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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.

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 <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

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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 (Boote et al., 2010; Li et al., 2015; Araya 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 Finnup farm near Garden City, Kansas with geographical location of 38°01′20.87″N, 100°49″26.95 W 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 ago-climactic class of the study area is categorized as semi-arid with long-term mean annual rainfall and reference evapotranspiration (ETo) of 477 and 1810 mm, respectively (Klocke et al., 2011). The long-term (1950–2013) seasonal (May to Oct.) average rainfall and ETo are 349 and 962 mm, respectively. The long-term mean monthly rainfall and ETo 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 × 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, 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).

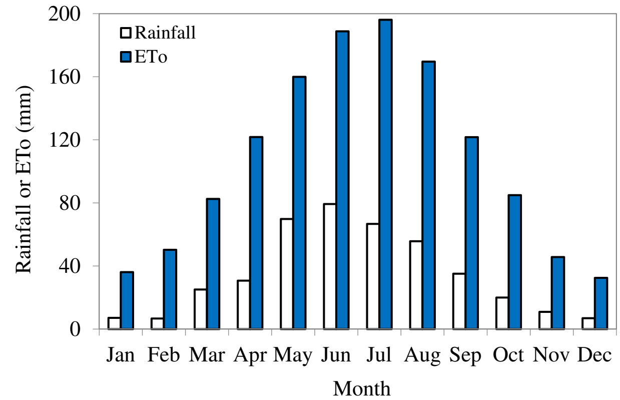

Fig. 1. Long-term (1950–2013) mean monthly rainfall versus reference evapotranspiration for Garden City, Kansas. The ETo was estimated using Hargreaves equation as presented in Allen et al. (1998).

2.3. Data collection

Soil water was measured using neutron attenuation (Evett 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 runon 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

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