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Crop Water Production Functions of Grain Sorghum and Winter Wheat in Kansas and Texas

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Abstract: Productivity of water-limited cropping systems can be reduced by untimely distribution of water as well as cold and heat stress. The objective of this study was to evaluate the predictive accuracy of the Kansas Water Budget (KSWB) model for crop water use and grain productivity of grain sorghum and winter wheat grown in a range of crop sequences. The relationship of grain yield to crop water use, reported in several crop sequence studies conducted in Bushland, TX, and Colby and Tribune, KS, was compared against the KSWB modeling results. Field studies showed that the yield responses of grain sorghum to an increment of water use was generally 75% greater than that of winter wheat, as expected for crops with C4 and C3 physiology, respectively. The relationship of winter wheat yield to crop water use, simulated by the KSWB model, was comparable to relationships developed in four of five studies, with the exception of one study conducted in Bushland that suggested less crop water productivity. For grain sorghum, experimental yield response to an increment of water use was less than that calculated for three of five cases; for one study at Colby and Tribune, simulated and experimental yield response to water use were similar. Simulated yield thresholds were consistent with observed yield thresholds for both wheat and sorghum in all but one case. The KSWB model provides a useful analytic framework for distinguishing water supply constraints to grain productivity.

Keywords: *crop yield, water budget model, cropping system, Kansas, water*

Productivity of water-limited cropping systems in the High Plains is controlled by many factors. Grain yields for dryland crop production systems in the semiarid Great Plains of the United States are difficult to predict because of the variable distribution of growing season precipitation (Nielsen et al. 2010). Water deficits can affect productivity at specific growing periods throughout the crop season and in the overall total supply of water (Brown 1959; Passioura 2006). Generally, the timing of water supply has a larger effect on grain yield than total water supply, for many crops (Maman et al. 2003). Weeds, diseases, pests, and extreme weather events can destroy crops and limit productivity as well. Climate change could also contribute to changes of crop productivity (Tao and Zhang 2013). The frequency of years when temperatures exceed the thresholds for crop damage is likely to increase for some crops and regions (Hatfield et al. 2013). In a western Kansas study, Stone and Schlegel (2006) found a positive relationship between grain yield of wheat and sorghum, with both available soil water at emergence (22.1 kg ha^{-1} mm^{-1} available soil water), and in-season precipitation (16.4 kg ha^{-1} mm^{-1} in-season precipitation). They found similar yield responses for winter wheat (9.8 kg ha^{-1} mm^{-1} available soil water and 8.3 kg ha^{-1} mm^{-1} in-season precipitation). The greater yield responses of grain sorghum were expected due to more effective carbon gain per water loss associated with the C4 physiology of sorghum, compared with the C3 physiology of wheat. In the same study, 63% of grain sorghum and 70% of winter wheat variations in grain yield were explained by variations in available soil water at emergence and in-season precipitation. Because of the high input costs for production, farmers can benefit from a tool that will help them assess the risks associated with dryland crop production (Nielsen et al. 2010).

Grain sorghum and winter wheat are the primary dryland crops in the semiarid regions of the High Plains (USDA Census of Agriculture 2012). The precipitation pattern of a region influences the cropping sequence used in order to maximize the use of rainfall received (Sherrod et al. 2014). Grain sorghum and winter wheat are important crops in the High Plains region due to their drought resistance and ability to produce under limited precipitation. Dryland production is regaining its importance in this region as irrigated crop production decreases due to groundwater depletion (Steward et al. 2013). Diverse (more crop types) and intensive (more crops in a period of time) cropping systems have the potential to improve crop production without increasing inputs (Tanaka et al. 2005). Peterson et al. (1996) found that the most direct and practical solution for increasing precipitation use efficiency may be to include a summer crop following winter wheat that would make better use of summer precipitation. They also found that dryland cropping systems with more diverse crops and less fallow per unit time may be one strategy to make more efficient use of precipitation lost to evaporation during fallow.

While there are multiple environmental variables controlling crop yield, comparing actual to expected yield can still be instructive (Passioura 2006). Models can be used to calculate an estimated yield based on a soil water balance equation. It can be challenging to understand the interactions of changing climatic variables because of the interactions among temperature and precipitation on plant growth and development (Hatfield et al. 2013). Crop species respond differently to the timing of rainfall and need to be evaluated separately (Sherrod et al. 2014). Water use-yield relationships are the foundation for efficient water management (Siahpoosh and Dehghanian 2012). These relationships can be developed by simulating the field water balance, including simulated drainage for each location (Stone et al. 2011). Mathews and Brown (1938) related crop yield to water use for winter wheat in the southern Great Plains and reported a wheat water productivity of 5.19 kg ha^{-1} mm^{-1} with a yield threshold (the level of water use where yield response begins) of 187 mm. Aiken et al. (2013) reported that in Colby, KS, wheat water productivity was 9.97 kg ha^{-1} mm^{-1} with a yield threshold of 110 mm, and Nielsen et al. (2011) reported an even greater wheat water productivity of 12.49 kg ha^{-1} mm^{-1} with a yield threshold of 132 mm for northeast Colorado. The difficulty in measuring the components of the soil water balance encourages the use of simulation models to investigate the processes involved (Lascano 1991). Process-based modeling can be used to investigate separate parts of the system and can also be used as a tool to investigate solutions to crop production problems, which are normally site-specific (Lascano 1991). Models are representations of complex systems and do not include every environmental factor that can influence yield, but they can still be useful in order to observe and understand relationships between water use and grain productivity. The Kansas Water Budget (KSWB) model solves the soil water balance and calculates actual evapotranspiration, drainage, and crop water use. The model uses crop production functions to estimate yields (Khan et al. 1996). The objective of this study was to evaluate the predictive accuracy of the model for crop water use and grain productivity of grain sorghum and winter wheat grown in a range of crop sequences.

Methods

The predictive accuracy of a modified form of the KSWB (Stone and Schlegel 2006) model was evaluated through two variables: crop water use and yield. The KSWB model was modified to include non-crop periods while maintaining continuity of the soil water balance needed to simulate multi-crop sequences for multiple years. Each of these values was calculated for grain sorghum and winter wheat using different sites, years, and crop rotations. Modeled crop water use and yield data from three sites (Bushland, TX; Colby, KS; and Tribune, KS) were compared with experimental water use and yield data for each crop in order to determine how accurately experimental data could be modeled. Crop water use and yield were then used to generate functional relationships showing yield response to an increment of water use, where yield was the dependent variable and water use was the independent variable. This function was used to find the yield threshold, which is the level of water use where yield response begins.

The KSWB model (Khan et al. 1996) solves the water balance with a daily time step. To calculate the daily total water content of the soil profile, it is necessary to include a water balance equation:

$$SW_i = SW_{i-1} - ET_{a_{i-1}} - DR_{i-1} + EPR_{i-1} \quad [1]$$

where i is the day of the year and $i-1$ is the previous day of the year, SW is the total soil water in the profile (mm), ET_a is the daily actual evapotranspiration taken out of the profile (mm), DR is the daily amount of drainage coming out of the bottom of the profile, and EPR is the effective precipitation (mm), which is daily precipitation after taking out runoff. During model implementation, the first day of the soil water balance was initialized as the total soil water at planting as provided in the experimental data. If data were not provided, such as when the first year was a non-crop period, a value of 60% of available soil water was used. The model assumes stubble mulch tillage as the conventional tillage. A flowchart depicting the procedure of the KSWB model is shown in Figure 1.

Yields are calculated using crop production functions, which include an effective ET term. A crop's source of water is stored soil water, and if there is not sufficient water to meet a specific crop's water requirement, water stress develops in the plant which has a negative effect on photosynthesis, crop growth, and yield. Water stress does not have the same effect on crop yield at every crop growth stage. To account for this, weighting factors were assigned to each growth period. Weighting factors are different for each growth period of a crop depending on the sensitivity of the growth period to water stress. They relate yield with actual ET relative to maximum ET. The KSWB model divides the crop growing season into four growth

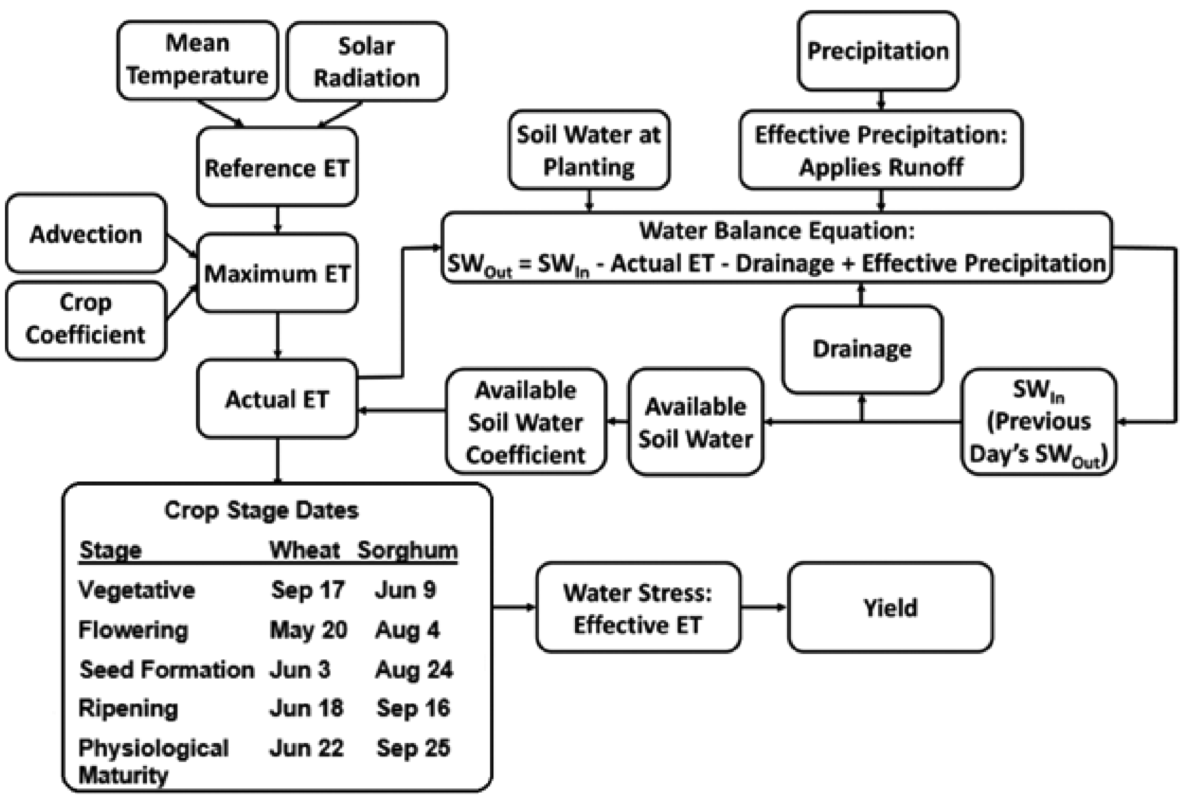

Figure 1. Kansas water budget (KSWB) flowchart. SW denotes soil water and ET is the evapotranspiration.

periods: vegetative, flowering, seed formation, and ripening. The effective ET is a sum of the weighted ET values for each of the four growth periods. The crop yield production function is:

$$Y = CWP \bullet (eET - YT) \quad [2]$$

where Y is yield (kg ha^{-1}), CWP is the slope of a crop water productivity function (kg ha^{-1} mm^{-1}), eET is effective ET (mm), and YT is yield threshold (mm), the quantity of expected eET corresponding to the onset of expected grain yield. Effective ET is used to represent a crop under water stress and can be calculated from:

$$eET = \sum mET_i \bullet \sum \left(w_i \bullet \frac{aET_i}{mET_i} \right) \quad [3]$$

where mET_i is maximum ET (mm) calculated by a Jensen-Haise relationship (Jensen and Haise 1963), corresponding to crop development stage 'i' (see Figure 1); w_i represents weighting functions (wheat: 0.49, 0.31, 0.19, and 0.01; grain sorghum: 0.44, 0.39, 0.14, and 0.03) corresponding to the crop development stages; and aET (mm) is ET calculated from the KSWB model.

Effective Precipitation

Effective precipitation was calculated daily in order to account for runoff:

$$EPR = P(1 - RF) \quad [4]$$

where P is precipitation (mm) and RF is the runoff fraction from either the equation:

$$RF = 0.106 + (0.000062 * AP^2) \quad [5]$$

for the Tribune and Colby, KS soils which are part of soil hydrologic group BC, or from the equation (Stone et al. 2006; Stone pers. comm.):

$$RF = 0.157 + (0.000072 * AP^2) \quad [6]$$

for the Bushland, TX soil which is part of soil hydrologic group C (Stone pers. comm.). In these equations, AP was the total annual precipitation in inches. This RF value was developed with corn as the base crop. In order to account for crop type, 0.01 is added to the base value to adjust for grain sorghum, and for winter wheat, 0.10 is subtracted from the base value.

The KSWB was modified to simulate multi-year crop sequences. The user initiates a simulation run by selecting a location, cropping sequence (continuous wheat - CW, continuous sorghum - CS, wheat-fallow - WF, wheat-sorghum-fallow - WSF, wheat-wheat-sorghum-fallow - WWSF, or wheat-sorghum-sorghum-fallow - WSSF), the starting year of the simulation, and the number of years to run the simulation. Weather data are compiled from the first day of the first crop phase to the last day of the last crop phase, so that for each day the model runs the correct weather data will be used. The total soil water (mm) in the soil profile at planting was used for the first crop at the beginning of the chosen sequence. At the start of each crop or non-crop phase, the water balance was calculated until the end of the phase, then switched to the next phase while changing the necessary parameters and carrying over the water balance. Upon completion of the final phase, the model was re-initialized at the first harvest year and the simulation was then run using the second crop in the crop sequence, if applicable. The user provided the soil water at planting for that crop. If it is a non-crop period (fallow in wheat-sorghum-fallow rotation), then the user can enter a 0, which was set into a default value of 60% of available soil water in the profile. The simulation was conducted until there was a harvest for each of the years specified by the user.

Field Studies – Experimental Data

Simulation results from the KSWB model runs were compared with experimental data from three locations. For each location, crop water use (CWU) was calculated as:

$$CWU = SW_i - SW_f + P \quad [7]$$

where SW_i is soil water at planting (mm), SW_f is soil water at physiological maturity (mm), and P is in-season precipitation (mm).

Table 1 shows the experimental data for all studies. The soil type at the USDA-ARS Conservation and Production Research Laboratory in Bushland, TX was a Pullman clay loam (fine, mixed, superactive, thermic Torrertic Paleustoll). The soil type at the Northwest Research-Extension Center in Colby, KS was a Keith silt loam (fine-silty, mixed, superactive, mesic Aridic Argiustoll). The soil type at the Southwest Research-Extension Center near Tribune, KS was a Richfield silt loam (fine, smectitic, mesic Aridic Argiustoll). The crop

Table 1. Experimental data for all studies. Crop Sequences: CW - Continuous Wheat, CS - Continuous Sorghum, WF - Wheat-Fallow, WSF - Wheat-Sorghum-Fallow, WWSF - Wheat-Wheat-Sorghum-Fallow, and WSSF - Wheat-Sorghum-Sorghum-Fallow. Tillage: SM - Stubble Mulch, NT - No-Till, RT - Reduced Tillage, ST - Sweep Tillage.

Study Citation	Location	Crop Sequences	Duration	Soil Depth (m)	Tillage Practices
Jones and Popham 1997	Bushland, TX	CW, CS, WF, WSF	1984-1993	1.8	SM, NT
Schlegel et al. 2002	Tribune, KS	CW, WWSF, WSSF	1996-2000	1.8	CW and sorghum – NT, wheat following sorghum – RT
Aiken et al. 2013	Colby, KS	WSF	2002-2008	1.8	NT
Aiken Unpublished	Colby, KS	WSF	2007-2014	2.4	ST
Baumhardt and Jones 2002	Bushland, TX	WSF	1990-1995	1.8	SM, NT
Moroke et al. 2011	Bushland, TX	CS	2000-2001	2.4	SM, NT

water use and yield values using stubble mulch tillage were taken from the experimental data. Results from Moroke et al. (2011) and Baumhardt and Jones (2002) were combined due to similarity in site location, study period, and the limited number of site years. Tables 2 and 3 show starting and ending dates (planting and physiological maturity dates) for each crop and for each of the individual studies.

Modeling Measures

Simple linear least square regression models were developed and used to relate modeled results to experimental data for crop water use and yield for each crop at each location with a level of significance of 0.05. A t-test using standard error and n-1 degrees of freedom (where n is the number of points determining the regression) was used to test slope and intercept against a slope of one and an intercept of zero.

The Nash-Sutcliffe (NS) model was used to assess the predictive power of each model. It evaluated the deviation of observations from model predictions relative to deviations of observed values from their mean:

$$NS = 1 - \frac{\sum(Observed - Modeled)^2}{\sum(Observed - Mean\,(Observed))^2} \quad [8]$$

where *Observed* values are those from the experimental data, and *Modeled* values are those from the KSWB model. If the *NS* coefficient is 0, then the model predictions are as accurate as the mean of the observed data; a *NS* coefficient of 1 indicates perfect model performance. Marek et al. (2016) indicate that *NS* coefficients between 0.5 and 1 are generally considered acceptable. *NS* values between 0 and 0.5 are considered to have greater predictive skill than the mean value.

Crop water use and yield data were plotted together for both observed and modeled results for each crop at each location. Plots of the CWU-yield relationship were made for both modeled and observed values and were compared for both wheat and sorghum. Tests for linearity were done

Table 2. Starting and ending dates for wheat crop for experiments and for the Kansas Water Budget model.

Reference	Location	Planting Date	Physiological Maturity Date
Jones and Popham 1997	Bushland	Late September, Early October	Late June, Early July
Baumhardt and Jones 2002	Bushland	Late September, Early October	Early July
Aiken et al. 2013 Aiken Unpublished	Colby	September 17 to October 20	June 18 to July 3
Schlegel et al. 2002	Tribune	September	Late June, Early July
KSWB	-	September 17	June 22

Table 3. Starting and ending dates for sorghum crop for experiments and for the Kansas Water Budget model.

Reference	Location	Planting Date	Physiological Maturity Date
Jones and Popham 1997	Bushland	Late September, Early October	Late June, Early July
Baumhardt and Jones 2002	Bushland	Late September, Early October	Early July
Aiken et al. 2013 Aiken Unpublished	Colby	September 17 to October 20	June 18 to July 3
Schlegel et al. 2002	Tribune	September	Late June, Early July
KSWB	-	September 17	June 22

using a simple least squares regression model. The level of significance was 0.05 and coefficients of determination (R^2) values were calculated to determine how well the linear model fit the data. Root mean square error (RMSE) was calculated to measure the model accuracy. A t-test was calculated to compare slope of the observed CWU-yield relationship with that of the pooled modeled CWU-relationship for each study to determine if the two slopes were significantly different. The following formula from Cohen et al. (2003) was used to calculate the t-value:

$$t = \frac{b_1 - b_2}{\sqrt{s^2_{b_1} + s^2_{b_2}}}, \qquad df = n_1 + n_2 - 4 \qquad [9]$$

where t is the t-value, b_1 and b_2 are the slopes of the two regression lines, s_{b_1} and s_{b_2} are the standard errors of the two regression lines, df is the degrees of freedom, and n_1 and n_2 are the sample sizes for the two lines. When the observed t-value is greater than a corresponding t-value at the 0.05 significance level, we reject the null hypothesis that there is no difference between the slopes.

Results

This section is divided into two parts: results of the performance measures for winter wheat and those of grain sorghum. In each section are the performance measures for crop water use, yield, and the yield-crop water use relationship, comparing observed and modeled results.

Winter Wheat

Simulation results were compared against field observations of water use and yield for each set of field studies. Regressing modeled wheat crop water use with observed yields (Fig. 2, Table 4) resulted in a linear relationship in four of the five cases (Aiken Unpublished, Jones and Popham 1997, Baumhardt and Jones 2002, and Schlegel et al. 2002), as well as the two cases of pooled results (one case with all the data and one case with all data except Jones and Popham (1997)). The KSWB model had satisfactory predictive skill for the Baumhardt and Jones (2002) and Schlegel et al. (2002) observations using the Nash-Sutcliffe method, meaning they had a NS coefficient greater than 0.5. The KSWB model had more predictive skill than the mean for both sets of pooled results. In two of the five cases (Jones and Popham 1997, and Schlegel et al. 2002), and both sets of pooled results, predictive accuracy had a negative bias in slope (indicated by slopes significantly different from one) which was offset by a positive bias in intercept (indicated by intercept significantly different from zero). Predicted crop water use was generally equal to or greater than observed water use. Predictive accuracy (RMSE = 57.3 mm, restricted pooled results) declined when the Jones and Popham (1997) study was included in pooled results.

Modeled wheat yields regressed on observed yields (Fig. 3, Table 5) resulted in a linear relationship in one of five cases, as well as for the pooled results of all cases. The predicted yields in this case, as well as the pooled results, exhibited negative bias in slope and offsetting positive bias in intercept. The KSWB model demonstrated more predictive skill than the mean for wheat yields reported in Schlegel et al. (2002) and Aiken et al. (2013), as well as both sets of pooled results. Predictive accuracy (excluding Jones and Popham 1997) was 0.90 Mg ha^{-1}.

Observed yield thresholds for the yield-crop water use relationship for wheat (Table 6) ranged between 129 and 218 mm (excluding the Jones and Popham (1997) case, with an unrealistic negative value for yield threshold). Corresponding observed slopes of the relationship were between 8.6 and 19.6 kg ha^{-1} mm^{-1}. Three of the five cases and both of the pooled cases were found to be linear. No differences were detected between observed slopes and slope of the restricted pooled results for four of the five cases. The modeled yield threshold was numerically greater than the observed yield threshold. Figure 4 presents crop yield (Mg/ha) in relation to crop water use (mm) for winter wheat; the solid black line represents pooled modeled yield regressed on pooled modeled water use (all studies), the symbols represent observed yield and crop water use, and the dashed lines represent regression of observed yield regressed on observed water use.

The modeled yield thresholds for the yield-crop water use relationship for wheat (Table 7) ranged between 171 and 304 mm. Modeled slopes of the same relationship ranged between 9.95 and 19.60 kg ha^{-1} mm^{-1}. All cases were found to be linear.

Grain Sorghum

In two of the five cases of sorghum crop water use, as well as the pooled results, there was a linear relationship (Aiken Unpublished, and Baumhardt and Jones 2002 with Moroke et al. 2011) when the modeled values were regressed on observed values (Fig. 5, Table 8). The model had satisfactory predictive skill in one of these cases, and greater skill than the mean value for the other case as well as in both sets of the pooled results. No bias was detected in one linear case; a negative bias in slope was observed in the other linear case. Pooled results exhibited offsetting negative bias in slope and positive bias in intercept.

For modeled sorghum yields regressed on observed yields (Fig. 6, Table 9), two of five cases (Jones and Popham 1997, and Schlegel et al. 2002) and both sets of pooled results exhibited a linear relationship. A negative bias in slope was offset by a positive bias in intercept for this case and both pooled results. The KSWB model demonstrated more predictive skill than the mean for one case (Aiken et al. 2013), as well as the restricted pooled results. Three of the five cases and one of the pooled

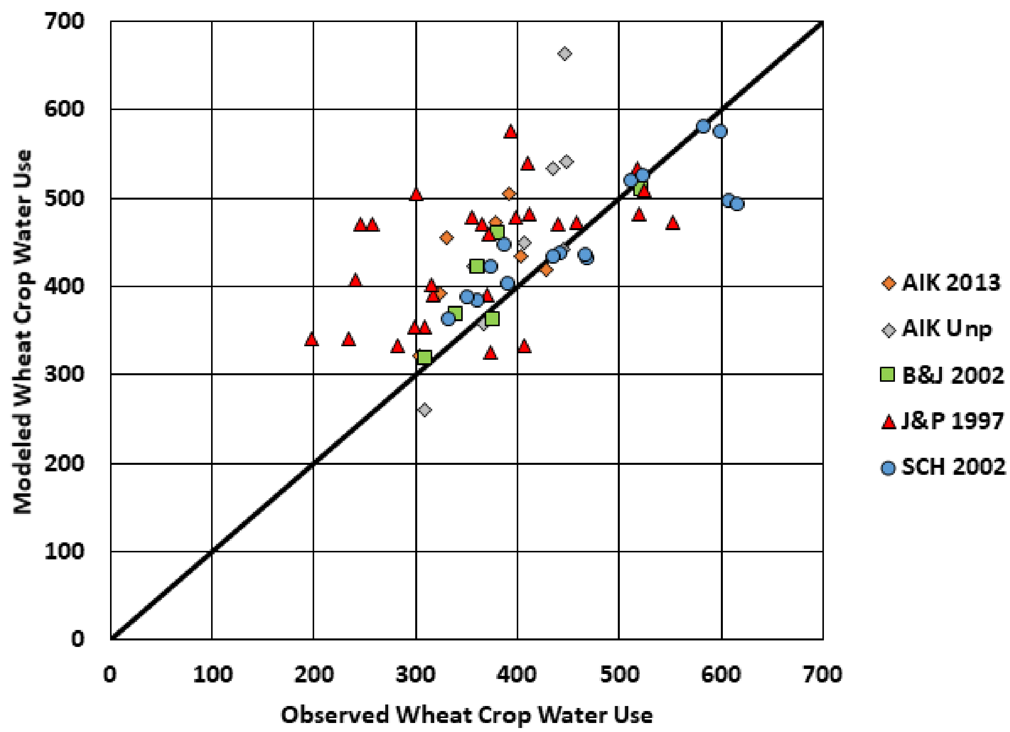

Figure 2. The predictive accuracy for the Kansas Water Budget (KSWB) simulation for crop water use (mm) is presented in relation to field observations of water use for winter wheat; studies were conducted in Bushland, TX (Jones and Popham 1997; Baumhardt and Jones 2002), Tribune, KS (Schlegel et al. 2002), and Colby, KS (Aiken et al. 2013; Aiken Unpublished).

Table 4. Regression performance between modeled and observed crop water use for wheat.

Study	n	Slope	Intercept	R^2	P - value	RMSE	Nash-Sutcliffe
AIK 2013	7	0.734	160	0.328	0.1793‡	53.4	-2.32
AIK Unp	8	2.01	-349	0.730	0.0069	68.9	-2.88
B&J 2002	6	0.826	90.7	0.739	0.0281	40.3	0.598
J&P 1997	27	0.398*	293†	0.228	0.0047	62.7	-0.382
SCH 2002	16	0.595*	180†	0.771	<0.0001	32.8	0.720
Pooled	64	0.499*	244†	0.375	<0.0001	61.0	0.103
Pooled – No J&P 1997	37	0.659*	167†	0.505	<0.0001	57.3	0.378

* Slope different from one at a significance level of 0.05.

† Intercept different from zero at a significance level of 0.05.

‡ Did not pass the test for linearity (from p-value).

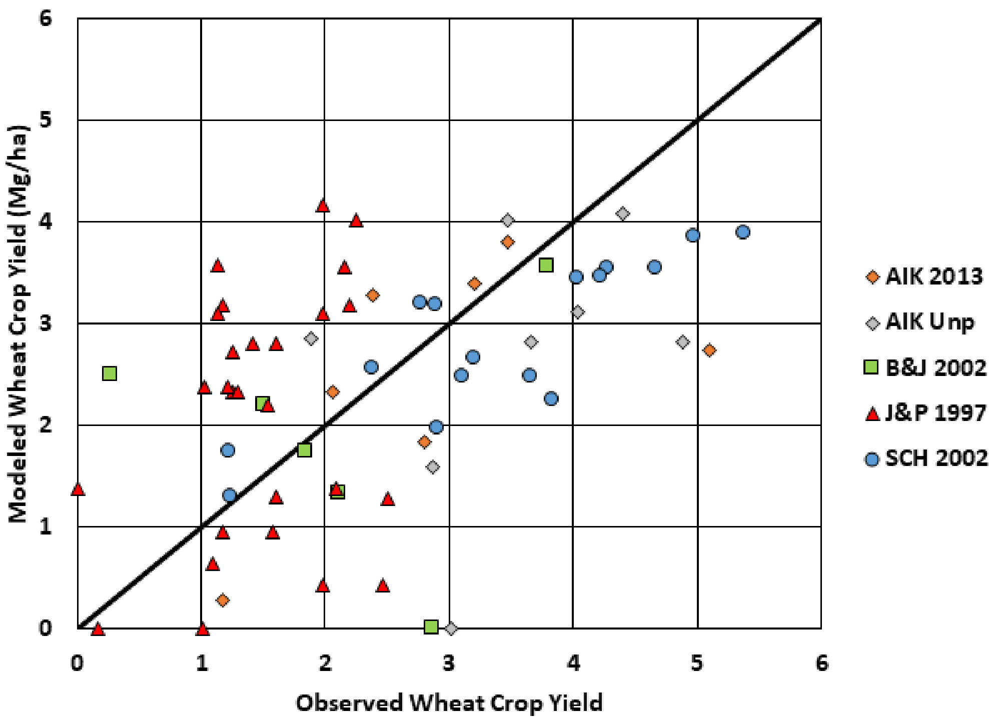

Figure 3. The predictive accuracy for the Kansas Water Budget (KSWB) simulation for crop yield (Mg/ha) is presented in relation to field observations of crop yield for winter wheat; studies were conducted in Bushland, TX (Jones and Popham 1997; Baumhardt and Jones 2002), Tribune, KS (Schlegel et al. 2002), and Colby, KS (Aiken et al. 2013; Aiken Unpublished).

Table 5. Regression performance between modeled and observed yields for wheat.

Study	n	Slope	Intercept	R^2	P - value	RMSE	Nash-Sutcliffe
AIK 2013	7	0.559	0.915	0.337	0.1715‡	1.06	0.0946
AIK Unp	8	0.535	0.777	0.146	0.3508‡	1.33	-1.84
B&J 2002	6	0.0159	1.86	0.000255	0.9760‡	1.34	-0.989
J&P 1997	27	0.501	1.35†	0.0624	0.209‡	1.22	-4.02
SCH 2002	16	0.552*	0.960†	0.717	<0.0001	0.430	0.432
Pooled	64	0.417*	1.37†	0.217	0.00011	1.04	0.0298
Pooled – No J&P 1997	37	0.491*	1.06†	0.316	0.00030	0.898	0.0242

* Slope different from one at a significance level of 0.05.
† Intercept different from zero at a significance level of 0.05.
‡ Did not pass the test for linearity (from p-value).

Table 6. Regression performance between observed yields and observed crop water use for wheat.

Study	n	Slope (kg ha^{-1} mm^{-1})	Intercept (kg ha^{-1})	R^2	P - value	RMSE	Yield Threshold (mm)
AIK 2013	7	19.6	-4280	0.538	0.0606†	0.921	218
AIK Unp	8	14.0	-2080	0.590	0.0260	0.655	149
B&J 2002	6	8.58	-1210	0.276	0.2843†	1.140	141
J&P 1997	27	3.08*	365	0.230	0.0114	0.552	-118
SCH 2002	16	10.2	-1310	0.686	<0.0001	0.695	129
Pooled	64	8.71	-1020	0.399	<0.0001	1.010	117
Pooled – No J&P 1997	37	10.0	-1090	0.503	<0.0001	0.876	109

Note: n is the sample size, the p-value is for a test of linearity at a significance level of 0.05, and the yield threshold is the level of water use where yield response begins, or where the regression line intercepts the x-axis.

* Differed significantly from the pooled modeled regression.

† Did not pass the test for linearity (from p-value).

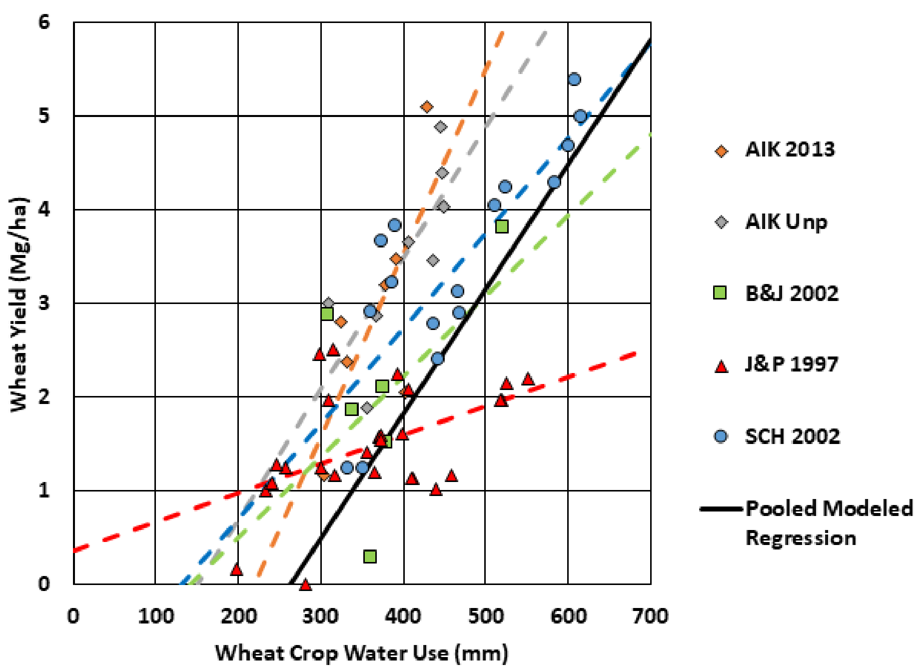

Figure 4. Crop yield (Mg/ha) is presented in relation to crop water use (mm) for winter wheat; the solid black line represents modeled yields from all studies regressed on modeled water use, the symbols represent observed yield and crop water use, and the dashed lines represent observed yield regressed on observed water use. Studies were conducted in Bushland, TX (Jones and Popham 1997; Baumhardt and Jones 2002; Moroke et al. 2011), Tribune, KS (Schlegel et al. 2002), and Colby, KS (Aiken et al. 2013; Aiken Unpublished).

Table 7. Regression performance between modeled yields and modeled crop water use for wheat.

Study	n	Slope (kg ha^{-1} mm^{-1})	Intercept (kg ha^{-1})	R^2	P - value	RMSE	Yield Threshold (mm)
AIK 2013	7	19.6	-5860	0.956	0.0001	0.274	299
AIK Unp	8	9.99	-1920	0.850	0.0011	0.556	192
B&J 2002	6	15.8	-4540	0.872	0.0064	0.478	287
J&P 1997	27	15.6	-4740	0.832	<0.0001	0.518	304
SCH 2002	16	9.95	-1700	0.712	<0.0001	0.434	171
Pooled	64	13.3	-3500	0.770	<0.0001	0.561	263
Pooled – No J&P 1997	37	11.8	-2660	0.788	<0.0001	0.500	225

cases had slopes that were not different from one, and three of the five cases and none of the pooled cases had intercepts that were not different from zero at a significance level of 0.05.

Observed yield thresholds for the yield-crop water use relationship for sorghum (Fig. 7, Table 10) ranged between 89 and 275 mm, excluding the case of Jones and Popham (1997). Corresponding slopes ranged from 13.8 to 39.5 kg ha^{-1} mm^{-1}. Three of the five cases and both of the pooled cases were found to be linear. Three of the cases, Aiken (Unpublished), Jones and Popham (1997), and Baumhardt and Jones (2002) with Moroke et al. (2011), had slopes that differed from that of the pooled modeled regression. Figure 7 presents crop yield (Mg/ha) in relation to crop water use (mm) for grain sorghum; the solid black line represents pooled modeled yield regressed on pooled modeled water use (results from all studies), the symbols represent observed yield and crop water use, and the dashed lines represent regression of observed yield regressed on observed water use.

The modeled yield thresholds for the yield-crop water use relationship for sorghum (Fig. 7, Table 11) ranged between 191 and 213 mm. The modeled slopes were very similar as well, ranging between 25.9 and 32.0 kg ha^{-1} mm^{-1}. All cases were found to be linear.

For both wheat and grain sorghum, the precision of the yield-water use relationship was greater for modeled results (RMSE = 0.50 and 0.52 kg ha^{-1} mm^{-1}, respectively) than the relationship derived from observations (RMSE = 0.88 and 1.62 kg ha^{-1} mm^{-1}, respectively).

Discussion

Analysis of pooled results are differentiated with respect to the Jones and Popham (1997) study; either excluding or including the results of this 10-yr field study. Review of predictive accuracy for individual studies and pooled studies support this approach. Results of the earlier Bushland, TX study (Jones and Popham 1997) appear to differ from the later Bushland study (Baumhardt and Jones 2002), especially in slopes and yield thresholds of the yield-water use relationship for both wheat and sorghum. The later study had greater slopes and yield thresholds than the earlier study in both crops, based on experimental results. In contrast, the modeled results were very similar for the two studies, indicating similarity of conditions considered by the model. Nielsen and Vigil (2017) reported a range of slopes for grain sorghum water productivity (11.1 to 34.4 kg ha^{-1} mm^{-1}) from studies conducted in Bushland, TX, attributing this

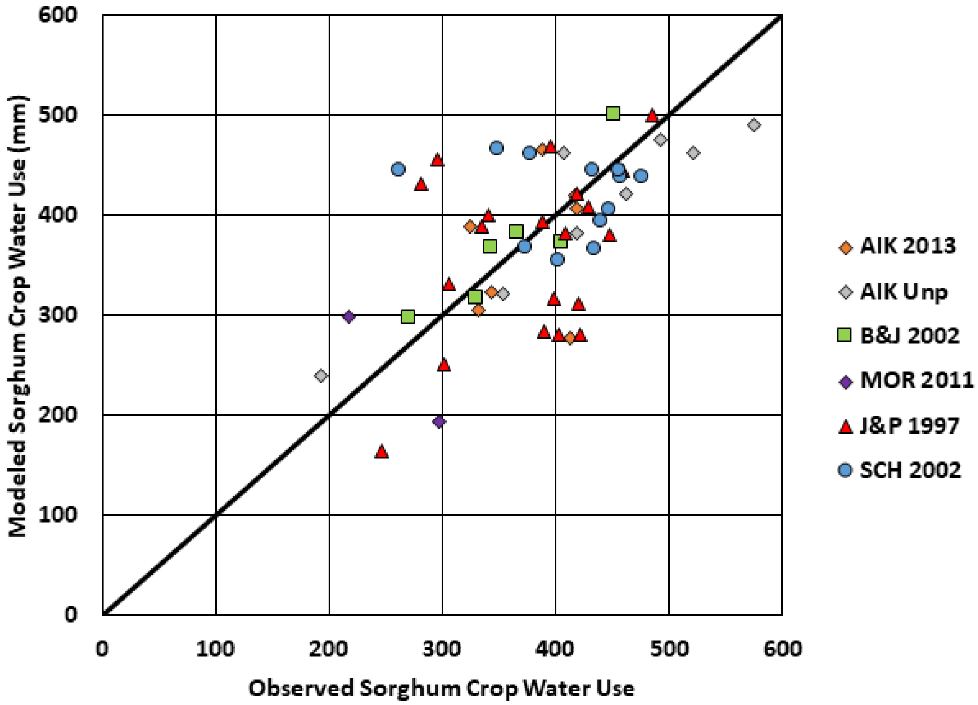

Figure 5. The predictive accuracy for the Kansas Water Budget (KSWB) simulation for crop water use (mm) is presented in relation to field observations of water use for grain sorghum; studies were conducted in Bushland, TX (Jones and Popham 1997; Baumhardt and Jones 2002; Moroke et al. 2011), Tribune, KS (Schlegel et al. 2002), and Colby, KS (Aiken et al. 2013; Aiken Unpublished).

Table 8. Regression performance between modeled and observed crop water use for grain sorghum.

Study	n	Slope	Intercept	R^2	P - value	RMSE	Nash-Sutcliffe
AIK 2013	7	0.448	201	0.0761	0.5493‡	72.2	-1.77
AIK Unp	8	0.688*	112	0.857	0.0010	35.8	0.787
B&J 2002 and MOR 2011	8	0.915	33.9	0.603	0.0234	59.9	0.435
J&P 1997	20	0.496	177	0.147	0.0950‡	80.3	-0.725
SCH 2002	12	-0.109*	463.2†	0.0282	0.6020‡	40.6	-0.662
Pooled	55	0.584*	154†	0.322	<0.0001	65.0	0.101
Pooled – No J&P 1997	35	0.605*	152†	0.446	<0.0001	56.0	0.389

* Slope different from one at a significance level of 0.05.

† Intercept different from zero at a significance level of 0.05.

‡ Did not pass the test for linearity (from p-value).

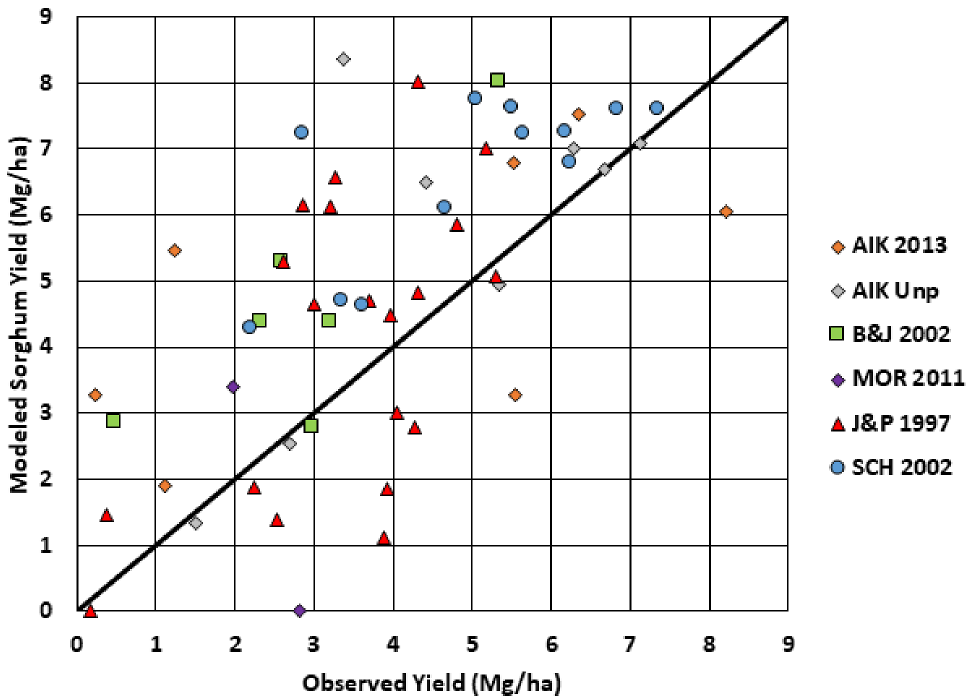

Figure 6. The predictive accuracy for the Kansas Water Budget (KSWB) simulation for crop yield (Mg/ha) is presented in relation to field observations of crop yield for grain sorghum; studies were conducted in Bushland, TX (Jones and Popham 1997; Baumhardt and Jones 2002; Moroke et al. 2011), Tribune, KS (Schlegel et al. 2002), and Colby, KS (Aiken et al. 2013; Aiken Unpublished).

Table 9. Regression performance between modeled and observed yields for grain sorghum.

Study	n	Slope	Intercept	R^2	P - value	RMSE	Nash-Sutcliffe
AIK 2013	7	0.423*	3.19†	0.396	0.1301‡	1.78	0.304
AIK Unp	8	0.814	1.76	0.456	0.0663‡	1.95	-0.0437
B&J 2002 and MOR 2011	8	0.980	1.23	0.336	0.1319‡	2.03	-1.74
J&P 1997	20	0.932	0.946	0.311	0.0106	1.94	-1.22
SCH 2002	12	0.582*	3.68†	0.538	0.0066	0.930	-0.510
Pooled	55	0.770	1.92†	0.423	<0.0001	1.74	-0.148
Pooled – No J&P 1997	35	0.690*	2.49†	0.464	<0.0001	1.62	0.0329

* Slope different from one at a significance level of 0.05.

† Intercept different from zero at a significance level of 0.05.

‡ Did not pass the test for linearity (from p-value).

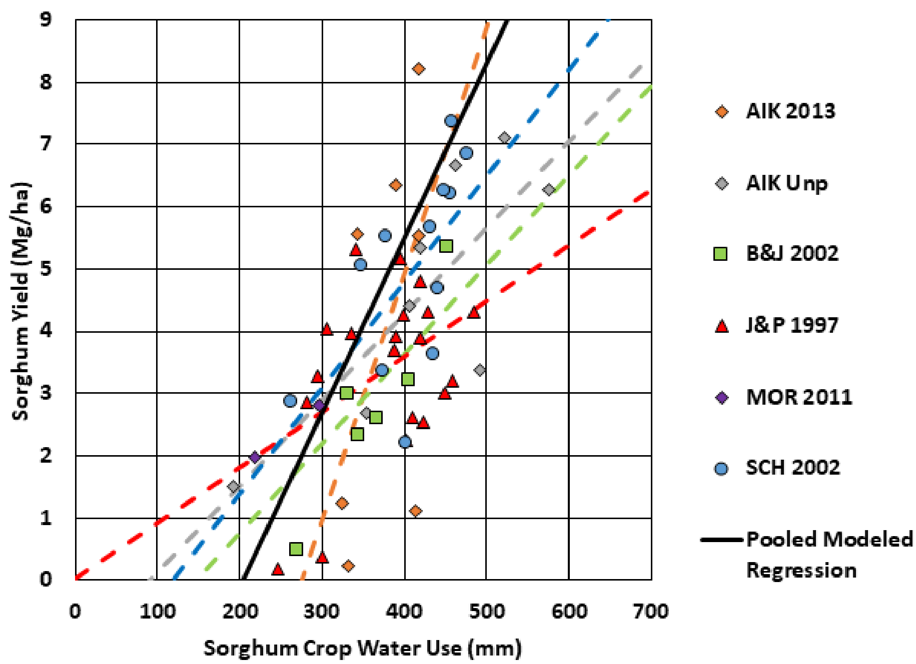

Figure 7. Crop yield (Mg/ha) is presented in relation to crop water use (mm) for grain sorghum; the solid black line represents modeled yields from all studies regressed on modeled water use, the symbols represent observed yield and crop water use, and the dashed lines represent observed yield regressed on observed water use. Studies were conducted in Bushland, TX (Jones and Popham 1997; Baumhardt and Jones 2002; Moroke et al. 2011), Tribune, KS (Schlegel et al. 2002), and Colby, KS (Aiken et al. 2013; Aiken Unpublished).

Table 10. Regression performance between observed yields and observed crop water use for grain sorghum.

Study	n	Slope (kg ha^{-1} mm^{-1})	Intercept (kg ha^{-1})	R^2	P - value	RMSE	Yield Threshold (mm)
AIK 2013	7	39.5	-10800	0.287	0.2155†	2.88	275
AIK Unp	8	13.8*	-1230	0.645	0.0164	1.30	89.4
B&J 2002 and MOR 2011	8	14.4*	-2110	0.618	0.0206	0.910	147
J&P 1997	20	8.91*	25.6	0.184	0.0594†	1.26	-2.88
SCH 2002	12	17.0	-2010	0.392	0.0294	1.34	118
Pooled	55	15.5	-2090	0.377	<0.0001	1.53	135
Pooled – No J&P 1997	35	17.5	-2640	0.447	<0.0001	1.62	151

Note: n is the sample size, the p-value is for a test of linearity at a significance level of 0.05, and the yield threshold is the level of water use where yield response begins, or where the regression line intercepts the x-axis.

* Differed significantly from the pooled modeled regression.

† Did not pass the test for linearity (from p-value).

Table 11. Regression performance between modeled yields and modeled crop water use for grain sorghum. Performance measures for modeled sorghum yields regressed on modeled sorghum crop water use.

Study	n	Slope ($kg\ ha^{-1}\ mm^{-1}$)	Intercept ($kg\ ha^{-1}$)	R^2	P - value	RMSE	Yield Threshold (mm)
AIK 2013	7	30.3	-6300	0.984	<0.0001	0.287	208
AIK Unp	8	26.8	-5350	0.927	0.0001	0.713	200
B&J 2002 and MOR 2011	8	25.9	-5700	0.977	<0.0001	0.379	191
J&P 1997	20	26.1	-5410	0.944	<0.0001	0.553	207
SCH 2002	12	32.0	-6830	0.927	<0.0001	0.369	213
Pooled	55	28.0	-5720	0.929	<0.0001	0.612	204
Pooled – No J&P 1997	35	28.5	-5670	0.944	<0.0001	0.520	199

Note: n is the sample size, the p-value is for a test of linearity at a significance level of 0.05, and the yield threshold is the level of water use where yield response begins, or where the regression line intercepts the x-axis.

variability to differences in evaporative demand, timing of water stress, crop residue management, and soil fertility. The combined grain sorghum results of Baumhardt and Jones (2002) and Moroke et al. (2011) indicate a crop water productivity value (14.4 kg ha^{-1} mm^{-1}) within this range.

The KSWB model had similar predictive accuracy for crop water use of wheat and grain sorghum, considering RMSE, Nash-Sutcliffe, and the coefficient of determination for the restricted pooled results. Furthermore, the predictive accuracy for yield was similar for both crops, though accuracy was substantially reduced and the Nash-Sutcliffe criteria for predictive skill was not met. Therefore, it is remarkable to observe the performance of the KSWB model in replicating the yield-water use relationship for both wheat and grain sorghum.

The relationship of wheat yield to water use simulated by the model was similar to the relationships developed in four of the five field studies. Both the slopes and yield thresholds for the five cases analyzed for this study were similar to those reported in Mathews and Brown (1938) and Aiken et al. (2013), with the exception of Jones and Popham (1997). However, the magnitude of the yield thresholds in each of the five studies was numerically less than that derived from the pooled simulated results, indicating that yield response to water use began with less water than calculated by the model. This suggests the KSWB model systematically underestimates wheat productivity in response to water use.

In contrast, the sorghum yield response to water use relationship simulated by the KSWB model (28.0 kg ha^{-1} mm^{-1}, pooled modeled regression, Table 11) differed from that of three studies (Aiken Unpublished, Jones and Popham 1997, and Baumhardt and Jones 2002 with Moroke et al. 2011, Table 10) – particularly the slope of the yield response to an increment of water use. Simulated sorghum yield thresholds (191 – 213 mm, Table 11) were consistent with observed yield thresholds for four of the five locations (89 – 275 mm, Table 10). Experimental yield response to an increment of water use was substantially less (approximately half) than calculated by the KSWB model (28.0 kg ha^{-1} mm^{-1}, pooled modeled regression, Table 11) for four of the five studies (8.9 – 17.0 kg ha^{-1} mm^{-1}, Table 10). This result indicates that the model predicted a much higher yield response to water than was observed and a substantial gap between actual and potential sorghum yields.

Regional trends

Most of the slopes of the yield to water use relationship (derived from field observations) were smaller in Bushland, TX than in Tribune or Colby, KS for both wheat and sorghum. One possible reason for this is that Bushland has higher temperatures, on average. Growing seasons with higher temperatures can decrease crop yields and decrease the slope of the yield-water use relationship because of the heat stress. Increased evaporative demand in Bushland could also contribute to this apparent regional trend of decreased crop water productivity at the lower latitude.

Uncertainty in planting date likely contributes to the apparent lack of predictive skill in the KSWB model. Though this model uses constant planting dates and subsequent crop development dates for wheat and grain sorghum, the start and end dates for the crop seasons at each of the sites are not the same day as indicated by the date range given in Table 2. Factors such as timing of precipitation influence when planting begins. For example, in Bushland the planting dates for wheat could be anywhere between late September and late October, but for Colby the planting date could be as late as October 20th. For sorghum, harvest dates could be as early as September 20th (Colby) or as late as early November (Bushland). This contributes to uncertainty associated with model output, because if the model has a shorter growing season than the study, the precipitation simulated during the growing season will likely differ from the field conditions. For example, large precipitation events that occur after the end of the simulated growing season but before the end of the observed growing season could introduce substantial discrepancies in simulated and observed water use, which are independent of the model's predictive skill. Apparent differences between simulated and observed crop water use and yield formation could be affected by regional differences in planting date and crop development, which are not represented with the constant planting dates used in the implementation of the KSWB model.

Most of the modeled points used to define the yield to water use relationship fall on the same line and have very small dispersion, especially for sorghum, but also for wheat. The yield formation algorithm calculates yield as a weighted average of crop water use with stress factors comprising the weighting factors. If there is no stress, weighting factors will have no effect, and yield-water use relationship will be a straight line. The smaller coefficient of determination for the simulated yield-water use relationship for wheat suggests a greater role of stress factors in wheat yield calculation. The dispersion of observed data points about the yield-water use relationships of wheat and sorghum are substantially greater than for the modeled relationship, as indicated by the smaller coefficient of determination for the observed relationship. This suggests that factors other than water may be limiting yield responses. The model accounts for some of the stress factors such as water and temperature effects on evaporative demand, but there are many factors other than these that influence yields. Weeds, pests, diseases, tillage, fertility, hail, and management practices could all be potential factors limiting yields in the experimental results. These factors are beyond the scope of the KSWB model. One of the sources of uncertainty in the model is that the actual planting and physiological maturity dates for each of the field studies differ from the model assumptions. Other factors include the uncertainty of hydraulic properties and that the soil profile was treated as a block of homogenous soil instead of being broken up into layers, each with different properties.

While this study analyzed a number of different cropping sequences of wheat and sorghum, these sequences were not compared with each other. Although this analysis could be useful, it was not undertaken in this work. For example, Aiken et al. (2013) found that replacing an uncropped fallow period with an oilseed crop could reduce grain yield response of continuous wheat by 31%. A study done by Mohammad et al. (2012) found that wheat grain yield was significantly greater in wheat-summer legume-wheat and wheat-fallow-wheat than in a wheat-summer cereal-wheat rotation. Peterson et al. (1996) found that the most direct and practical solution to improve the efficient use of precipitation may be to include a summer crop following winter wheat that would make better use of summer precipitation than the use of a fallow period.

Conclusion

The KSWB model demonstrated predictive skill for crop water use, but not for grain sorghum and winter wheat yield. The simulated yield-water use relationship was consistent with that of four of five field studies of wheat and two of five field studies of sorghum. Simulated yield response of wheat to water use indicated the actual yield threshold of water use may be smaller than simulated, but observed yield response to subsequent water use was similar to that which was simulated. In contrast, the simulated yield threshold for grain sorghum appeared similar to the measured value, but observed yield response to subsequent water use was approximately half the potential value identified by the KSWB simulation on one of the field studies reported here. The KSWB model provides a useful analytic framework for quantifying water supply constraints to grain productivity.

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