat; the subscripts g and p stand for the g-th CDS group and the p-th phenological phase, respectively; P is the total number of phenological phases considered during the wheat growing season; and $\lambda_{g,\mathrm{p}}$ is the sensitivity of winter wheat to drought for the g-th CDS group during the p-th phenological phase.

2. Materials and Methods

2.1. Selecting Sites and Obtaining Data

To calculate the relative yields of winter wheat at a location in a year ($Y_{R_{l,y}}$), both dryland and irrigated yield data would be needed. Based on the availability of such data, Bushland, TX (35.21˚N, 101.91˚W) and Clovis, NM (34.60˚N, 103.21˚W) were selected as the representative locations for the Llano Estacado region. Then, the winter wheat yield data generated at these locations through variety trials conducted over several years (Bushland: 49 yrs. during 1947-2021; Clovis: 47 yrs. during 1962-2019) under both dryland and irrigated conditions were obtained from the Hard Winter Wheat Regional Nursery Program of the USDA Agricultural Research Service agency. The details on the data are provided by [20].

Each trial year at each location involved as many as 50 cultivars. However, except for "Kharkof", a hard red winter wheat cultivar introduced to the United States during the early 20th century and used as the long-term check for the Southern and Northern Regional Performance Nurseries since 1930 [21], there was no other cultivar that was grown under both dryland and irrigated conditions for a sufficiently long period (at least 20 years).

The daily weather data on ambient temperatures (minimum, maximum, and dewpoint), precipitation, windspeed, and solar radiation, which were needed for calculating ARID and the thermal time to estimate the durations of various phenological phases of winter wheat, for the locations and years associated with the yield data were obtained online from various sources, including the National Centers for Environmental Information (NCEI; https://www.ncei.noaa.gov/access/search/data-search/daily-summaries). Due to the absence of observed data, the daily solar radiation data for these locations and years were generated using a reliable global solar radiation model for the southeastern United States [22].

2.2. Estimating the Durations of Phenological Phases

Taking into account the limited phase duration data and the phase selection approach used by [23], five phenological phases for winter wheat were considered in this study: i) planting-emergence (PE); ii) emergence-tillering (ET); iii) tillering-booting (TB); iv) booting-anthesis (BA); and v) anthesis-maturity (AM). These five phases were chosen based on the works of [20] and [23]. From the viewpoint of getting relevant data and estimating the phase durations accurately, reference [23] grouped ten various phases considered by previous researchers into four groups, namely germination-emergence, emergence-double ridge (tillering), double ridge-anthesis, and anthesis-maturity. Considering the availability of phase duration data and assuming the double ridge-anthesis phase to be too wide from the practical standpoint, reference [20] split this group further into two groups, namely tillering-booting and booting-anthesis, thus obtaining the five phenological phases stated above.

Due to the absence of related planting-date data, the representative planting dates of October 21 and October 15 were obtained for Bushland and Clovis, respectively, from the literature. The duration of each phenological phase needed for splitting a winter wheat growing season in the semi-arid region of the southern United States into several phases was estimated for by [20] using the total thermal time (TTT; ˚C d) needed for each phase under dryland conditions [24]-[28]. Using these phase duration values, each wheat growing season at each location was split into the five phenological phases considered above.

2.3. Computing Phenological Phasic Values of ARID

Using the ARID equations provided by [12] and the related computational procedure (MATLAB program) described by [9], the daily values of ARID for each wheat growing season at each location that had both dryland and irrigated yield data were computed from the daily weather data. The daily ARID values for each location-year then were averaged by the phenological phase. Consequently, there were 245 phasic values of ARID for Bushland (49 × 5) and 235 phasic values of ARID for Clovis (47 × 5). Finally, the phasic values of ARID were converted into the corresponding phasic values of "1 – ARID", which are used in the yield model (Equation (1)).

2.4. Classifying Cultivars into Various CDS Groups

To classify the winter wheat cultivars into different groups in terms of the sensitivity to drought, the degree of sensitivity of each cultivar involved needed to be estimated. However, for the cultivars that were not involved in the long-term trials, estimating the degree of drought sensitivity based on their own data was not possible. Such an estimation was possible only for the cultivar Kharkof due to the availability of long-term data. This possibility provided an option for estimating the drought sensitivities of all the cultivars involved and, ultimately, classifying then into various CDS groups. For drought sensitivity estimation and CDS group classification, the following procedure was used.

First, not all the irrigated trials involved might have received full irrigation to the level of non-water-limited production condition. Thus, to eliminate the effect of deficit irrigation, if any, that did not allow the crop to achieve the non-water-stressed production level in any wheat season (year) involved in the trials, the term *full irrigation fraction* (FIF) was applied. The FIF value in a given season, thus, would represent itself as the fraction of complete irrigation achieved that season. The FIF was calculated from the deficiently-irrigated and the fully-irrigated (non-water-stressed or potential) yields of Kharkof (Equation (3)). For FIF calculation, the Kharkof yields were used because this was the only cultivar having the long-term data.

$$\mathrm{FIF} = \frac{\mathrm{Y}_{\mathrm{I}_\mathrm{K}}}{\mathrm{Y}_{\mathrm{P}_\mathrm{K}}}, \tag{3}$$

where Y_{I_K} and Y_{P_K} are the deficiently-irrigated and the potential yields of Kharkof, respectively. The observed irrigated yield of Kharkof that was the greatest across the 96 seasons involved in the trials conducted in Bushland and Clovis during 1947 through 2021 was assumed to be the potential yield of Kharkof. This Y_{P_K} value was 5814 kg·ha^{-1}.

Second, the relative yield of Kharkof in each year at each location was calculated from the fraction of the dryland yield per unit of the deficiently-irrigated yield and the fraction of full irrigation achieved in that year-location (Equation (4)).

$$Y_{R_K} = \left(\frac{Y_{D_K}}{Y_{I_K}}\right) \times \text{FIF}, \tag{4}$$

where Y_{R_K}, Y_{D_K}, and Y_{I_K} are the relative, dryland, and deficiently-irrigated yields of Kharkof, respectively; and FIF is the full irrigation fraction.

Third, the Y_{R_K} values computed for various years involved in the trials were regressed against the seasonal ARID values associated with the corresponding locations and years to obtain the slope of the ARID- Y_{R_K} relationship (**Figure 1**). This slope value (−0.668) represented the degree of sensitivity of Kharkof to drought and acted as the drought sensitivity index (χ) value for this cultivar ($\chi_K = -0.668$).

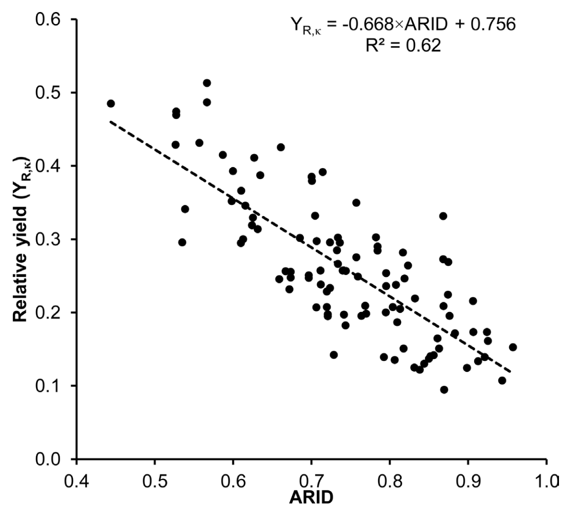

Figure 1. The relationship between the Agricultural Reference Index for Drought (ARID) values and the relative yields of the Kharkof cultivar of winter wheat in the Llano Estacado region of the southern United States (1947-2021).

Fourth, to identify the degree of sensitivity for the other cultivars involved in the trials, their χ values were estimated using Equation (5).

$$\chi_c = \chi_K \times \left(\frac{Y_{R_K}}{Y_{R_c}}\right), \tag{5}$$

where χ_c is the drought sensitivity index for the c-th cultivar, χ_K is the drought sensitivity index for Kharkof, Y_{R_K} is the relative yield of Kharkof, and Y_{R_c} is the relative yield of the c-th cultivar, which in turn was calculated using Equation (6).

$$Y_{R_c} = \left(\frac{Y_{D,c}}{Y_{I_c}}\right) \times \text{FIF}, \tag{6}$$

where Y_{D_c} and Y_{I_c} are the dryland and the deficiently-irrigated yields of the c-th cultivar, respectively; and FIF is the full irrigation faction achieved in a location-year.

Finally, in terms of the degree of sensitivity to drought, all the cultivars involved in a trial conducted at each location each year were classified into three groups: highly-sensitive, moderately-sensitive, and non-sensitive. The primary purpose of including the non-sensitive group, which presumably would not be impacted by drought, was to assess ARID in terms of reflecting the phenomenon of water stress impacting the yields, irrespective of the degree of drought sensitivity of the cultivar involved.

For this classification, the following approach was used. Principally, the values of both ARID and Y_R range from 0 to 1. When there is no drought at all, ARID is 0, and Y_R is 1; whereas, when there is a complete drought, ARID is 1, and Y_R is 0. As the ARID value approaches 1 from 0, the Y_R value decreases linearly from 1 to 0 with the slope value of −1 (**Figure 2**). Thus, if a cultivar is extremely sensitive to drought, the slope value of the ARID-Y_R relationship is −1. On the other hand, if a cultivar is completely insensitive to drought, the slope value of the ARID-Y_R relationship is 0. To classify various cultivars in terms of the sensitivity to drought, therefore, the slope range of 0 to −1 was equally split into three sub-ranges: (i) 0 to −1/3, (ii) −1/3 to −2/3, and (iii) −2/3 to −1. The first sub-range represented the non-sensitive group, the second sub-range the moderately-sensitive group, and the third sub-range the highly-sensitive group of cultivars (Equation (7)).

$$CDS_g = \begin{cases} \text{highly sensitive} & \text{if } \chi_c < -2/3 \\ \text{moderately sensitive} & \text{if } -2/3 \le \chi_c < -1/3, \\ \text{non-sensitive} & \text{if } \chi_c \ge -1/3 \end{cases} \tag{7}$$

where CDS_g is the g-th drought sensitivity group to which the c-th cultivar belonged; and χ_c is the drought sensitivity index for the c-th cultivar, which was computed using Equation (5).

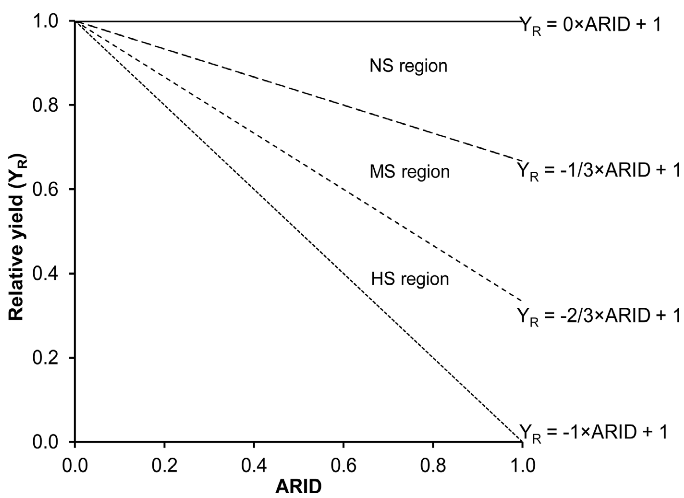

Figure 2. The relationship between the Agricultural Reference Index for Drought (ARID) and the relative yield (Y_R) with the three regions of cultivar drought sensitivity: non-sensitive (NS), moderately-sensitive (MS), and highly-sensitive (HS).

Based on the CDS definition (Equation (7)), the Kharkof cultivar (slope = −0.668) belonged to the highly-sensitive group. Regarding the other cultivars involved in the trials conducted during 1947-2021, a total of 11 cultivars (5 at Bushland and 6 at Clovis) were identified as non-sensitive, 73 cultivars (36 at Bushland and 37 at Clovis) as moderately-sensitive, and 90 cultivars (49 at Bushland and 41 at Clovis) as highly-sensitive to drought stress.

2.5. Developing the CDS Group-Specific Yield Models

Once the relative yield values of winter wheat and the phenological phasic values of (1 – ARID) were calculated for each year at each location under each CDS group, a matrix of dataset comprising 11 rows (years) and six columns was prepared for the non-sensitive group, that comprising 73 rows and six columns for the moderately-sensitive group, and that comprising 90 rows and six columns for the highly-sensitive group. The first column in the matrix contained the values of the relative yield as the dependent variable, and the remaining columns contained the corresponding phenological phasic values of (1 – ARID) for the five phases as the independent variables.

For developing the CDS group-specific yield models, estimating the drought-sensitivity coefficient for winter wheat during the phenological phase **p**, denoted as λ_p, for each CDS group would be necessary. This would require regressing the linearized form (Equation (8)) of the CDS group-specific yield model (Equation 2). Accordingly, all the values in the matrix prepared for each CDS group as explained above were converted to 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 yield model is as follows.

$$\ln\left(Y_{R_{g,l,y}}\right) = \sum_{p=1}^{P}\left\{\lambda_{g,p} \times \ln\left(1 - ARID_{g,l,y,p}\right)\right\}, \quad (8)$$

where $Y_{R_{g,l,y}}$ is the relative yield of winter wheat for the g-th CDS group at l-th location in the y-th year, P is the total number of phenological phases of winter wheat considered, and p is the p-th phenological phase.

2.6. Evaluating the CDS Group-Specific Yield Models

Given the limited number of years available, especially for the non-sensitive group, the leave-one-out technique of cross-validation was used to evaluate the yield model. Following this technique, the available dataset (the transformed matrix) for each CDS group was divided into two parts: one for parameterization and the other for evaluation. That is, of the total 11 input-output combinations for the non-sensitive group, for instance, the first 10 combinations (rows) were used as the parameterization set for estimating the λ_p values through the regression of Equation (8) and the last one combination (row) as the evaluation set for yield estimation through the use of the just estimated $\lambda_{g,p}$ values in the yield model (Equation (2)). Leaving one combination out and adding one combination in, both parameterization and the evaluation sets were moved forward 10 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 and, finally, a yield estimate (using Equation (2)). This process, consequently, provided 11 relative yield estimates for the non-sensitive group, 73 for the moderately-sensitive group, and 90 for the highly-sensitive group. Finally, using the mean absolute error, the root mean square error (RMSE), the Nash-Sutcliffe Index [29], 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 under each CDS group were compared with the corresponding observed relative yields to evaluate the performance of a CDS group-specific winter wheat yield model.

3. Results and Discussion

3.1. CDS Group-Specific Yield Models

Table 1 shows the phenological phase-specific relative drought sensitivity coefficients estimated for the CDS group-specific winter wheat yield model (Equation (2)) for the Llano Estacado region in the southern United States. Using these sensitivity coefficients in Equation (2) resulted in the following CDS group -specific relative yield models for winter wheat.

$$Y_{R_N} = 0.30 \times (1-\text{ARID})_{N,\text{PE}}^{0.02} \times (1-\text{ARID})_{N,\text{ET}}^{0.03} \times (1-\text{ARID})_{N,\text{TB}}^{0.04} \times (1-\text{ARID})_{N,\text{BA}}^{0.01} \times (1-\text{ARID})_{N,\text{AM}}^{0.00}, \quad (9)$$

$$Y_{R_M} = 0.58 \times (1-\text{ARID})_{M,\text{PE}}^{0.09} \times (1-\text{ARID})_{M,\text{ET}}^{0.15} \times (1-\text{ARID})_{M,\text{TB}}^{0.11} \times (1-\text{ARID})_{M,\text{BA}}^{0.07} \times (1-\text{ARID})_{M,\text{AM}}^{0.05}, \quad (10)$$

$$Y_{R_H} = 0.50 \times (1-\text{ARID})_{H,\text{PE}}^{0.15} \times (1-\text{ARID})_{H,\text{ET}}^{0.18} \times (1-\text{ARID})_{H,\text{TB}}^{0.19} \times (1-\text{ARID})_{H,\text{BA}}^{0.07} \times (1-\text{ARID})_{H,\text{AM}}^{0.00}, \quad (11)$$

where Y_{R_N}, Y_{R_M}, and Y_{R_H} are the relative yields of winter wheat for the non-sensitive (N), moderately-sensitive (M) and highly-sensitive (H) group of cultivars, respectively; and the subscripts PE stands for the phenological phase planting-emergence, ET for emergence-tillering, TB for tillering-booting, BA for booting-anthesis, and AM for anthesis-maturity.

Table 1. The drought sensitivity coefficients (λ_p) for various phenological phases of winter wheat in the Llano Estacado region of the United States for three drought sensitivity groups of cultivars: non-sensitive (NS), moderately-sensitive (MS), and highly-sensitive (HS).

		Drought sensitivity group		
Phenological phase	λ_p	NS	MS	HS
	intercept	0.30	0.58	0.50
Planting-emergence	λ_1	0.02	0.09	0.15
Emergence-tillering	λ_2	0.03	0.15	0.18
Tillering-booting	λ_3	0.04	0.11	0.19
Booting-anthesis	λ_4	0.01	0.07	0.07
Anthesis-maturity	λ_5	0.00	0.05	0.00

All the sensitivity coefficients in each CDS group had positive values, indicating that the water stress during any phenological phase of winter wheat would have negative impacts on yields in any CDS group. This result was in agreement with the findings of several previous studies. In a similar study conducted in the Llano Estacado region, but without considering the cultivar sensitivity to drought, [20] and [31] also found that water stress during any phase could be detrimental. In an experiment carried out in Arizona, USA, [32] observed that wheat grain yields were reduced by the water stress that occurred at any growth stage. In a review study, [23] demonstrated that wheat yields could be impacted by water stress during any phenological phase, depending on the weather conditions. Reference [33] also exhibited through a review paper that winter wheat yield might be vulnerable to drought at any growth stage. Reference [34] promulgated that water stress occurring at any particular stage would result only in high yield losses, not crop failure, whereas that occurring during the entire growing season would result in crop failure.

In all CDS groups, the emergence-tillering or tillering-booting phenological phase had the largest value of the drought sensitivity coefficient of all the phenological phases of winter wheat considered (**Table 1**), indicating that these phases were the most sensitive to drought stress. References [20] [23] [32] [34] [35] found that tillering-booting was the most sensitive phase because the crop water demand during this phase would be high [36], and the water stress during this phase would reduce the numbers of stems, heads, spikelets per head, and grains per spikelet [23] [32] [37] [38]. The high drought sensitivity during the emergence-tillering phase was likely because the plant water stress during this phase would severely restrict leaf growth and tiller development [37] [39]-[43]. When water stress is very high, about 50% reduction in tillering may occur [40] [42]. When water stress occurs immediately before floral initiation, the number of spikelet primordia may decrease drastically [44].

As the sensitivity coefficients in each CDS group showed, the emergence-tillering and tillering-booting phases were followed by the planting-emergence phase in terms of drought sensitivity. References [20] and [34] also found similar results. The high drought sensitivity during the planting-emergence phase was possibly caused by the restrictions in wheat germination and crop establishment due to an early drought in the growing season [45].

In drought sensitivity, the planting-emergence phase was followed by the booting-anthesis phase in all CDS groups. The drought sensitivity during the booting-anthesis phase was possibly due to the reduction in the availability of carbon and nitrogen, the critical elements for spike growth, caused by plant water stress [23]. This reduction could lead to a sharp decrease in the kernel number and, thus, a decrease in wheat yields at a maximum rate [46]. Water stress at heading could increase sterile spikelets and florets and that around anthesis might affect pollination and fertilization, thus reducing the seed setting rate and eventually the grain yield [43].

The smallest value of the sensitivity coefficient during the anthesis-maturity phase in each CDS group, compared with the other phases, indicated that winter wheat yields would be the least sensitive to the drought occurring during this phase. Several previous studies showed similar results [32] [35]. The water stress at anthesis and grain-filling stages decreased carbohydrate accumulation in the stem by accelerating development [47] [48] and shortened the grain-filling period by accelerating senescence [46] [49]. The terminal part of the grain-filling period in the Llano Estacado region is generally hot and dry, which tends to terminate grain-filling early. For high yields under these conditions, a greater grain-filling rate during the anthesis-maturity phase may be less important than more grains set during the tillering-booting and booting-anthesis phases [37]. The smaller sensitivity coefficient for the anthesis-maturity phase relative to those of the tillering-booting and booting-anthesis phases well reflected this phenomenon (**Table 1**). The logical values of the sensitivity coefficients suggested that the yield models (Equations (9), (10), and (11)) were able to accurately express the CDS group-specific relationship between ARID and the relative yields of winter wheat in the Llano Estacado region.

3.2. The Performance of the Yield Models

The values of the various measures used to evaluate the performance of the CDS group-specific winter wheat yield models for the Llano Estacado region in the southern United States are presented in **Table 2**. The RMSE value ranged from 0.04 to 0.08 (water-limited yield per unit of non-water-limited yield), whereas the mean absolute error value ranged from 0.04 to 0.07. The percentage error of the yield model, computed as the ratio of RMSE to the mean observed relative yield, ranged from 22 to 32. The Willmott Index ranged from 0.24 to 0.92, whereas the Nash-Sutcliffe Index values were between 0.01 and 0.72. As the values of these measures indicated, the winter wheat yield model for the highly-sensitive group performed satisfactorily, whereas that for the moderately-sensitive group worked fairly.

Table 2. Values of various measures used to evaluate the performance of the yield models for three drought sensitivity groups of winter wheat cultivars in the US Llano Estacado region: non-sensitive (NS), moderately-sensitive (MS), and highly-sensitive (HS).

	Drought sensitivity group		
Measures	NS	MS	HS
Mean observed relative yield	0.253	0.270	0.201
Mean predicted relative yield	0.250	0.272	0.204
Mean absolute error	0.07	0.05	0.04
Root mean square error (RMSE)	0.08	0.06	0.04
Willmott Index	0.24	0.88	0.92
Nash-Sutcliffe Index	0.01	0.65	0.72
Percentage error	32	23	22

The performance of the yield model for the non-sensitive group, however, was very poor. Nonetheless, for a cultivar that is not sensitive to drought and thus not impacted by drought, no stakeholder is expected to predict the drought-induced yield losses. Nevertheless, this poor performance caused by the weak correlation between drought and wheat yields supported the assumption that ARID-based yield models could accurately reflect the phenomenon of water stress impacting the yields of winter wheat, irrespective of the degree of drought sensitivity of the cultivar involved.

The Willmott Index values indicated that the relative yields of winter wheat estimated by the yield models for the moderately- and highly-sensitive groups of cultivars agreed fairly closely with those calculated from the observed data.

The Nash-Sutcliffe Index values also indicated that the agreements between the observed yields of winter wheat and those estimated by these two yield models were acceptable, and thus the predictive power of each of these yield models was relatively good. Although the Nash-Sutcliffe Index value for the non-sensitive group was very low, the positive values of this index for all sensitivity groups indicated that the model predictions were more accurate than the means of the observed data. For each sensitivity group yield model, the mean values of both observed and predicted yields were about the same and ranged from 0.20 to 0.27 across the CDS group-specific models. The percentage error, if computed as the absolute difference between the predicted and the observed values relative to the observed value, would be 0.19 for the moderately-sensitive group and 0.18 for the highly-sensitive group, an indication of small errors. This error value for the non-sensitive group, however, would be 0.27, an indication of a large error. For the highly-sensitive group, the range of the predicted relative yields was 0.06 to 0.39 and that of the observed relative yields was 0.07 to 0.44. That is, the width of the range of the predicted yields (0.32) relative to that of the observed yields (0.37) was about 0.88, which indicated that the model error based on this statistic was about 12%. Similarly, the errors of this kind for the moderately-sensitive and non-sensitive groups were 28% and 83%, respectively. These values were also an indication of a low modeling error for the moderately-sensitive and highly-sensitive groups and a high modeling error for the non-sensitive group. All the above metrics indicated that the yield models for moderately to highly-sensitive groups of cultivars were able to fairly reflect the phenomenon of water stress decreasing the yields of winter wheat in the Llano Estacado region (**Figure 3**).

The performances of yield models for both moderately-sensitive and highly-sensitive groups were significantly better than that of the generic yield model developed by [20], which did not consider the cultivar-specific sensitivity of winter wheat yields to drought stress. Compared with the generic yield model, the yield models for the moderately-sensitive and highly-sensitive groups of cultivars increased the Willmott Index by 3% and 7% and the Nash-Sutcliffe Index by 6% and 18%, respectively. Similarly, these yield models, respectively, reduced the mean absolute error and the RMSE each by 43% and 60% and the percentage error by

11% and 15%. However, the performance of the yield model for the non-sensitive group was so poor that, compared with the generic model, the Willmott Index and the Nash-Sutcliffe Index values of this model decreased, respectively, by 72% and 99%, whereas the percentage error value increased by 23%. Relative to the generic yield model [21], the yield models for the moderately-sensitive and highly-sensitive groups of cultivars better reflected the impacts of genetic difference in wheat cultivars on drought sensitivity and ultimately yields in the Llano Estacado region.

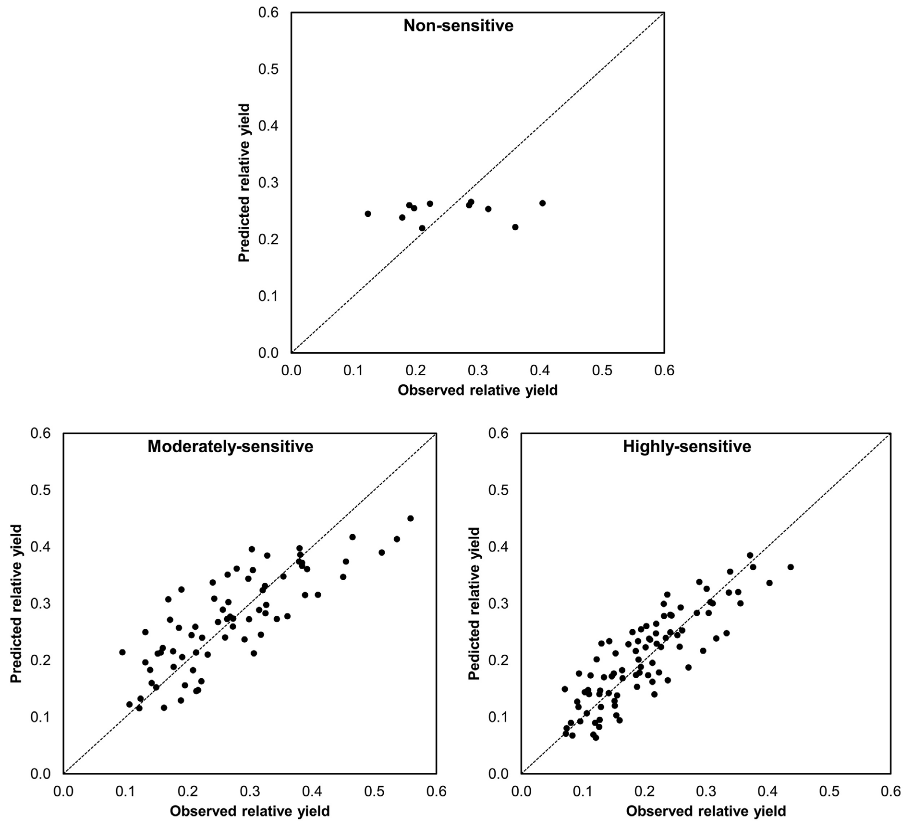

Figure 3. The winter wheat relative yields predicted by the models for three different drought sensitivity groups of cultivars compared with the observed ones in the Llano Estacado region of the southern United States (1947-2021).

Reference [14] developed similar ARID-based yield models to estimate the drought-induced yield losses for cotton, maize, peanut, and soybean in the southeastern United States and showed that the ARID-based relative yield models for these crops would perform reasonably well in this region. Both studies (this and [14]) demonstrated that the ARID-based yield models could be applied to a wide range of conditions, including different soils, regions, management practices, climates, and crops and their cultivars, especially those that are more sensitive to water stress.

4. Conclusions

This study developed the cultivar drought sensitivity (CDS) group-specific, Agricultural Reference Index for Drought (ARID)-based models for predicting the yield loss of winter wheat due to drought in the semi-arid region of Llano Estacado in the southern United States. The yield models account for the sensitivity of winter wheat during various phenological phases to drought. The reasonable values of the drought sensitivity coefficients of each CDS group-specific model indicated that the yield models were able to accurately express the relationship between ARID and winter wheat yields in this region as impacted by the genotypic difference in wheat cultivars. The yield models were able to predict the drought-induced yield loss of winter wheat satisfactorily by reflecting the CDS group-specific phenomenon of water stress decreasing the wheat yields in this region.

By using the phenological phase-specific ARID values obtained from the long-term historical weather data in the CDS group-specific yield models (Equations (9)-(11)), various stakeholders in the Llano Estacado region, including wheat growers and the scientific community, can estimate the yield loss from an anticipated drought for a wheat cultivar belonging to a particular CDS group in advance. The CDS group-specific yield models may also be useful for scheduling irrigation allocation tailored to a wheat cultivar belonging to a particular CDS group to ensure water access to the phenological phases that are more sensitive to drought.

Conflicts of Interest

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

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