Evaluation of Water-Limited Cropping Systems in a Semi-Arid Climate using DSSAT-CSM

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Abstract

Water is the major factor limiting crop production in western Kansas due to declining groundwater levels in the Ogallala aquifer resulting from withdrawals for irrigation exceeding recharge rates coupled with erratic semi-arid rainfall. Study objectives were to assess yield and water productivity of water limited cropping systems in western Kansas using DSSAT-CSM (Decision Support System for Agrotechnology Transfer Cropping Systems Model). The cropping systems evaluated included continuous (corn, wheat, and grain sorghum) and rotation (corn-wheat, corn-wheat-grain sorghum, and corn-wheat-grain sorghum-corn). Results showed that the model adequately reproduced measured days to flowering and maturity as well as yield and aboveground biomass of all three crops. Crop rotation improved water productivity of corn. Under deficit irrigation, corn in rotation produced higher yields, crop water productivity, and irrigation water use efficiency compared to continuous corn, implying that crop rotation is a better option under limited well capacities. Under full irrigation, yield and water productivity of continuous wheat were lower than wheat in rotation. In contrast, continuous wheat yields under deficit irrigation were better than under crop rotation. Deficit irrigation substantially improved irrigation water use efficiency of grain sorghum under both continuous and crop rotations. Long-term average grain sorghum yields under rotation were higher than those of continuous grain sorghum. Indicating grain sorghum should be grown in rotation under deficit irrigation. This research did not simulate the impacts of pests, weeds and diseases, hail and freeze damage on crop yield. However, the study identifies cropping systems that are more likely to produce highest water productivity under semi-arid climate similar to that in western Kansas.

32 **Keywords:** DSSAT-CSM, crop rotation, water productivity, deficit irrigation, corn, wheat, grain
33 sorghum.

1. Introduction

Water is the major crop production limiting factor in semi-arid areas such as western Kansas, USA. Rainfall is spatially and temporally variable and not adequate to meet crop water needs, and thus crops are often grown with irrigation (Kansas Department of Agriculture, 2009). Ogallala aquifer is the major source of irrigation water in western Kansas. However, the water levels of the aquifer have declined due to the withdrawal of water for irrigation exceeding mean annual recharge (McGuire, 2012). In some areas, groundwater has already been depleted while other areas have less than 75 years of the usable aquifer life (Buchanan et al., 2009). Groundwater level declines have resulted in many wells being unable to meet full crop water needs (Kansas Department of Agriculture, 2009). Therefore, there is uncertainty about the future of irrigation in western Kansas unless conservation practices and policy changes are adopted to extend the usable life of the aquifer.

Sustainable use of groundwater from the Ogallala requires improving water use efficiencies and water productivity. According to Batchelor (1999), factors to consider in improving farm level irrigation efficiency can be categorized into agronomical, technical, managerial and institutional (Winpenny, 1994; Seckler, 1996). For example, as components of the institutional improvement, there is a need to create policies for promoting more efficient use of water, e.g., the Water Conservation Areas (WCAs) and Local Enhanced Management Areas (LEMAs) that are being pioneered in Kansas. According to Seckler (1996), agronomic improvements include increasing yield per unit of crop water use, reducing losses of usable water and prioritizing water use to high value crops/uses.

Producers with limited water in western Kansas irrigate a mix of crops under different water and land allocations. The producer's decisions regarding cropping systems and water allocation can be affected not only by commodity prices but also by farm level resources constraints (Wichelns, 2003). Klocke et al. (2006) developed a decision support tool based on yield response curves and Kansas Water Budget (Crop Water Allocator) that can help identify the most suitable crop mixes for a given water allocation. While this tool is very useful for long term planning, it is not dynamic, i.e., does not account for effects of residual soil water within a crop sequence. Dynamic

cropping systems models provide an additional tool for assessing water-limited crop rotations (Soler et al., 2007; Cammarano et al., 2012; Masikati et al., 2014; Dietzel et al., 2016). Cropping systems models can also be used to extend results from short term field experiments over long term historical weather, different soils, and management to provide a robust assessment of crop yield response to water (Ahuja et al. 2000; Boote et al. 2010; Li et al., 2015; Kisekka et al. 2016).

The main goal of this study was to apply DSSAT-CSM (Decision Support System for Agro-Technology transfer Cropping Systems Model) version 4.6.1 (Jones et al., 2003; Hoogenboom et al., 2015) for assessing yield and water productivity of water limited cropping systems in western Kansas. Specific objectives were to: (1) calibrate and validate DSSAT-CSM for the dominant grain crops (corn, wheat, and grain sorghum) in western Kansas, (2) compare and evaluate water productivity and irrigation water use efficiency of various cropping systems (continuous versus crop rotation) and determine optimum limited irrigation crop rotation for western Kansas using long term historical weather data (1950-2013).

2. Materials and methods

2.1 Site description

The experimental site was located at the Kansas State University Southwest Research-Extension Center Finnpup farm near Garden City, Kansas with geographical location of 38°01'20.87''N, 100°49'26.95W and elevation of 887 m above mean sea level. The soil at the experimental site is characterized as a deep well drained Ulysses silt loam with average organic matter content of 1.5% and pH of 8.1 (Klocke et al. 2011). The wilting point and field capacity of the soil were estimated as 15 and 33 vol% (Klocke et al. 2011). The soil physical properties of the experimental site are presented in Table 1. The agro-climatic class of the study area is categorized as semi-arid with long-term mean annual rainfall and reference evapotranspiration (ET_o) of 477 and 1,810 mm, respectively (Klocke et al., 2011). The long-term (1950 - 2013) seasonal (May to Oct.) average rainfall and ET_o are 349 and 962 mm, respectively. The long-term mean monthly rainfall and ET_o of the study site are presented in Fig. 1. The mean warm growing season (May to Oct.) maximum and minimum temperatures were 28.3 and 12.3 °C, respectively. The study area has frost-free period of about 170 days (Klocke et al., 2012).

2.2 Experimental setup and treatments

Field experiments were carried out to evaluate the response of corn, grain sorghum, and wheat to various irrigation water levels. Corn was planted in 2010 (5-May 2010) after corn in a soybean-wheat-grain sorghum-sunflower-corn-corn rotation. Grain sorghum was planted in 2009 (20-May, 2009) after wheat in sunflower-corn-corn-wheat-grain sorghum rotation and wheat was planted in 2011 (28-Sep. 2011) after corn in grain sorghum-sunflower-corn-corn-wheat rotation.

Each crop received six irrigation treatments representing approximately 100%, 80%, 70%, 50%, 40% and 25% of full irrigation. The irrigation treatments were arranged in a randomized complete block design replicated four times with plot sizes of 13.7 x 27.4 m. Irrigation was applied using linear move sprinkler system (model 8000, Valmont Corp., Valley, NE) modified to apply irrigation in any desired treatment combination (Kisekka, et al. 2016). Irrigation amount per irrigation event was uniform (25 mm). Irrigation for the full irrigation treatment was applied depending on the soil water status in the top 1.2 m of the soil profile. Irrigation scheduling for the full irrigation treatment was triggered when management allowable depletion reached 50% (Klocke et al. 2011; 2012). The irrigation application for the other five deficit irrigation treatments was based on predetermined percentage of the full irrigation and was targeted to responsive growth stages as presented in Klocke et al. 2011 and 2012. However, while implementing these predetermined water allocations, within season irrigation frequency adjustments were made depending on rainfall and ET-based water balance as reported in Klocke et al. (2011; 2012). The frequency of irrigation for each irrigation treatment of the different crops was different due to the differences in crop water demand and difference in seasonal rainfall amount. Agronomic practices such as fertilizer application and weeding were applied uniformly to all treatments of a particular crop to meet potential yield according to the recommended best practices for the region (Klocke et al., 2011).

2.3 Data collection

Soil water was measured using neutron attenuation (Evelt and Steiner, 1995) to a depth of 2.44 m. The measurements were done at depth increments of 0.3 m on average twice a month during the growing season and at physiological maturity. The crop evapotranspiration was estimated from soil water balance based on Eq. 1 as presented in Klocke et al. 2011.

$$ET = I + P - (SW2 - SW1) - D \quad (1)$$

where I is applied irrigation water (mm), P is precipitation during the sampling period (mm), $SW1$ and $SW2$ are the total profile soil water at the start and end of the sampling period respectively (mm) and D is the drainage during the sampling period. Drainage was estimated based on Stone et al. (2011). Runoff or runoff during the sampling period was assumed negligible. The sampling period refers to the period between the first and last neutron probe readings during the growing season. Soil water measurement were not conducted from planting to $SW1$ for all crops. The product of crop coefficient and ETo approach was used to estimate ET values before the start of neutron probe measurements.

Crop phenology (emergence, tasseling, silking, senescence and maturity) were recorded considering the development stages of the crop during the growing season. For corn and grain sorghum, the final biomass was obtained from the middle row of a plot from a length of approximately 3 m whereas two other 3 meter rows were used for obtaining grain yield. Harvesting was done by hand, and aboveground biomass were recorded after oven drying. Corn and grain sorghum yields were adjusted to nominal moisture contents of 15.5% and 14%, respectively. However, since model simulations are on dry matter basis, 14% and 15.5% of the weight of grain was deducted from measured yields to derive dry weight for grain sorghum and corn, respectively. In the case of wheat, the final harvest was made from an area of 2 m² from each plot and biomass was oven dried while 12.5% of seed moisture weight was deducted to derive oven dry seed weight.

2.4 Model calibration

When calibrating the model, all management (seeding rates, fertility, and irrigation), soil physical characteristics of the experimental site and climate information that included maximum and minimum temperature, precipitation, and solar radiation data were provided as model inputs as presented in Hoogenboom et al. (2012). Fertilization was based on optimum yield potential requirements (corn, 319 kg N and 88 kg P/ha; wheat, 177 kg N/ha; grain sorghum, 145 kg N and 29 kg P/ha). For corn and wheat about 14 and 13 kg N/ha of the total were applied at sowing and the other 305 and 163 kg N were applied after 45 and 215 days after planting, respectively. For grain sorghum, all fertilizers were applied at once a month after planting. Initial available soil

water and nitrogen were assumed as 65% and 15%, respectively. Soil initial conditions (at planting) were not measured but considered to be reasonable based on undocumented information obtained from the study site.

When calibrating soils data, a default silt loam soil that closely resembles our experimental site was chosen from the DSSAT-CSM soils database and then some of the soil parameters were adjusted as presented in Timsina et al. (2008). For all crops (grain sorghum, corn, and wheat), the model was calibrated based on data from the optimal irrigation treatment (100% of full irrigation). The crop cultivar genetic coefficients were calibrated by choosing default cultivars (e.g. Timsina et al., 2008) first by assessing their days to flowering and maturity and followed by growth and yield. When calibrating the model, default cultivar genetic coefficients for corn (cultivar name = 2750 – 2800; identification code = PC0005; and ecotype IB0001), wheat (cultivar name = NEWTON; identification code = IB0488; ecotype = 1, 6 USWH01) and grain sorghum (cultivar name = W. African; identification code = 990004 and ecotype IB0001) in DSSAT were slightly adjusted in order to simulate the measured results of experimental corn, wheat and grain sorghum, respectively.

The Priestly-Taylor/Ritchie and the Suleiman-Ritchie (Suleiman-Ritchie, 2003) options in the model were selected for estimating reference evapotranspiration and soil evaporation, respectively. The soil conservation service (Soil Conservations Service, 1985) option of the model was also used for estimating infiltration.

2.5 Model validation

Validation was done using experimental data from other five deficit irrigation treatments of corn, wheat and grain sorghum grown during their respective experimental seasons (grain sorghum in 2009, corn in 2010 and wheat in 2012). Model validation conducted by comparing the observed/measured against simulated phenology, yield and biomass was quantified using statistical goodness of fit test indicators such as normalized root mean square error (*NRMSE*) (Eq.1), index of agreement (IoA) (Willmott,1982), percent deviation (d) Eq. 2, and linear regression:

$$NRMSE = \left[\frac{RMSE}{x} \right] \times 100 \quad (1)$$

$$RMSE = [\sum (S_i - O_i)^2 / n]^{0.5} \quad (2)$$

In Eq. 1, $\bar{x}$, is the average of the measured values; *RMSE* is the root mean square error (Eq. 2). The *NRMSE* is the normalized RMSE. *NRMSE* values: 0 – 15%, 15 – 30% and > 30% classified as good, moderate, and poor agreement, respectively (Liu et al., 2013), which are almost similar to those described in Soler et al. (2007) (0 – 10% excellent; 10 – 20%, good; 20 – 30, fair and > 30%, poor). Similarly, IoA values show the degree of agreement and values <0.7, 0.7 – 0.8, 0.8 – 0.9 and > 0.9 - 1 based on Willmott (1982) are considered as poor, moderate, good and excellent agreement, respectively (Liu et al., 2013). In Eq.2 & 3, S_i and O_i are the corresponding simulated and observed/measured values in a given treatment.

$$d = \left[\frac{S_i - O_i}{O_i} \right] \times 100\% \quad (3)$$

d , is percent of deviation; the lower percent of deviation indicates good model performance.

2.5 Scenarios

The calibrated and validated corn, wheat and grain sorghum models were used in DSSAT-CSM sequential mode for three continuous (C-C, W-W, and GS-GS) and three separate crop rotation treatments (C-W-GS-C, C-W-GS and C-W) assessments. Each of the crops in the rotation or continuous cropping were allocated three levels of irrigation as presented in Ibendahl et al. (2015a-c). The three levels of irrigation represented low (deficit), moderate and high (full) irrigation which also varies with crop type. Fertilizer (nitrogen and phosphorus) were applied based on crop type as per the farmer's management (Pers. Com). Irrigation treatments and fertilizer for each of the crops under rotation was applied based on Table. 2. Similar to the experimental study, the initial conditions for available soil water, and nitrogen in our model simulation scenarios were set as 65% and 15 kg/ha, respectively, and then the recalculate menu in the model allowed the estimations of the soil water and nitrogen values by layer. After setting all required information in the model, yield, biomass and ET under each of the cropping systems and irrigation scenarios were simulated for 64 years (1950 – 2013) of historical weather data. Crop water productivity and irrigation water use efficiency were then calculated.

2.5.1 Crop water productivity

Crop water productivity for dry biomass (WP_B) and grain yield (WP_G) were estimated based on Eqs. 4 and 5, respectively.

$$WP_B = \left[\frac{B}{ET} \right] \quad (4)$$

$$WP_G = \left[\frac{GY}{ET} \right] \quad (5)$$

where B and GY are end of season biomass and grain yield in kg/ha [dry matter basis], respectively, and ET is seasonal crop evapotranspiration in (mm).

2.5.2 Irrigation water use efficiency

Irrigation water use efficiencies for dry biomass ($IWUE_B$) and grain yield ($IWUE_G$) were estimated based on Eqs. 6 and 7, respectively.

$$IWUE_B = \left[\frac{B}{IN} \right] \quad (6)$$

$$IWUE_G = \left[\frac{GY}{IN} \right] \quad (7)$$

where, B , is the dry biomass; GY , is irrigated grain yield (kg/ha) and IN is applied irrigation (mm).

3. Results

3.1 Model calibration

Percent deviation values between simulated and observed days to flowering and maturity for corn, wheat, and grain sorghum were very low (<10%) (Table 3). Implying the model simulated well the phenology of the experimental cultivar. Yield of the full irrigation treatment (that were used for model calibration) for all crops were also adequately simulated by the model ($d - 14$ to 18%). The biomass and ET were also satisfactorily simulated by the model with deviation of –

18 to 22% and – 22 to 11% respectively. The slight increase in measured ET when compared to simulated values might be due to the empirical estimations used to derive the ET for pre-neutron probe measurement period. In general, the experimental cultivars were satisfactorily represented by the genetic coefficients presented in Table 4.

3.2. Model validation

Validation goodness of fit indicators for corn, wheat, and grain sorghum phenology, grain yield, biomass, and ET are presented in Table 5 - 8. The days to flowering and maturity of corn, wheat, and grain sorghum were simulated with an excellent agreement ($d < 10\%$ and NRMSE $< 10\%$) (Table 5). Similarly, the simulated grain yield and biomass for all crops strongly agreed with measured values (Table 6 and 7). For example, the NRMSE values for grain yield of corn, wheat, and grain sorghum were 14.3, 19.5 and 9.5%, respectively (Table 6). The corresponding values for dry aboveground biomass were 10.8, 14 and 17%, respectively (Table 7). These NRMSE values for both grain and biomass are within the ranges of good agreement.

The deviation of the simulated from observed yield and dry biomass for corn ranged between -30 to 10% and -20 to 10%, respectively (Table 6 and 7). One of the water stressed treatments for corn was not accurately simulated probably the model was not able reproduce growth and development under severe water stress. The d values including the severe water stressed treatments were within the range of -30 to 10% which still indicated the model simulated the water stressed treatment satisfactorily. For grain sorghum, the deviation ranged from 3.9% to 11% and 13 to 21% for grain yield and biomass, respectively (Table 6 and 7). These ranges of deviation indicated good model performance. The index of agreement (IoA) for corn, wheat, and grain sorghum yield were 0.92, 0.81 and 0.74, respectively, whereas, the IoA values for biomass for the corresponding crops were 0.93, 0.90 and 0.4, respectively. Most of the IoA values were above 0.8 indicating the model simulated the measured values adequately. Whereas the simulated biomass for grain sorghum was slightly overestimated by the model. However, the NRMSE (17%), d (13 – 21%) and R^2 (0.77) values showed the model satisfactory predicated measured results. Similarly, the R^2 values for yield (Fig. 2) and biomass (Fig. 3) were 0.81 and 0.81 for corn, 0.82 and 0.92 for wheat, and 0.97 and 0.77 for grain sorghum, respectively.

Overall, the model showed satisfactory performance in simulating the yield and biomass of corn, wheat, and grain sorghum.

The ET of corn, wheat, and grain sorghum were simulated with NRMSE of 15, 10, 9.5%, respectively (Table 8). The IoA and R^2 values for the corresponding crops were 0.79 and 0.86, 0.97 and 0.89 and 0.96 and 0.77, respectively (Fig. 4). This shows that the ET of the experimental cultivars were adequately simulated.

Overall, the statistical evaluation showed that the model simulated the grain yield, biomass, and ET of corn, wheat and grain sorghum adequately. Therefore, the model can be used for assessing water productivity and irrigation water use efficiency of various cropping systems (continuous versus crop rotation) and determine optimum limited irrigation crop rotations for western Kansas using long term historical weather data (1950-2013).

3.3 Evapotranspiration (ET), yield and crop water productivity

The long-term mean ET for continuous and crop rotation cropping systems treatments is presented in Fig. 5. The highest long-term (1950-2013) mean ET was observed for continuous corn (C-C) which is substantially different from all other continuous and crop rotation cropping systems considered in this study, whereas, the lowest was observed for continuous grain sorghum. For crop rotations, the highest long-term mean ET per season per hectare was simulated for the C-W rotation but was not substantially different from C-W-GS and C-W-GS-C (Fig. 5).

The long-term mean ET-corn in rotation under full and moderate irrigation was 17 to 35% and 7 to 27% lower than the respective ET-corn in continuous cropping. The decrease in ET under full irrigation in the rotation treatment did not substantially decrease corn yield. However, under deficit irrigation, ET-corn in continuous cropping decreased by up to 11 and 7% in rotation C-W-GS-C and C-W-GS, respectively (Fig. 5) while, the long-term mean corn yield in rotation under deficit irrigation increased by 4 to 19 and 27 to 38 %, respectively, when compared to the corresponding corn yield in continuous cropping (Fig. 6; Table 9). The highest ET-corn in the

rotation under low irrigation produced the highest yield which corresponds to corn after wheat in C-W rotation (Fig. 6; Table 9).

The long term mean ET of wheat was slightly lower in continuous cropping (487 – 514 mm) when compared to that of wheat in rotation (C-W = 508 – 576 mm; C-W-GS = 483 – 562 mm; C-W-GS-C = 487 – 572 mm) (Table 9). These ET values for continuous wheat were slightly higher than those reported by Oweis et al. (1998). This difference might be attributed to climate as well as cultivar (e.g. days to maturity) differences. Except for low irrigation, wheat yield in continuous cropping was slightly lower than that of wheat in the rotation.

Long-term mean ET-wheat in rotation under full irrigation was 9 to 11% higher than that in continuous cropping as a result, wheat yield in rotation increased by up to 36% (Fig. 7; Table 10). However, the long-term mean wheat yield and biomass in the rotation under low (deficit) irrigation were lower by up to 34% and 24%, respectively, when compared to that of continuous wheat grown under low irrigation (Fig. 7; Table 10). Similarly, ET-grain sorghum in the rotation was only 1 to 6% higher than that in continuous grain sorghum. There was no substantial difference between the long-term mean grain sorghum biomass and yield in rotation and continuous cropping under all irrigation scenarios (Fig. 8). However, there was a slight yield and biomass increase in rotation when compared to continuous cropping although not substantially different.

The dry biomass (WP_B) and grain (WP_G) water productivity for corn, wheat and grain sorghum are presented in Table 9 - 11. Corn WP_B and WP_G were not substantially affected by the three levels of irrigation treatments, but there was a considerable difference in corn WP_B and WP_G between the crop rotation and continuous treatments. The highest WP_B and WP_G for corn were observed in rotation that ranged from 39 to 42 kg/ha/mm and 22 to 24 kg/ha/mm, respectively. The lowest corn WP_B (28 to 29.5 kg/ha/mm) and WP_G (16.8 to 17 kg/ha/mm) were observed for continuous corn.

There were differences in wheat grain and biomass water productivities among the three levels of irrigation (Table 10). The highest WP_B (28.5 kg/ha/mm) corresponded to wheat in rotation C-W-

GS under moderate irrigation whereas the lowest ($WP_B = 15.4$ kg/ha/mm) corresponded to wheat after corn in rotation C-W-GS-C under deficit irrigation. Similarly, the highest (11 kg/ha/mm) WP_G was observed in rotation C-W-GS under full and deficit irrigation. Whereas, the highest WP_G (6.4 kg/ha/mm) under deficit irrigation was observed in continuous wheat. Therefore, this study showed that continuous wheat was relatively more productive than wheat in rotation under deficit irrigation whereas wheat in rotation C-W-GS was more productive than continuous wheat under full irrigation. The WP_G values in this study are similar to those reported by Oweis et al. (1998).

There were no considerable differences in WP_B and WP_G among the grain sorghum crop rotation treatments across the three irrigation treatments (Table 11). Continuous grain sorghum was found to be less productive in terms of WP_B and WP_G when compared to grain sorghum in rotation of the same irrigation treatment.

3.4 Irrigation water use efficiency

Regardless of the type of cropping system, irrigation water use efficiency (IWUE) for corn dry biomass and yield under deficit irrigation increased by 27 – 36% and 27 – 38%, respectively, compared to continuous corn (Fig. 9). Under moderate irrigation, there was an increase of IWUE for both biomass (3 – 12%) and grain (3– 18%) when compared to continuous corn under similar irrigation (Fig. 9). Under full irrigation, there was no substantial difference in IWUE of corn regardless of the cropping system (Fig. 9). The highest corn $IWUE_B$ (71.3 kg/ha/mm) and $IWUE_G$ (42.0 kg/ha/mm) were observed under deficit irrigation for rotation C-W whereas the lowest IWUE ($IWUE_B = 36$ kg/ha/mm) values were simulated for full irrigation under rotation C-W-GS (Table 9) although not substantially different from crop rotation cropping systems with similar levels of irrigation. $IWUE_G$ of corn under full irrigation in rotation were relatively lower by 46% when compared to that under deficit irrigation.

The $IWUE_B$ and $IWUE_G$ for wheat in rotation under low irrigation decreased by 9 – 24% and 23– 34% compared to that in continuous whereas, under high irrigation, wheat in rotation showed higher $IWUE_B$ (19 – 20%) and $IWUE_G$ (31 – 36%) when compared to that under

continuous wheat (Fig. 10). Under low irrigation, the wheat in C-W-GS rotation was more efficient in terms of $IWUE_G$ when compared to the other rotation treatments in this study.

Fig. 11. Shows the percent change for grain sorghum $IWUE_B$ and $IWUE_G$ as affected by rotation and irrigation level relative to the corresponding continuous cropping under the respective irrigation levels. There was a small increase in grain sorghum $IWUE_B$ and $IWUE_G$ with crop rotation compared to continuous grain sorghum. The $IWUE_B$ and $IWUE_G$ of grain sorghum increased by 45% under low irrigation relative to high irrigation in both rotation and continuous cropping systems. The highest $IWUE_B$ and $IWUE_G$ of grain sorghum ranged from 85 to 90 and 31 to 36 kg/ha/mm, respectively, for low irrigation treatments whereas the lowest $IWUE_B$ and $IWUE_G$ values ranged from 43 to 46 and 16 to 19 kg/ha/mm, respectively, for high irrigation treatments. There were slight differences in $IWUE_B$ and $IWUE_G$ between grain sorghum in rotation and in continuous cropping under similar irrigation treatments but were not substantially different. Grain sorghum yield showed slight increase in rotation treatments when compared to that in continuous cropping under similar irrigation.

4. Discussion

4.1 Evapotranspiration, yield and crop water productivity

Predicted mean seasonal irrigation water applied over 64 years for corn in rotation was lower than that for continuous corn. Corn is sensitive to water stress (Cakir, 2004) and the long-term mean irrigation water requirement for corn in monoculture was higher than the long-term mean irrigation water requirement of corn in rotation because some of the crops in the rotation used less water than corn. This study also showed that the water requirement for wheat and grain sorghum was by far lower than that of corn. Some studies have shown that wheat can be grown with deficit irrigation without significant yield loss (Zhang and Oweis, 1999). Similarly, grain sorghum was also reported to withstand water stress and considered suitable when water supplies are limited (Klocke et al., 2012). Therefore, growing corn in rotation with wheat and grain sorghum may save irrigation water and this implies crop rotation may contribute to the sustainable utilization of groundwater if economic conditions allow.

One of the advantages of rotating corn with less water consumptive crops is to improve the soil water recharge (Benjamin et al., 2015). Crop rotations might also provide carry over advantages for the next crop such that soil water left after harvest (e.g., due to different rooting characteristics) may be utilized by the next crop. Klocke et al. (2012) reported that growing grain sorghum under limited water in companion with high water consumptive crops like corn might enable producers to allocate more water to sensitive crop such as corn. For this reason, Benjamin et al (2015) also recommended the use of less water consumptive crops in rotation with corn under deficit irrigation.

Corn yield in continuous cropping under moderate and deficit irrigation was slightly lower compared to corn yield under similar irrigation levels in rotation. One of the reasons could be due to the lower extractable soil water when compared to corn grown in rotation with less water consumptive crops. Another reason for the lower yield in continuous corn under deficit irrigation might be due to mining of mineral nutrients and water from the same layers of the soil profile throughout the 64-year simulation period. In line with our findings, Schlegel et al. (2012) reported that yield and water productivity of corn in rotation was higher than that in continuous cropping. Soil water utilization was reported to be higher in rotations than continuous cropping (e.g. there was more time for soil water accumulation) (Schlegel et al., 2012). Schneekloth, et al. (1991) obtained higher ET in dryland rotations than in continuous corn though yields were not significantly different. Crop rotation was found to be effective in improving soil water recharge (Benjamin et al., 2015) and was reported to have positive impact on dryland yields when compared to irrigated cropping systems (Schneekloth, et al., 1991). In this study, the evaporation component of ET in rotation was slightly lower than that under continuous cropping and the simulated yield in rotation was slightly higher than continuous cropping. This condition eventually led to having higher crop water productivity in rotation when compared to continuous cropping.

The grain water productivity for continuous corn under deficit or full irrigation were almost the same (17 kg/ha/mm), whereas, these values were improved for corn under rotation (21 to 25 kg/ha/mm) regardless of the irrigation level. The WP_G values for continuous corn were similar to those values obtained for corn by Ko and Piccinni (2009). These water productivity values of

corn in this study are close to those reported (16.4 – 20.2 kg/ha/mm) in Schlegel et al. (2016). Other studies also indicated reductions in corn water productivity as a result of a reduction in soil water reserve under continuous corn and deficit irrigation when compared to full irrigation (Benjamin et al. 2015). Schlegel et al. (2016) reported better performance of corn under full irrigation when compared to corn under deficit irrigation. Our study confirms these findings in that water productivity of corn increased when corn was grown under full irrigation. For corn in rotation, there was an average yield increase of 0.4 – 0.6 t/ha for every 150 mm increase in irrigation water over the base 300 mm while in continuous corn, there was an increase of yield of 2.1 – 2.2 t/ha for every 150 mm increase in irrigation water over the 300 mm.

In contrast, grain sorghum yield in both rotation and continuous cropping were not substantially different, and the yield levels were within ranges reported by Schlegel et al. (2012; 2016). Also, there was no substantial difference between grain sorghum yield grown under deficit and full irrigation scenarios. One of the reasons for having similar yields under both continuous and rotation as well as under both full and deficit irrigation scenarios could be due to sufficient soil water availability for grain sorghum during the cropping season (despite the growers conventional practice as documented in Ibendahl et al. (2015c). For example, the estimated maximum grain sorghum ET under full irrigation was approximately 500 mm and the estimated seasonal mean evapotranspiration of grain sorghum under deficit irrigation in this study was about 460 mm which is almost close to the maximum ET. These ET values are within the ranges reported by Stewart et al. (1983). The second reason is sorghum has well developed rooting system that enables the crop to extract soil water from deeper soil profile. Also, grain sorghum has the ability to build up solutes and osmotically regulate opening of the stomata in response to water stress (Feres, et al. 1978; Munamava and Riddoch 2001; Wani et al. 2012). Grain sorghum was reported to resist water stress by reducing water loss from leaves by rolling its leaves and exude wax cover as well as its ability to minimize its leaf area to withstand severe water stresses (Munamava and Riddoch, 2001). Furthermore, some studies have also shown that grain sorghum has sensitive stomata to reduce water loss from the leaves and has small leaf area per plant; it can also produce tillers to produce grain under severely water stressed conditions (Munamava and Riddoch, 2001; ARC-Grain Crops Institute 2008).

There was no substantial differences in grain water productivities of grain sorghum under full, moderate and deficit irrigation scenarios. The grain water productivity of continuous grain sorghum for full, moderate and deficit irrigation treatments were 13.5 – 15.6 kg/ha/mm. These values are slightly higher than those reported (11.8 – 12.9 kg/ha/mm) by Schlegel et al. (2016). The main reason for this disparity in WP_G might be due to differences in grain sorghum ET which could be caused by climatic differences between the two locations. Cultivar difference might also contribute to disparity in WP_G . However, in line with our study, Schlegel et al. (2016) reported no significant difference in grain sorghum WP_G under various irrigation treatments. This indicates that deficit irrigation was as productive as full irrigation and there is no need for irrigating grain sorghum beyond 200 mm. However, slightly higher grain water productivities were obtained for grain sorghum in the rotation (14 to 15 kg/ha/mm) compared to continuous (13.5 kg/ha/mm) grain sorghum. Implying that grain sorghum could do better with rotation under deficit irrigation compared to continuous cropping under full irrigation. There is a well-established fact that crop rotation can improve soil structure, reduce soil erosion, improve soil water holding capacity over time and improve soil fertility. We also believe that crops in the rotation might benefit from soil water and important nutrients left unused from previous season due to differences in the nature of rooting or differences in root soil water extraction or nutrient absorption patterns. However, Benjamin et al. (2015), reported that long-term use of deficit irrigation without replacement of soil water reserve might significantly reduce yields (e.g. crops such as corn) and water productivity. There is a need for further investigation of the importance of rotation with regard to soil water recharge and improving irrigation productivity for sustainable utilization of the available groundwater. Reduction of pests and diseases would constitute other important benefits of crop rotation but this was not simulated in this study.

Some studies indicated that soil water from stubble wheat was relatively better than that of corn stubble, implying crops planted after wheat would gain advantage of utilizing better stored soil water (Schneekloth, et al., 1991) probably wheat residue may reduce soil evaporation compared to corn or grain sorghum residue. Thus, wheat in continuous cropping under low irrigation might enjoy advantages of utilizing the soil water and nutrient from past season (which otherwise would have been utilized by high water consumptive crops like corn or other crops in rotation). Schlegel et al (2012), in their 10-year (2001 – 2010) study, reported that wheat under continuous

cropping was poor due to spring freeze and hail damage. In our study, we did not simulate the impact of hail damage or frost, and disease on wheat yield and water productivity.

Grain water productivity of continuous wheat under full irrigation was substantially lower than that of wheat in the rotation but under deficit irrigation, a substantial increase in WP_G in treatment with continuous wheat was noticed. For example, grain water productivity in continuous wheat varied from 6.4 kg/ha/mm under deficit irrigation to 8.2 kg/ha/mm under full irrigation whereas the corresponding values for wheat in rotation ranged from 4.2 – 5.2 kg/ha/mm under deficit irrigation to 9.7 to 10.6 kg/ha/mm under full irrigation. These values are similar to those reported by Zhang et al. (1998) and Oweis et al. (2000). This study shows, rotation may not improve yield and water productivity of wheat under deficit irrigation although agronomic problems such as diseases and pests resulting from monoculture wheat would be a problem. This implies that wheat growers should consider growing wheat in rotation under full irrigation whereas they should consider continuous wheat under deficit irrigation. However, growing wheat in rotation might be encouraged as an option for reducing risks of crop failure due to pests especially when there is an adequate supply of irrigation water.

4.2 Irrigation water use efficiency

Continuous corn $IWUE_G$ increased with decrease in irrigation whereas yield substantially reduced from full to deficit irrigation. One of the reasons could be due to higher loss of soil water via evaporation under full when compared to deficit irrigation. Some seasons are wet while others are dry but assuming full irrigation of uniform amount throughout the long-term seasons (1950 – 2013) would result in loss of substantial amount of irrigation water. However, the main reason for the substantial yield reduction under low irrigation might be due to the water stress as corn is reported to be sensitive to water stress (Cakir, 2004).

Like for continuous corn, $IWUE_G$ increased with decrease in irrigation for similar reasons mentioned above. However, $IWUE_G$ of corn in rotation was substantially higher than that of corn in continuous cropping. The increase in $IWUE_G$ was due to increase in corn yield under rotation. Corn yield was high because of the relatively higher mean extractable soil water in rotation

compared to continuous corn for example, Cakir (2004) showed a linear increase in corn yield with ET. However, to support decisions whether to use deficit or full irrigation for corn as well as whether to grow corn in rotation or in continuous cropping systems, might need further detailed information because decisions made only based solely on IWUE might significantly affect performance of the farm. Decisions might be made based on grain irrigation water use efficiencies in conditions when crops perform well under low irrigation without substantial yield reduction when compared to maximum yield and when the grower's interest is limited to a specific crop.

In this study grain sorghum gave high $IWUE_G$ under low irrigation. In that case yields under low irrigation were not substantially different from those of high irrigation. Also, it might be possible to decide which cropping system to follow under limited irrigation based on estimates of IWUE among other things. For example, in this study, corn yield under deficit irrigation in continuous cropping was substantially lower than that of corn in rotation. Thus, IWUE could be considered as a useful criterion for making useful farm level decisions in such scenarios. However, to understand the cropping systems comprehensively, important information such as presence or absence of production limiting factors (pests, diseases and weeds, hail, frost and others) and economic feasibilities of the cropping systems under various irrigation scenarios needs to be explored.

Deficit irrigation improved $IWUE_G$ of corn and grain sorghum both in rotation and continuous cropping when compared to full irrigation. This was due to reduced losses of water in deficit irrigation via deep drainage and evaporation. In addition, most crops are responsive to irrigation directed to sensitive growth stages (deficit irrigation) rather than applying uniform irrigation water to all growth stages. Earlier work by Klocke et al. (2015) showed that there is a curvilinear relationship between corn relative yield and irrigation application. Similarly, the relationship between irrigation application and grain sorghum yield was also reported to be curvilinear (Tolk and Howell, 2002; Klocke et al. 2012) which means the increase in yield per irrigation water applied would decrease after some threshold. Some reports also indicated that there is curvilinear relationship between wheat yield and irrigation water applied (Zhang and Oweis, 1999). This indicates that irrigation water use efficiency might decrease with increase in irrigation water as

yield per applied water above certain threshold do not increase. In some cases, there may be an increase in $IWUE_G$ with increase up to some level due to positive interaction between fertilizer and irrigation. According to Tolk and Howell (2002), water stress at critical stages, loss of water due to runoff, drainage, and soil water evaporation could reduce irrigation water use efficiencies. Schlegel et al. (2016) reported that growing corn could be the best option for yield advantages under higher irrigation whereas there could be many alternative crops to grow with less economic and yield difference under low (deficit) irrigation.

Conclusions

DSSAT-CSM was applied to assess water limited cropping systems under semi-arid climate in western Kansas. The observed phenology, yield and above ground biomass for corn, wheat, and grain sorghum were adequately simulated by the model. Corn under full irrigation produced more yield compared to deficit irrigated corn. Grain water productivity of corn under full irrigation was also slightly improved when compared to deficit irrigation though not substantial. Thus when sufficient water is available, growing corn under full irrigation might be preferable to deficit irrigation. Under deficit and moderate irrigation, corn in rotation produced higher yields and crop water productivity compared to continuous corn.

In contrast, this simulation study showed that yield and water productivity of continuous wheat under deficit irrigation was better than wheat in rotation with similar irrigation level. Wheat yield under full irrigation in continuous cropping system was lower than that in rotation which implies that under high irrigation, the best option is to grow wheat in rotation with corn and grain sorghum while under low irrigation wheat in continuous cropping system works well.

There were no substantial differences among the crop rotation treatments of grain sorghum in terms of water productivity and yield. Deficit irrigation substantially improved water productivities and yields of grain sorghum under continuous and crop rotation cropping systems. Long-term mean grain sorghum yields under crop rotation were higher than those of continuous grain sorghum cropping systems. Therefore, producers should grow grain sorghum with deficit irrigation under crop rotation.

One of the limitations of this work is that it considers all production factors (except water) optimal. For example, it did not take into account effects of hail, freezing or frost, pest, disease or weeds damage on the crop productivity yet in reality these factors might limit practicability of monoculture cropping systems for some crops. Another limitation is the study did not take into account cost-benefit economic analysis which might influence the producer's decision on which cropping system to adopt. In addition this study is limited to cropping practices (irrigation and fertilizer application) for farmers in western Kansas. Cultivar (such as early, late maturing, drought sensitive and resistant etc) and management (irrigation and fertilizer application rates for more cropping systems) might also affect productivity thus more detailed analysis might be needed that includes cultivars, and cropping systems, soils, fertilizer and irrigation under diversify production systems. However, the study highlights the potential possibilities of identifying suitable/optimal cropping systems for water limited areas.

588 **Acknowledgements**

589 The authors would like to thank the following for providing funding for this research USDA
590 Ogallala Aquifer Project, and USDA Project No. 2016-68007-25066, through the NIFA Water
591 for Agriculture Challenge Area. The authors would also like to thank Mr. Dennis Tomsicek for
592 data collection and compilation. We would also like to thank Mr. Jaylen Koehn for coordinating
593 all agronomic field operations.

594 Contribution no. 16-304-J from the Kansas Agricultural Experiment Station.

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Table 1. Soil physical characteristics of experimental site at the Kansas State University Southwest Research-Extension Center near Garden city, Kansas.

Depth (cm)	Soil texture	Wilting point (Vol.%)	Field capacity (Vol.%)	Saturation (Vol%)	Bulk density (g/cm ³)
0 to 245	Silt loam	15	33	45	1.38

Table 2. Irrigation and fertilizer applied to corn, wheat and grain sorghum used for scenario analysis based on surveyed data from western Kansas.

	C	W	GS	C		W		GS	
				N	P	N	P	N	P
Irrigation	(mm)	(mm)	(mm)	(kg/ha)	(kg/ha)	(kg/ha)	(kg/ha)	(kg/ha)	(kg/ha)
Full	600	300	400	226	99	125	43	102	51
Moderate	450	250	300	190	83	101	35	95	46
Deficit	300	200	200	154	67	79	27	87	40

Source: Ibendahl et al., 2015a-c; C, corn; W, wheat; GS, grain sorghum

Table 3. Calibration results for corn, wheat and grain sorghum cultivars from an experimental site at the Kansas State University Southwest Research-Extension Center near Garden city, Kansas.

Crop	Days to flowering			Days to maturity			Grain (t/ha)			Biomass (t/ha)			ET (mm)		
	Sim.	Obs.	d (%)	Sim.	Obs.	d (%)	Sim.	Obs.	d (%)	Sim.	Obs.	d (%)	Sim.	Obs.	d (%)
Corn	78	78	0.0	137	138	-0.7	12.6	12.0 (1.86)	4.7	22.0	22.4 (2.21)	-1.8	531	678 (26)	-21.5
Wheat	225	222	1.4	260	260	0.0	5.1	4.9 (0.3)	5.8	12.2	14.8 (3.2)	-17.6	525	637 (20)	-17.6
Grain Sorghum	77	80	0.0	131	140	-6.4	7.7	6.5 (1.7)	18.5	18.0	14.8 (2.7)	22.0	516	464.2 (17)	11.2

Sim, simulated; Obs, observed; d, deviation; ET, evapotranspiration; values in bracket are standard deviations.

Table 4. Starting (default) versus calibrated genetic cultivar coefficients for corn, wheat and grain sorghum grown at the Kansas State University Southwest Research-Extension Center near Garden city, Kansas.

Corn Cultivar parameter	Description	Starting value	Calibrated value
P1	Emergence to end of juvenile phase (in degree days)	260	230
P2	The extent to which development is delayed for each hour increase in photoperiod above the longest photoperiod at which development proceeds at max. rate.	0.75	0.78
P5	Degree days silking to physiological maturity	850	990
G2	Maximum number of kernels per plant	800	920.4
G3	Kernel filling rate during the linear grain filling stage and under optimum condition (mg/day);	8.5	7.3
PHINT	Phylochron interval (degree days)	49	65.9
Wheat cultivar parameters	Description	Starting value	Calibrated value
P1V	Days optimum vernalizing temperature, required for vernalization	45	49
P1D	Photoperiod response (% reduction in rate/10 h drop in pp)	75	70
P5	Grain filling (excluding lag) phase duration (degree days)	500	600
G1	Kernel number per unit canopy weight at anthesis (#/mg)	25	25
G2	Standard kernel size under optimum condition (mg)	30	40
G3	Standard, non-stressed mature tiller weight (including grain) (g dwt)	2	0.5
PHINT	Interval between successive leaf tip appearance (degree days).	95	75
Grain sorghum cultivar parameter	Description	Starting value	Calibrated value
P1	Degree days emergence to end of juvenile phase	413	365
P2	Degree days from end of juvenile stage to tassel initiation under short day (above base)	102	102
P20	Critical photoperiod or the longest day length (hrs) at which maximum development occurs	13.6	15.6
P2R	The extent to which development is delayed for each hour increase in photoperiod above the longest photoperiod at which development proceeds at max. rate.	40	40
PANTH	Degree day from end of tasseling to anthesis;	617.5	617.5
P3	Degree days end of flag leaf expansion to anthesis;	152.5	152.5
P4	Degree days anthesis to beginning of grain filling	81.5	81.5
P5	Degree days beginning of grain filling to physiological maturity	640	640
PHINT	Phylochron interval; the interval in thermal time between successive leaf tip appearance	49	49
G1	scaler for relative leaf size	3	3
G2	scaler for partitioning of assimilates to the panicle (head);	6.5	6.5

Table 5. Validation goodness of fit indicators for grain yield of corn, winter wheat and grain sorghum grown at the Kansas State University Southwest Research-Extension Center near Garden city, Kansas.

Corn						Wheat						Grain Sorghum					
Flowering			Maturity			Flowering			Maturity			Flowering			Maturity		
Sim.	Obs.	d (%)	Sim.	Obs.	d (%)	Sim.	Obs.	d (%)	Sim.	Obs.	d (%)	Sim.	Obs.	d (%)	Sim.	Obs.	d (%)
78	78	0.0	137	138	-0.7	225	222	1.4	260	260	0.0	77	80	-3.8	131	140	-6.4
78	78	0.0	137	131	4.6	225	222	1.4	260	260	0.0	77	80	-3.8	131	140	-6.4
78	78	0.0	137	131	4.6	225	222	1.4	260	260	0.0	77	80	-3.8	131	140	-6.4
78	78	0.0	137	131	4.6	225	222	1.4	260	252	3.2	77	80	-3.8	131	133	-1.5
78	78	0.0	137	131	4.6	225	222	1.4	260	252	3.2	77	80	-3.8	131	133	-1.5
NRMSE	0			3.53			1.35			1.39			3.2			5.1	

NRMSE, normalized root mean square of error; d, deviation; Sim, simulated; Obs. Observed.

Table 6. Validation goodness of fit indicators for grain yield of corn, winter wheat and grain sorghum grown at the Kansas State University Southwest Research-Extension Center near Garden city, Kansas.

Corn			Wheat			Grain sorghum			
Yield (t/ha)									
Statistics	Sim.	Obs.	d (%)	Sim.	Obs.	d (%)	Sim.	Obs.	d (%)
	12.5	11.3 (0.9)	10.2	4.2	3.8 (0.4)	9.4	7.2	6.4 (0.4)	11.2
	10.0	9.7 (1.3)	3.3	3.4	3.2 (0.4)	7.6	6.9	6.2 (0.3)	11.1
	8.0	8.3 (1.7)	-3.1	3.1	3.6 (0.4)	-14.1	6.8	6.1 (0.3)	10.3
	5.7	8.1 (1.7)	-30.0	2.0	2.2 (0.3)	-9.9	5.8	5.4 (0.5)	7.4
	5.9	5.9 (1.4)	0.9	-	-	-	5.8	5.6 (0.7)	3.9
NRMSE (%)		14.3			19.5			9.52	
IoA		0.92			0.81			0.74	
R ²		0.81			0.82			0.97	

GY, grain yield; NRMSE, normalized root mean square of error; IoA, index of agreement; d, deviation; Obs., Measured; Sim., Simulated; STDVE, standard deviation.

Table 7. Validation goodness of fit indicators for biomass yield of corn, winter wheat and grain sorghum grown at the Kansas State University Southwest Research-Extension Center near Garden city, Kansas.

corn				wheat			Grain sorghum		
Biomass (t/ha)									
Statistics	Sim.	Obs.	d (%)	Sim.	Obs.	d (%)	Sim.	Obs.	d (%)
	21.9	23.2 (2.3)	-5.6	11.7	11.6 (3.1)	1.0	17.3	14.3 (1.2)	21.2
	18.2	17.7 (1.5)	2.8	12.7	11.1 (3)	14.9	16.5	14.4 (0.4)	14.5
	15.9	17.8 (2.6)	-10.7	8.2	9.5 (1.2)	-13.8	16.3	14.0 (2.3)	16.8
	12.7	15.9 (1.9)	-20.1	5.6	7.2 (1.5)	-21.9	15.0	13.3 (1.7)	12.8
	12.9	11.7 (3)	10.3	3.5	4.4 (1.3)	-19.5	15.0	12.5 (2.1)	19.7
NRMSE (%)		10.76			14.0			17.29	
IoA		0.93			0.9			0.41	
R ²		0.81			0.92			0.77	

BM, above ground dry biomass; NRMSE, normalized root mean square of error; IoA, index of agreement; d, deviation; Obs., Measured; Sim., Simulated; STDVE, standard deviation.

Table 8. Validation goodness of fit indicators for ET of corn, winter wheat and grain sorghum grown at the Kansas State University Southwest Research-Extension Center near Garden city, Kansas.

corn				wheat			Grain sorghum		
ET (mm)									
Statistics	Sim.	Obs.	d (%)	Sim.	Obs.	d (%)	Sim.	Obs.	d (%)
	531	610.0 (13)	-13.0	523.0	557.0 (20)	-6.1	493.0	436.0 (6)	13.1
	465	541.0 (19)	-14.0	481.0	447.0 (12)	7.6	471.0	435.0 (2)	8.3
	431	520.0 (40)	-17.1	406.0	356.0 (6.0)	14.0	473.0	431.0 (16)	9.7
	413	517.0 (22)	-20.1	309.0	285.0 (10)	8.4	451.0	416.0 (13)	8.4
	390	426.0 (23)	-8.5	255.0	224.0 (13)	13.8	451.0	423.0 (28)	6.6
NRMSE		15.3			10.0			9.48	
(%)									
IoA		0.79			0.97			0.96	
R ²		0.86			0.89			0.77	

NRMSE, normalized root mean square of error; IoA, index of agreement; d, deviation; ET, evapotranspiration; Obs., adjusted; Sim., Simulated; STDVE, standard deviation.

Table 9. Long-term (1950 – 2013) mean crop water productivity (B-WP and G-WP) (kg/ha/mm) and irrigation water use efficiency (IWUE_B and IWUE_G) (kg/ha/mm) for corn under three levels of irrigation with the various rotation and continuous cropping system evaluated near Garden City Kansas

Irrigation level	Cropping system	Biomass (t/ha)	WP _B (kg/ha/mm)	IWUE _B (kg/ha/mm)	Grain (t/ha)	WP _G (kg/ha/mm)	IWUE _G (kg/ha/mm)	ET (mm)
Full	C1 - W - GS - C	23.0 (1.2)	35.1	38.3	13.9 (1.1)	21.2	23.2	656.0 (51)
	C - W - GS – C2	21.5 (0.9)	43.2	35.8	12.6 (0.6)	25.3	21.0	498.0 (25)
	C - W- GS	21.6 (0.9)	42.2	36.0	12.7 (0.7)	24.8	21.2	512.0 (68)
	C - W	22.5 (1.3)	38.8	37.5	13.6 (1)	23.4	22.7	580.0 (63)
	C - C	22.4 (2.1)	28.3	37.3	13.5 (1.9)	17.0	22.4	789.5 (44)
Moderate	C1 - W - GS - C	22.2 (1.2)	35.2	49.3	13.3 (0.9)	21.1	29.6	631.0 (48)
	C - W - GS – C2	20.6 (1)	42.0	45.8	11.7 (0.7)	23.8	26.0	491.0 (26)
	C - W- GS	20.9 (0.9)	41.3	46.4	12.0 (0.8)	23.8	26.7	505.0 (57)
	C - W	22.3 (1.2)	39.1	49.6	13.4 (1)	23.5	29.8	571.0 (53)
	C - C	20.0 (2.9)	29.5	44.3	11.3 (1.9)	16.8	25.2	676.5 (62)
Deficit	C1 - W - GS - C	21.1 (2.3)	36.1	70.3	12.6 (1.6)	21.5	42.0	585.0 (51)
	C - W - GS – C2	20.0 (3.3)	41.9	66.7	11.7 (2)	24.4	38.9	477.0 (78)
	C - W- GS	20.2 (1.5)	40.8	67.3	11.8 (1.3)	23.7	39.2	495.0 (38)
	C - W	21.4 (3.3)	38.6	71.3	12.7 (2.2)	22.9	42.3	555.0 (76)
	C - C	15.7 (4.3)	29.3	52.3	9.2 (2.3)	17.1	30.5	534.5 (135)

C1, corn in the start of each rotation; C2, corn in the end of each rotation; W, wheat; GS, grain sorghum; WP_B and WP_G, are biomass and grain water productivity both in kg/ha/mm, respectively; IWUE_B and IWUE_G, are irrigation water use efficiency for biomass and grain yield, (kg/ha/mm), respectively; values in bracket are standard deviations

Table 10. Long-term (1950 – 2013) mean crop water productivity (B-WP and G-WP) (kg/ha/mm) and irrigation water use efficiency (IWUE_B and IWUE_G) (kg/ha/mm) for wheat under three levels of irrigation with the various rotation and continuous cropping system evaluated near Garden City Kansas

Irrigation level	Cropping system	Biomass (t/ha)	WP _B (kg/ha/mm)	IWUE _B (kg/ha/mm)	Grain (t/ha)	WP _G (kg/ha/mm)	IWUE _G (kg/ha/mm)	ET (mm)
Full	C - W - SG - C	14.8 (1.2)	25.9	49.3	5.5 (0.5)	9.7	18.5	572.0 (34)
	C - W- GS	15.0 (1.1)	27.8	50.0	5.7 (0.7)	10.6	19.0	539.0 (32)
	C - W	11.4 (2)	20.3	38.0	5.5 (0.8)	9.8	18.3	562.0 (39)
	W - W	12.4 (1.9)	24.2	41.5	4.2 (1)	8.2	14.0	514.0 (39)
Moderate	C - W - SG - C	9.4 (1.7)	18.1	37.6	2.8 (0.6)	5.4	11.2	520.0 (55)
	C - W- GS	14.6 (1.2)	28.5	58.4	5.8 (0.7)	11.2	23.0	513.0 (46)
	C - W	13.1 (1.2)	22.7	52.4	4.5 (0.7)	7.8	18.0	576.0 (58)
	W - W	10.9 (1.8)	21.8	43.6	3.6 (0.9)	7.1	14.2	500.0 (40)
Deficit	C - W - SG - C	7.5 (2.8)	15.4	37.5	2.1 (0.8)	4.2	10.3	487.0 (82)
	C - W- GS	8.9 (1.5)	18.3	44.3	2.5 (0.7)	5.2	12.7	483.0 (48)
	C - W	8.9 (2.2)	17.5	44.5	2.4 (1)	4.7	12.0	508.0 (54)
	W - W	9.9 (1.9)	20.3	49.4	3.1 (1)	6.4	15.5	487.0 (44)

C1, corn in the start of each rotation; C2, corn in the end of each rotation; W, wheat; GS, grain sorghum; WP_B and WP_G, are biomass and grain water productivity both in kg/ha/mm, respectively; IWUE_B and IWUE_G, are irrigation water use efficiency for biomass and grain yield, (kg/ha/mm), respectively; values in bracket are standard deviations.

Table 12. Long-term (1950 – 2013) mean crop water productivity (B-WP and G-WP) (kg/ha/mm) and irrigation water use efficiency (IWUE_B and IWUE_G) (kg/ha/mm) for grain sorghum under three levels of irrigation with the various rotation and continuous cropping system evaluated near Garden City Kansas

Irrigation level	Cropping system	Biomass (t/ha)	WP _B (kg/ha/mm)	IWUE _B (kg/ha/mm)	Grain (t/ha)	WP _G (kg/ha/mm)	IWUE _B (kg/ha/mm)	ET (mm)
Full	C - W - SG - C	17.9 (1)	36.9	44.8	7.0 (0.8)	14.4	17.5	485.0 (45)
	C - W- GS	18.6 (1)	37.3	46.5	7.6 (0.8)	15.1	18.9	499.0 (48)
	GS - GS	17.3 (1)	36.8	43.3	6.5 (0.5)	13.7	16.1	469.5 (36)
Moderate	C - W - SG - C	17.8 (1)	36.1	59.2	6.9 (0.7)	14.0	23.0	492.0 (49)
	C - W- GS	18.6 (1)	38.2	62.0	7.6 (0.8)	15.6	25.3	487.0 (48)
	GS - GS	17.1 (1)	36.7	57.0	6.4 (0.7)	13.6	21.2	466.5 (32)
Deficit	C - W - SG - C	17.4 (2.4)	37.8	87.0	6.7 (1.4)	14.6	33.5	460.0 (64)
	C - W- GS	18.1 (1.2)	38.2	90.5	7.2 (0.9)	15.1	35.9	474.0 (53)
	GS - GS	17.1 (1.1)	36.8	85.5	6.3 (0.8)	13.5	31.5	464.5 (31)

C, corn; W, wheat; GS, grain sorghum; WP_B and WP_G, are biomass and grain water productivity both in kg/ha/mm, respectively; IWUE_B and IWUE_G, are irrigation water use efficiency for biomass and grain yield, (kg/ha/mm), respectively; values in bracket are standard deviations

Fig. 1. Long-term (1950 – 2013) mean monthly rainfall versus reference evapotranspiration for Garden City, Kansas. The ETo was estimated using Hargreaves equation as presented in Allen et al. (1998).

Fig. 2. Simulated versus measured grain yield for corn, wheat and grain sorghum (horizontal bars are standard deviations) grown in Kansas State University, Southwestern Research-Extension Center Kansas near garden city.

Fig. 3. Simulated versus measured biomass for corn, wheat and grain sorghum (horizontal bars are standard deviations) grown in Kansas State University, Southwestern Research-Extension Center Kansas near garden city.

Fig. 4. Simulated versus measured evapotranspiration (ET) for corn, wheat and grain sorghum (horizontal bars are standard deviations) grown in Kansas State University, Southwestern Research-Extension Center Kansas near garden city.

Fig. 5. The long-term (1950 – 2013) mean seasonal evapotranspiration (ET) for the cropping system under full, moderate and deficit irrigation. C, corn; W, wheat; SG, grain sorghum.

Cropping system and irrigation levels

Fig. 6. Percent of change in corn yield and biomass as affected by rotation cropping system and irrigation levels (full, moderate and deficit) when compared to the continuous cropping of corn grown under the respective irrigation levels. C, corn; C2 is corn after grain sorghum; W, wheat; SG, grain sorghum.

Fig. 7. Percent of change in wheat yield and biomass as affected by rotation cropping system and irrigation levels (full, moderate and deficit) when compared to the continuous cropping of wheat grown under the respective irrigation levels. C, corn; W, wheat; SG, grain sorghum.

Cropping system and irrigation levels

Fig. 8. Percent of change in grain sorghum yield and biomass as affected by rotation cropping system and irrigation levels (full, moderate and deficit) when compared to the continuous cropping of grain sorghum grown under the respective irrigation levels. C, corn; W, wheat; SG, grain sorghum.

Fig. 9. Percent of change in corn IWUE_B and IWUE_G as affected by rotation cropping system and irrigation levels (full, moderate and deficit) when compared to the continuous cropping of corn grown under the respective irrigation levels. C, corn; C2 is corn after grain sorghum; W, wheat; SG, grain sorghum; IWUE_B and IWUE_G are irrigation water use efficiency for biomass and grain, respectively.

Fig. 10. Percent of change in wheat IWUE_B and IWUE_G as affected by rotation cropping system and irrigation levels (full, moderate and deficit) when compared to the continuous cropping of wheat grown under the respective irrigation levels. C, corn; W, wheat; SG, grain sorghum; IWUE_B and IWUE_G are irrigation water use efficiency for biomass and grain, respectively.

Cropping system and irrigation level

Fig. 11. Percent of change in grain sorghum $IWUE_B$ and $IWUE_G$ as affected by rotation cropping system and irrigation levels ((full, moderate and deficit) when compared to the continuous cropping of grain sorghum grown under the respective irrigation levels. C, corn; W, wheat; SG, grain sorghum; $IWUE_B$ and $IWUE_G$ are irrigation water use efficiency for biomass and grain, respectively.