ASSESSMENT OF DEFICIT IRRIGATION STRATEGIES FOR COTTON PRODUCTION IN THE TEXAS HIGH PLAINS

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Abstract

Texas High Plains (THP) is an important agricultural region in the United States and it contributes to about 25% of the US cotton (*Gossypium hissutum* L.) production. Production of cotton in the THP region depends mainly on irrigation with groundwater from the underlying Ogallala Aquifer. However, rapidly declining groundwater levels in the aquifer and increasing pumping costs pose challenges for sustainability of irrigated cotton production in this region. In addition, climate change studies from this region project warmer and drier summers in the future, which necessitate larger groundwater withdrawals to meet the higher evapotranspiration demand of cotton. Irrigation planning is further complicated by inconsistent seasonal rainfall patterns. The main objective of this study was to assess the sensitivity of cotton crop to water stress during five critical growth stages and identify appropriate crop-growth-stage-based deficit irrigation strategies for maximizing irrigation water use efficiency (IWUE) and cotton yield during 1978-2016 using the CROPGRO-Cotton module available in the Decision Support System for Agrotechnology Transfer (DSSAT) Cropping System Model (CSM). Critical cotton growth stages considered in this study include: i) germination and seedling emergence, ii) squaring, iii) flower initiation/early bloom, iv) peak bloom, and v) cutout, late bloom and boll opening stage. The amount of seasonal irrigation water applied under seven different irrigation scenarios varied from 120 to 600 mm with three different irrigation application rates of 3, 6 and 10 mm/day, and a total of six treatments (5 treatments in which irrigation was turned off in one of the five critical growth stages and the sixth treatment in which irrigation was applied during all critical growth stages) were implemented, resulting in a total of 42 treatments. The DSSAT-CSM-CROPGRO-Cotton model was previously calibrated using measured data from 27 treatments in a cotton IWUE field experiment at Halfway, Texas over a period of four years (2010-2013). The simulated results from this study revealed that water deficit imposed during initial stages of growth (germination and seedling emergence) or after the peak bloom stage did not contribute much towards increasing IWUE and cotton yield. Water stress during peak bloom growth stage caused greater losses in cotton yield and IWUE, because of the high demand of water in this stage. The IWUE declined and no substantial improvement in cotton yield was simulated with high irrigation (600 mm). The recommendations from this study are useful to producers to optimize the application of limited available irrigation water and maximize cotton yield and profit.

Introduction

Cotton (*Gossypium hissutum* L.) is the most important fiber crop for the textile industry, and it accounts for over 40% of total world fiber production. The Texas High Plain (THP) region in the west Texas is one of the major cotton producing regions, contributing about 64% and 25% of the Texas and USA cotton production, respectively (USDA, 2012). More than 90% of the irrigation water in the THP is pumped from the Ogallala Aquifer, a major groundwater source for the THP region (Allen et al., 2008). Water accessible from this aquifer prompted an agricultural revolution in the area and aided in building the economy. Because of redundant pumping of groundwater for irrigation, yearly withdrawal has outpaced natural recharge, resulting in a rapid depletion of the groundwater levels and increase in ground water pumping cost (Colaizzi et al., 2009; Chaudhuri and Ale, 2014a, b), which pose challenges for sustainability of irrigated cotton production in this region. The climate change studies for this region (Adhikari et al. 2016; Modala et al., 2017) also project warmer and drier summers in the future, which necessitate more withdrawals of groundwater to meet the higher crop evapotranspiration needs. Konikow (2013) reported that the water available from the Ogallala Aquifer has reduced by about 50% since the starting of large-scale irrigation for increased irrigated crop production in the THP. To prolong the usable lifetime of the Ogallala aquifer, the Underground Water Conservation Districts (UWCDs) in the THP region have started imposing restrictions on the groundwater pumping for irrigation purposes to ensure certain desirable future conditions (DFCs) (HPWD, 2015). The High Plains Water District set the annual allowable groundwater pumping for irrigation at 46 cm (18" or 1.5 acre-feet per contiguous acre). It is therefore essential to develop and adopt efficient irrigation strategies for sustaining irrigated cotton production in this region.

Cotton fiber quality, and the size and number of bolls are affected by timing and amount of irrigation (Ritchie et al., 2009, Sharma et al., 2015; Schaefer et al. 2018). Gowda et al. (2006) studied the irrigation water allocation for cotton crop in THP and suggested that in case of limited availability of irrigation water, the efficiency of water allocation can be increased by optimally allocating water among different growth stages of the crop. The response of crop to irrigation also depends on distribution and amount of precipitation during the growing season. Several studies have also shown that prolonged water deficit during the cotton cultivation cycle affects growth, productivity and quality of the fiber (Snowden et al., 2013). However, there are differences in opinions of researchers regarding the most sensitive cotton growth stage. Reddell et al. (1987) affirmed that onset of flowering period is the most sensitive stage to water deficit in cotton, while Orgaz et al. (1992) reported that the peak flowering period is the most sensitive stage to water stress. Several researchers investigated the effect of irrigation scheduling in different growth stages on cotton yield and reported large yield reduction when water deficits occurred during the early and peak flowering periods compared to earlier or later in the growing season (Buttar et al., 2007; Snowden et al., 2013; Bordovsky et al., 2015).

Sensitivity of cotton to water stress therefore changes according to crop growth stage. Excessive water deficit stress during critical growth stages can have a substantial negative impact on crop yield. Identification of critical crop growth stages and application of limited amount of available irrigation water accordingly could potentially enhance IWUE while maintaining/improving crop yields. Long-term studies are necessary for making appropriate recommendations for the THP region. The CROPGRO-Cotton module within the Decision Support System for Agrotechnology Transfer (DSSAT) Cropping System Model (CSM), which can rapidly and inexpensively simulate crop responses to irrigation management, is very useful for this purpose. Present study was carried out to assess the sensitivity of cotton crop to water stress during different crop growth stages in order to identify critical growth stages for irrigation application using the CROPGRO-Cotton module in the DSSAT CSM. In addition, efforts were made to suggest efficient crop-growth-stage-based deficit irrigation strategies for cotton under limited irrigation water availability.

Materials and Methods

Study area and Data description: The THP region consists of 41 counties in northwest Texas (Figure 1). The THP region is one of the most intensive agricultural areas in the United States. This region is characterized as a treeless, windy flat semi-arid region. Major crops grown in this region other than cotton includes sorghum (*Sorghum bicolor* L.), winter wheat (*Triticum aestivum* L.) and corn (*Zea mays* L.). The annual precipitation in the region ranges from about 36 cm in the west to 61 cm in the east. Most of the precipitation in the THP occurs during the months of May and September (Allen et al., 2008). The Ogallala Aquifer, which underlies all THP counties, is the major source of irrigation water for this region. Center pivot irrigation is the most common method of irrigation in the THP.

In this study, previously evaluated DSSAT CSM CROPGRO-Cotton model (Adhikari et al., 2016) was used. The model was initially evaluated using the field data from 27 treatments in a cotton irrigation water use efficiency field experiment at the Texas A&M AgriLife Research Center at Halfway, Texas (34°10' N, 101°56' W; elevation 1075 m) over a period of four years (2010-2013). The treatment factors in the field experiment were in-season irrigation capacity (0 mm/day, Low (L); 3.2 mm/day, Medium (M); and 6.4 mm/day, High (H)) and irrigation application within three specific growth stage namely, vegetative, reproductive and maturation stage by the low energy precision application (LEPA) center pivot irrigation system (Bordovsky et al., 2015). The climate at the study site is semi-arid and the soil is deep well-developed Pullman clay loam. The weather data (precipitation (mm), maximum and minimum air temperature (°C), wind speed (ms^{-1}), solar radiation (MJm^{-2}) and relative humidity (%)) for the period of 1977 to 2016 was obtained from the Texas High Plains Evapotranspiration Network (TXHPET) (Porter et al., 2005) weather station at Halfway, TX. The crop management data were obtained from cotton IWUE field experiment at Halfway (Bordovsky et al., 2015).

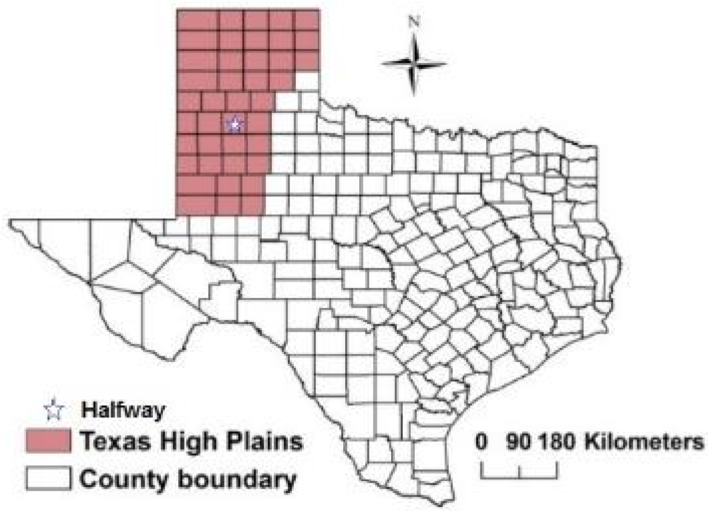

Figure 1. Study area location map

Crop-growth-stage-based Deficit Irrigation Strategies: Five critical growth stages of cotton were identified during the entire cycle of growth period based on recommendations by various researchers (Oosterhuis, 1990; Ritchie et al., 2007; Perry et al., 2012) (Table 1). Irrigation was applied within the specified days after planting (DAP) listed in Table 1 by considering the irrigation requirement during different growth stages. The amount of seasonal irrigation water applied under seven different irrigation scenarios varied from 120 to 600 mm with three different irrigation application rates of 3, 6 and 10 mm/day (Scenario-I: 120 mm applied @ 3 mm/d on 40 days during the growing season; Scenario-II: 180 mm, 3 mm/d, 60 days; Scenario-III: 240 mm, 3 mm/d, 80 days; Scenario-IV: 240 mm, 6 mm/d, 40 days; Scenario-V: 360 mm, 6 mm/d, 60 days; Scenario-VI: 480 mm, 6 mm/d, 80 days; Scenario-VII: 600 mm, 10 mm/d, 60 days). Under each irrigation scenario, six treatments were considered. Out of these six treatments, irrigation was skipped in a particular growth stage in five treatments, and irrigation was applied in all growth stages in the sixth treatment.

Table 1. Growth stages of cotton considered for irrigation strategy

Growth Stages of Cotton	Days after planting (DAP)	Irrigation requirement
1. Germination and Seedling Emergence	3 to 12	Low
2. Squaring	32 to 51	Low
3. Flower initiation/ Early Bloom	52 to 76	Moderate
4. Peak Bloom	77 to 106	High
5. Cutout, Late Bloom and Boll Opening	108 to 132	Moderate

DSSAT-CSM model description and simulations: The DSSAT CSM can simulate crop growth, development and yield in response to variability in weather conditions, soil properties and management practices (Jones et al., 2003; Hoogenboom et al., 2012; Thorp et al., 2014). The latest version of DSSAT contains over 42 different crop growth simulation models for fiber, cereals, legumes, oil, fruit, sugar, vegetables, and forage crops (Hoogenboom et al., 2015). The DSSAT CSM can expand the knowledge gleaned from field experiments by simulating crop responses under a broader set of experimental conditions. The DSSAT CROPGRO-Cotton module has been extensively used by researchers worldwide for various applications (Buttar et al., 2007; Thorp et al., 2014; Modala et al., 2015; Adhikari et al., 2016, 2017; Mauget et al., 2017; Amin et al., 2018). In the present study, long-term (1978-2016) simulations were performed using previously evaluated DSSAT CSM CROPGRO-Cotton model (Adhikari et al., 2016) to assess the effect of water stress during different crop growth stages on cotton irrigation water use efficiency (IWUE) and seed cotton yield. The following flow chart shows the methodology adopted in this study (Figure 2).

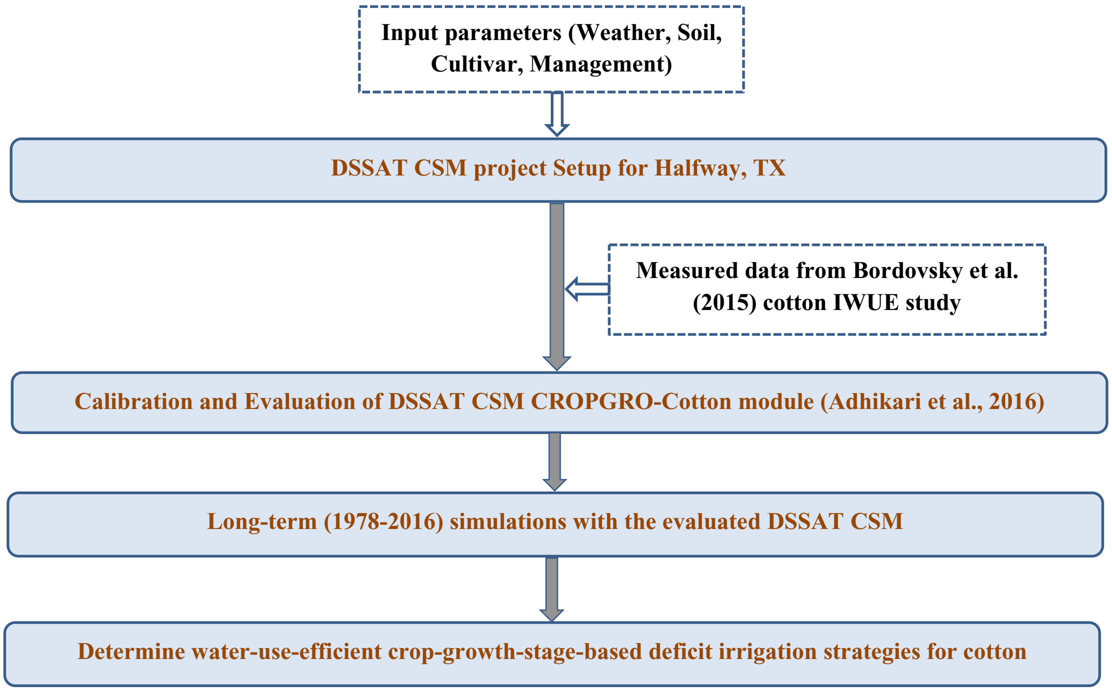

Figure 2. Flow chart showing the methodology adopted in this study

<u>Results and Discussion</u>

The simulated average (1978-2016) cotton yield and IWUE under different crop-growth-stage-based deficit irrigation strategies are presented in Figures 3 and 4, respectively. A substantial difference in simulated results were observed under different treatment plans due to varying response of cotton to water stress at different stages of the crop growth. Water stress during certain cotton growth stages caused severe effect on physiological processes, with consequent loss in yield and IWUE. When the water deficit was imposed in the initial stages of growth (germination and seedling emergence) or after the peak bloom stage, the reduction in simulated cotton yield was small (Figure 3). Early season irrigation water applications during germination and seedling emergence stages can be lost via evaporation or result in undesirable excessive plant growth, and hence do not contribute towards increasing IWUE and/or cotton yield. Similarly, as there is no reproductive structure after the peak bloom i.e., during cutout, late bloom and boll opening growth stage, water stress during this growth stage has also caused less effect on IWUE and cotton yield. Water stress during peak bloom growth stage caused greater losses in cotton yield and IWUE, because of the high demand for water in this phase due to growth and development of most of the reproductive structures. Water scarcity during peak bloom stage, in general, increases shedding (dropping of flower buds), reduces boll retention and flowering rate. However, skipping irrigation during peak bloom stage in case of high seasonal irrigation (Scenario VI and VII) had less effect on cotton yield and IWUE, because of availability of sufficient moisture from irrigation in previous stages (Figure 3).

The IWUE declined and not much improvement in seed cotton yield was simulated with high seasonal irrigation (Scenario-VII: 600 mm irrigation water applied with irrigation intensity of 10 mm/d for 60 days) compared to the Scenario-VI in which 120 mm less irrigation water was applied. This indicates that excess irrigation (> 480 mm) during cotton growth cycle may not contribute to increasing seed cotton yield and IWUE, because of excess soil moisture as compared to evapotranspiration needs. The IWUE of cotton was found to be the highest under scenario-V (360 mm irrigation water applied with irrigation intensity of 6 mm/d for 60 days), except for the T4 treatment (absence of irrigation during peak bloom) among all crop-growth-stage-based deficit irrigation strategies. Interestingly, the simulated IWUE of treatments 1 to 3 under scenario-III (240 mm irrigation water applied with irrigation intensity of 3 mm/d for 80 days) was comparable to scenario-V (360 mm irrigation water applied with irrigation intensity of 6 mm/d for 60 days). Also, applying 240 mm of irrigation water with irrigation intensity of 3 mm/d over 80 days (Scenario-III) resulted in higher cotton yield and IWUE as compared to applying 240 mm of irrigation water with irrigation intensity of 6 mm/d over 40 days (Scenario-IV), this might be due to the reason that supplying small amount of water for limited period resulted in less water stress during most of the time within the crop growth cycle.

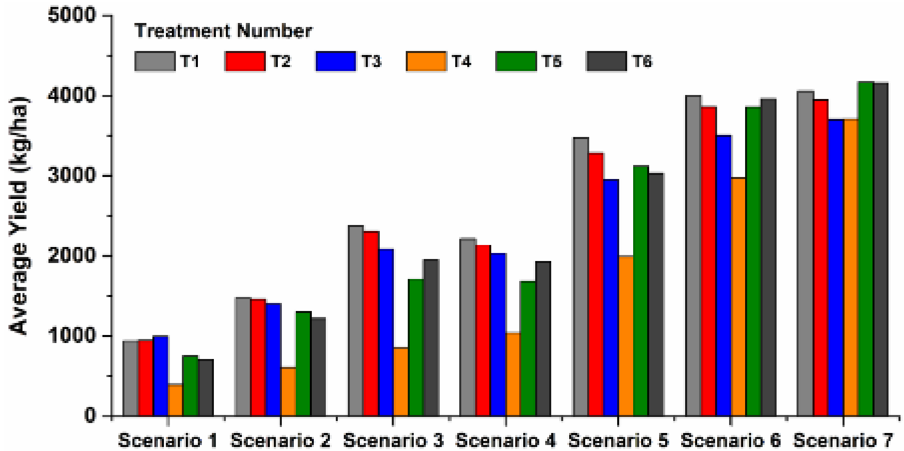

Figure 3. Simulated average (1978-2016) seed cotton yield

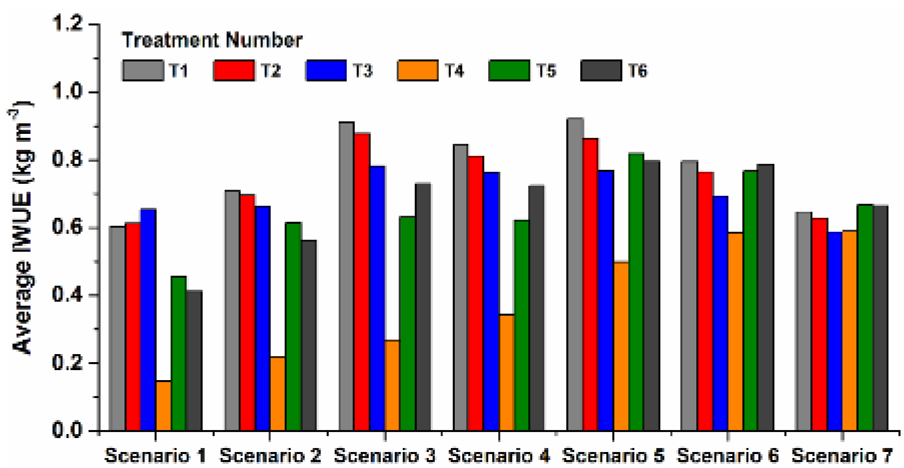

Figure 4. Simulated average (1978-2016) irrigation water use efficiency

Summary

Proper implementation of crop-growth-stage-based deficit irrigation strategies can result in substantial savings in irrigation water use. Decrease in simulated cotton yield was found to be less severe under water deficit condition during the first (germination and seedling emergence) and last growth stages (cutout, late bloom and boll opening). Water deficit during the peak bloom growth stage caused greater losses in simulated cotton yield, because of the high demand for water in this stage. Therefore, it is recommended to ensure the irrigation application at the peak bloom growth stage even in case of limited availability of irrigation water. The IWUE of cotton was found to be the highest under scenario-V (360 mm irrigation water applied with irrigation intensity of 6 mm/d for 60 days) among all crop-growth-stage-based deficit irrigation strategies. The IWUE declined and no substantial improvement in seed cotton yield was simulated with high seasonal irrigation (Scenario-VII: 600 mm irrigation water applied with irrigation intensity of 10 mm/d for 60 days). Therefore, with careful irrigation planning, it appears to be feasible to achieve high seed cotton yields and IWUE while complying with the High Plains Water District pumping limits in THP.

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