DETERMINING OPTIMUM IRRIGATION TERMINATION PERIODS FOR COTTON PRODUCTION IN THE TEXAS HIGH PLAINS

S. Ale, N. Omani, S. K. Himanshu, J. P. Bordovsky, K. R. Thorp, E. M. Barnes

HIGHLIGHTS

- Irrigation water use efficiency was consistently higher under deficit irrigation as compared to full irrigation.
- Irrigation water use was always less than the annual allowable pumping limit under deficit irrigation.
- The first/second week of September was ideal for terminating irrigation under full/deficit irrigation in normal years.
- Ideal irrigation termination periods in wet/dry years were a week earlier/later than those in normal years.

ABSTRACT. *Cotton (*Gossypium hirsutum *L.) production in the Texas High Plains (THP) region relies heavily 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. Adoption of efficient irrigation strategies, such as terminating irrigation at an appropriate time in the growing season, could enable producers to increase irrigation water use efficiency (IWUE) while maintaining desired yield goals. The objective of this study was to determine optimum irrigation termination periods for cotton production in the THP under full and deficit irrigation conditions using the Decision Support System for Agrotechnology Transfer (DSSAT) CROPGRO-Cotton model, which was evaluated in a prior study in the THP using measured data from an IWUE field experiment at Halfway, Texas. The treatment factors in the field experiment included irrigation capacities of 0 mm d^{-1} (low, L), 3.2 mm d^{-1} (medium, M), and 6.4 mm d^{-1} (high, H), applied during the vegetative, reproductive, and maturation growth stages. This study focused on a full irrigation (HHH) treatment and three deficit irrigation (LMH, LHM, and LMM) treatments. Eight irrigation termination dates with a one-week interval between 15 August and 30 September were simulated, and the impact of irrigation termination date on cotton IWUE and seed cotton yield were studied by dividing the 39-year (1978 to 2016) simulation period into dry, normal, and wet years based on the precipitation received from 1 April to the simulated irrigation termination date. Results indicated that the simulated IWUE was consistently higher under the LHM, LMH, and LMM treatments when compared to the HHH treatment. Based on the simulated average seed cotton yield and IWUE, optimum irrigation termination periods for cotton were found to be the first week of September (about 118 days after planting, DAP) for the HHH and LMH treatments and the second week of September (125 DAP) for the LHM and LMM treatments in normal years. In wet years, optimum irrigation termination periods were a week earlier than those in normal years and a week later in dry years for the HHH, LHM, and LMM treatments. For the LMH treatment, the optimum irrigation termination period in wet years was the same as that in normal years and two weeks later in dry years. The results from this study along with field-specific, late-season information will assist THP cotton producers in making appropriate irrigation termination decisions for improving economic productivity of the Ogallala Aquifer and thereby ensuring water security for agriculture. However, the recommendations from this study should be used with caution, as the optimum irrigation termination periods could potentially change with changes in cultivar characteristics, soil type, climate, and, crop management practices.*

Keywords. *CROPGRO-Cotton, Deficit irrigation, DSSAT, Full irrigation, Irrigation water use efficiency, Seed cotton yield.*

Accounting for over 40% of total world fiber production, cotton (*Gossypium hirsutum* L.) is the most important fiber crop for the textile industry. China, India, and the U.S. together produce more than 50% of the world's cotton (Pathak et al., 2007). The U.S. is the leading exporter of raw cotton among major cotton-producing countries, accounting for over one-third of global trade (MacDonald, 2000). The Texas High Plains

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(THP) region in west Texas is one of the major cotton-producing regions in the U.S., contributing about 64% and 25% of the cotton production in Texas and the U.S., respectively (USDA, 2012). Cotton production in the THP relies heavily on irrigation water pumped from the underlying Ogallala Aquifer. Water accessible from this aquifer prompted an agricultural revolution in the area and aided in building the economy (Allen et al., 2008). However, groundwater withdrawal for irrigation has outpaced natural recharge, resulting in a rapid depletion of the groundwater levels and increases in groundwater pumping cost (Musick et al. 1988; Torell et al., 1990; Colaizzi et al., 2009; Scanlon et al., 2012; Chaudhuri and Ale, 2014a, 2014b). To ensure certain desirable future conditions, the Groundwater Conservation Districts in the THP region have started imposing restrictions on the amount of groundwater that non-exempt wells, including irrigation wells, are authorized to produce from the Ogallala Aquifer during each calendar year (HPWD, 2015). The High Plains Water District (HPWD) set the annual allowable groundwater production rate from non-exempt wells at 460 mm (18 in.). Climate change studies for this region have also projected warmer and drier summers in the future (Adams et al., 1998; Nielsen-Gammon, 2011; Adhikari et al. 2016; Modala et al., 2017), which will necessitate more withdrawals of groundwater to meet higher crop evapotranspiration needs. It is therefore essential to develop and adopt efficient irrigation strategies to prolong the usable lifetime of the Ogallala Aquifer and sustain cotton production in this important production region.

Cotton yield and fiber quality are affected by the timing and amount of rainfall and irrigation (Dumka et al., 2004; Ritchie et al., 2009; Snowden et al., 2013; Sharma et al., 2015; Schaefer et al., 2018). Most importantly, irrigation termination is a critical decision in cotton production. While early termination of irrigation can result in yield loss, late termination can waste valuable irrigation water without any yield increase, delay harvest, and increase pest management costs (Silvertooth, 2001; Tronstad et al., 2003; Vories et al., 2006). Irrigation termination decisions for cotton are a function of many variables, including expected lint yield and quality, market value, and irrigation costs (Lascano et al., 2017), and the decision should be made on a field-by-field basis by taking into account plant developmental stage, soil type, soil moisture status, type of irrigation system used, geographic location, boll load, and crop health (Dodds, 2011, 2014; Reba et al., 2012).

The ideal irrigation termination time in a given year is therefore heavily dependent on the environmental conditions in that year, mainly air temperature and the distribution and amount of precipitation during the cotton growing season. It is therefore useful to evaluate the effect of irrigation termination date on cotton irrigation water use efficiency (IWUE) and yield under full and deficit irrigation conditions over a long-term period to make general recommendations for the THP region. The CROPGRO-Cotton module within the Decision Support System for Agrotechnology Transfer (DSSAT) cropping system model (CSM) is suitable for this purpose. 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, 2015; Thorp et al., 2014). The DSSAT CSM CROPGRO-Cotton model has been extensively used by researchers worldwide for various applications (Buttar et al., 2007; Pathak et al., 2007; Ortiz et al., 2009; Pereira et al., 2009; Thorp et al., 2010, 2014; Modala et al., 2015; Adhikari et al., 2016, 2017; Mauget et al., 2017; Loison et al., 2017; Amin et al., 2018; Spivey et al., 2018).

The DSSAT CSM CROPGRO-Cotton model was previously evaluated for the THP region using measured data from cotton irrigation water use efficiency (IWUE) experiments conducted at Halfway, Texas, during 2010-2013 (Adhikari et al., 2016). The field experiments consisted of 27 treatments with three different levels of irrigation applied (maximums of 0 mm d^{-1} (low, L), 3.2 mm d^{-1} (medium, M), and 6.4 mm d^{-1} (high, H)) in three cotton growth stages (vegetative, reproductive, and maturation) by a low-energy precision application (LEPA) center-pivot irrigation system (Bordovsky et al., 2015). The evaluated model was used in this study to determine optimum irrigation termination periods for a full irrigation (HHH) treatment and three deficit irrigation (LMH, LMM, and LHM) treatments from the Bordovsky et al. (2015) field experiment. Only deficit irrigation strategies with low irrigation (L) application during the vegetative stage were considered in this study because Bordovsky et al. (2015) reported that the treatments that received low irrigation during the vegetative stage in their field experiment used up to 20% less seasonal irrigation water with minor (<2%) yield loss compared to the treatments that received medium irrigation. Specific objectives of this study were to use the DSSAT CSM CROPGRO-Cotton model to assess (1) the long-term (1978-2016) effects of irrigation termination date on cotton IWUE and seed cotton yield under simulated full and deficit irrigation conditions, (2) the annual irrigation water use with different irrigation termination dates under full and deficit irrigation conditions in relation to the HPWD's allowable groundwater pumping rate, and (3) the optimum irrigation termination periods for cotton production under full and deficit irrigation conditions during dry, normal, and wet years.

Materials and Methods

Cotton Water Use Efficiency Experiments at Halfway

The measured data for evaluating the DSSAT CROPGRO-Cotton model (Adhikari et al., 2016) and building the DSSAT projects for assessing the effects of irrigation termination dates on seed cotton yield and IWUE were obtained from the cotton IWUE experiments conducted at the Texas A&M AgriLife Research Center at Halfway (34° 10′ N, 101° 56′ W; elevation 1075 m) during the 2010-2013 growing seasons (Bordovsky et al., 2015). The soil at this site is Pullman clay loam (fine, mixed, super active, thermic Torrertic Paleustolls). The mean (1977-2016) annual and growing season (from 1 May to 30 September) rainfall was 463 and 300 mm, respectively. The months from October to February are generally dry, and the months of March, April, and May are the windiest (Adhikari et al., 2016).

The treatment factors in the Bordovsky et al. (2015) experiment consisted of three in-season maximum irrigation capacities of 0 mm d^{-1} (L), 3.2 mm d^{-1} (M), and 6.4 mm d^{-1} (H) that were applied in three irrigation periods (P1, P2, and P3), which resulted in 27 treatments. The treatments were identified with letters representing the irrigation capacities during the P1, P2, and P3 irrigation periods. For example, the nine treatments with the lowest irrigation capacities in period P1 were LLL, LLM, LLH, LML, LMM, LMH, LHL, LHM, and LHH. The other 18 treatments (with the lowest irrigation capacities in P2 and P3) were similarly identified. The three irrigation periods were defined based on the accumulated growing degree days (GDD) at a threshold temperature of 15.6°C, and they were generally associated with the early vegetation/juvenile (P1; <525 GDD), reproductive (P2; 525 to 750 GDD), and maturation (P3; >750 GDD) periods of cotton development. Irrigation water was applied during the designated irrigation periods in each of the 27 treatment plots at the respective maximum rates (L, M, or H) according to a soil water balance method that allowed increases in estimated soil profile water up to 80% of field capacity. For example, the lowest irrigation treatment (LLL) received 0 mm d^{-1} of irrigation (L) in all three periods, and the highest irrigation treatment (HHH) received 6.4 mm d^{-1} of irrigation (H) in all three periods. Rain events reduced or terminated irrigations within a treatment if the estimated profile water was above the specified target water content for that day. The planting dates varied from 9 to 13 May, and conventional tillage was adopted. Additional details about these experiments are provided by Bordovsky et al. (2015).

DSSAT CSM CROPGRO-Cotton Model

The CROPGRO-Cotton module distributed with the DSSAT model was used. DSSAT integrates the database management system (soil, climate, and management practices) and crop models with various application programs (Jones et al., 2003). It brings together 42 individually developed crop models in a single platform. DSSAT version 4.7 (Hoogenboom et al., 2015) was used in the current study. The CSM-CROPGRO-Cotton model simulates cotton growth and yield as well as soil water, carbon, and nitrogen processes over time based on weather, soils, crop management, and crop cultivar information. The model also estimates the onset dates of various crop development stages based on photothermal unit accumulation from planting to harvest, such as emergence, first leaf, first flower, first seed, first crack boll, and 90% open boll. It also calculates flower and fruit numbers.

The CSM-CROPGRO-Cotton model requires various soil parameters as inputs, including soil texture, slope, albedo, color, drainage, drained upper limit, lower limit, saturated water content, hydraulic conductivity, organic carbon content, bulk density, and total soil nitrogen. Required crop management parameters include type of irrigation, irrigation dates and amounts, fertilizer application dates and method, fertilizer amount, tillage type, tillage depth and dates, planting date and method, seedling depth, plant population, row spacing, harvesting method and date, and cultivar variety. Environmental variables such as daily maximum and minimum temperature, incoming solar radiation, and precipitation are also required inputs for the model, while dew point temperature and wind speed are optional. More details about the model inputs for this study are provided by Adhikari et al. (2016).

Model Evaluation

The CSM-CROPGRO-Cotton model was evaluated using the data collected from cotton IWUE experiments conducted at Halfway (Adhikari et al., 2016). Observed data from four irrigation treatments (HHH, HHM, MHH, MHM), which represented well-watered and slightly water-limited conditions, over a period of four years from 2010 to 2013 (a total of 16 treatment-years) were used for model calibration. Observed data from the remaining 23 treatments over the 2010-2013 period (a total of 92 treatment-years) were used for model evaluation (Adhikari et al., 2016). The model was evaluated for prediction of dates of various cotton phenological stages and seed cotton yield. The evaluated model did an excellent job in responding to the various irrigation strategies implemented in the 27 treatments over four growing seasons with varying amounts and distribution patterns of precipitation. Simulated onset dates of different cotton growth stages, including emergence, anthesis, and physiological maturity, were within the range of generally observed onset dates in the study area. A good agreement between measured and simulated seed cotton yields was achieved after model calibration and evaluation, as indicated by several model performance statistics, as recommended by Moriasi et al. (2007) and Harmel et al. (2014) (table 1). The average percent error in seed cotton yield prediction was 0.1% during calibration and 6.5% during evaluation (table 1). More details about the model evaluation are provided by Adhikari et al. (2016).

Determination of Optimum Irrigation Termination Periods for Cotton

Weather data on precipitation (mm), minimum and maximum air temperature (°C), solar radiation (MJ m^{-2}), wind speed (m s^{-1}), and relative humidity (%) for the period from 1977 to 2016 were obtained from weather measurements at the Texas A&M AgriLife Research Center, Halfway, Texas. Long-term simulations were then run from 1977 to 2016 with eight irrigation termination dates at one-week intervals from 15 August to 30 September. Based on the dates adopted in the field experiments, planting and emergence dates were assumed as 11 May and 20 May, respectively, and the starting date for the P1 irrigation period and the end date for the P3 irrigation period were assumed as 15 June and 6 September, respectively, for all years. For each year, end dates of irrigation periods P1 and P2 were determined based on the estimated GDD accumulation (table 2) following the approach of Bordovsky et al. (2015). Irrigation was then ap-

Table 1. Performance statistics obtained during model calibration and evaluation (Adhikari et al., 2016).

Performance Statistic	Calibration	Evaluation
Coefficient of determination (R^2)	0.94	0.94
Root mean square error (RMSE, kg)	292	481
Relative RMSE (RRMSE, %)	9.0	21.0
Average percent error (PE, %)	0.1	6.5
Index of agreement (d)	0.90	0.83

Table 2. Heat unit accumulation in growing degree days (GDD) at threshold temperature of 15.6°C during the simulated cotton irrigation periods at Halfway, Texas, during 1978-2016. Dates shown in parentheses indicate the end dates of irrigation periods P1 and P2.

Year	Emergence to Start of P1	Emergence through P1	Emergence through P2	Emergence through P3	Emergence through 30 September
1978	185.7	518.5 (15 July)	742.9 (10 August)	961.6	1060
1979	145.7	519 (21 July)	740.6 (13 August)	956.9	1067.1
1980	222.9	518.5 (9 July)	746.5 (31 July)	1097.6	1221
1981	195.9	515.1 (19 July)	747.9 (15 August)	898.2	992.9
1982	143.9	521.6 (30 July)	743 (23 August)	886	1000.5
1983	104.5	523.1 (30 July)	747.1 (23 August)	905.3	1036.7
1984	184.7	522.9 (25 July)	742 (22 August)	882.7	1001.2
1985	219.4	514.2 (16 July)	749.1 (7 August)	1076.3	1171.8
1986	148.9	521.1 (25 July)	745.4 (15 August)	915.5	1065.6
1987	129.1	522.2 (31 July)	746.4 (29 August)	792.7	865.2
1988	145.7	518.3 (26 July)	743.7 (17 August)	874.4	983.1
1989	173	515.8 (19 July)	744.4 (15 August)	962.8	1003.9
1990	273.2	515.6 (6 July)	744.2 (4 August)	1058.5	1173.6
1991	212.9	524.9 (18 July)	747.8 (14 August)	940.2	997.1
1992	96.3	520.6 (30 July)	749 (28 August)	824.6	931
1993	204.3	523.2 (17 July)	740.7 (8 August)	982.6	1082.7
1994	254.7	516.8 (6 July)	747.8 (28 July)	1092.2	1202.5
1995	158.1	524.8 (24 July)	742.4 (18 August)	930.7	991.5
1996	203.2	519.6 (17 July)	743.1 (10 August)	986.7	1108.6
1997	132.5	523.9 (27 July)	750 (22 August)	901.3	1032.9
1998	225.4	523.6 (9 July)	739.5 (28 July)	1107.2	1273.2
1999	168.4	523.3 (23 July)	744 (13 August)	997.7	1074
2000	224	520.4 (17 July)	743.6 (8 August)	1041.2	1163.4
2001	214.7	515.5 (14 July)	743.8 (1 August)	1068.8	1171.2
2002	201.1	519.9 (20 July)	747.4 (12 August)	979.2	1063.2
2003	151.7	517.9 (24 July)	749.4 (14 August)	933.8	1020
2004	220.1	522.9 (21 July)	746.5 (24 August)	817.3	909.7
2005	195.3	522.7 (20 July)	743.6 (18 August)	891.6	1032.6
2006	279.9	513.5 (12 July)	747.8 (2 August)	1033.5	1101.8
2007	149.3	518 (30 July)	742.8 (23 August)	861.4	988.1
2008	268.2	521.2 (15 July)	741.8 (6 August)	963	1014.2
2009	170.5	521.5 (22 July)	743.7 (16 August)	916.2	978.9
2010	248.1	516.2 (16 July)	744.8 (10 August)	978.6	1123.1
2011	267.9	523.4 (7 July)	748.4 (25 July)	1253.2	1360.8
2012	222.7	520.9 (13 July)	738.2 (2 August)	1078.9	1158.3
2013	221.5	518.2 (18 July)	745.8 (11 August)	986.7	1105.7
2014	185.1	524.4 (23 July)	747.7 (17 August)	946.1	1040.6
2015	162.1	515.3 (23 July)	743.9 (13 August)	960.2	1119.7
2016	196.8	518.2 (12 July)	749.1 (1 August)	1052.6	1163.3

plied on each day of the year from the start date of P1 to the end date of P3. Depending on the treatment, irrigation was applied at one of three specified application rates of 0 mm d-1 (L), 3.2 mm d-1 (M), and 6.4 mm d^{-1} (H) in each of the irrigation periods. On rainy days, irrigation was either eliminated (when rainfall amount ≥ maximum irrigation capacity) or reduced by the difference between the maximum irrigation capacity and the rainfall received (when rainfall amount ≤ maximum irrigation capacity). If irrigation in the simulated experiment was terminated before the last date of irrigation in the field experiment (i.e., end date of irrigation period P3, 5 September), the actual amounts of irrigation water applied in the field experiment on all the dates after the simulated termination date were removed. Similarly, if irrigation in the simulated experiment was terminated after the last date of irrigation in the field experiment, additional amounts of irrigation water were applied until the simulated termination date according to the rates specified for the HHH, LHM, LMH, and LMM treatments.

The first year of simulation (1977) was used as a model warmup period and hence excluded from the analysis (Daggupati et al., 2015). The environmental impacts of growing season on cotton IWUE and yield under different irrigation termination dates were then studied by dividing the remaining 39-year simulation period into dry, normal, and wet years according to precipitation received from 1 April to the simulated termination date during the growing season (fig. 1). After sorting the 39 years based on the growing season precipitation, the 13 years that received the lowest precipitation were classified as “dry” years, and the 13 years with the highest precipitation were classified as “wet” years. Thirteen years that did not fall into either of the above categories were considered “normal” years. Recommendations for optimum irrigation termination periods for cotton production in the THP in dry, normal, and wet years under full (HHH) and deficit (LHM, LMH, and LMM) irrigation conditions were then made based on the simulated average IWUE and seed cotton yield while keeping in view the HPWD’s annual groundwater pumping limit for irrigation, which is currently 460 mm (18 in.). Based on the simulated seed cotton yield, a termination date was considered ideal if the increase in average seed cotton yield from that termination date to the next termination date was <5%. Similarly, based on the IWUE, a termination date was considered ideal if the increase in average IWUE from that termination date to the next termination date was <5%.

In this study, the IWUE (kg m^{-3}) was estimated using the following equation:

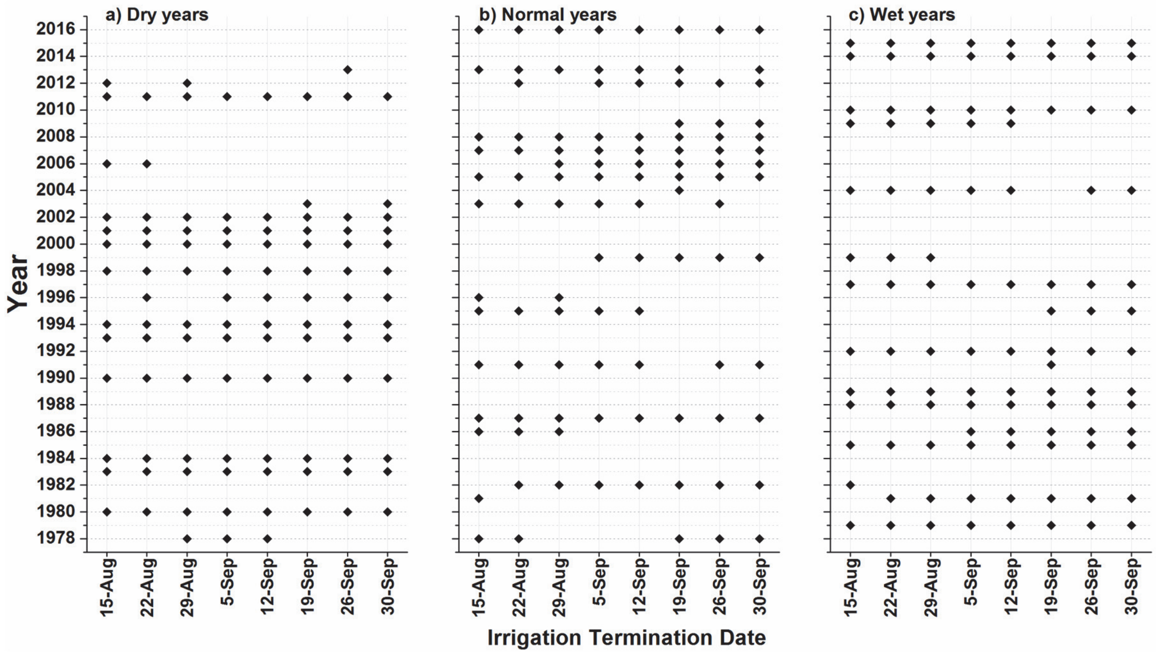

Figure 1. Classification of simulation period (1978-2016) into (a) dry, (b) normal, and (c) wet years based on accumulated precipitation during the growing season (from 1 April to the simulated irrigation termination date) at Halfway, Texas. For example, 1982 was classified as a normal year for all irrigation termination dates except 15 August, for which it was classified as a wet year.

$$\text{IWUE} = \frac{\left(Yield_{irr} - Yield_{dry}\right)}{Irrigation} \quad (1)$$

where

$Yield_{irr}$ = irrigated seed cotton yield (kg ha^{-1})
$Yield_{dry}$ = dryland seed cotton yield (kg ha^{-1})
Irrigation = total irrigation water applied (m^3).

Results and Discussion

Ideal Irrigation Termination Periods Based on Seed Cotton Yield

Simulated seed cotton yield was consistently higher under the HHH treatment than under the LHM, LMH, and LMM treatments for all irrigation termination dates (fig. 2). In general, as the irrigation termination date moved toward the end of the growing season, the simulated seed cotton yield increased until a certain termination date and then became stable for the remaining termination dates. Based on the simulated average seed cotton yield, the ideal irrigation termination date in normal years was 5 September (118 days after planting, DAP) for the HHH treatment and 19 September (132 DAP) for the LHM, LMH and LMM treatments (fig. 3; table 3). When compared to normal years, the ideal irrigation termination period in dry years was about one week later for all treatments (fig. 3; table 3). For wet years, the ideal termination period was the same as that in normal years, except for the LMM treatment for which the ideal termination period was about one week later (26 September) than that in normal years (fig. 3; table 3). This was mainly due to the classification of 2004 as a normal year for the 19 September termination date and as a wet year for all other termination dates per the methodology adopted for classifying simulation years as dry, normal, or wet years. The year 2004 was classified as a normal year for the 19 September termination date because no rainfall was received within a week before that date in that year. In the following week, about 99 mm of rainfall was received, and therefore year 2004 was classified as a wet year for the 26 September termination date. The 99 mm rainfall received during the week before the 26 September termination date resulted in a 222 kg ha^{-1} increase in seed cotton yield, which pushed the average seed cotton yield for wet years for that termination date substantially higher. Hence, 26 September was identified as the optimum irrigation termination date per the criteria used for determining ideal termination dates.

As expected, the ideal termination period occurred later in the season for the LHM, LMH, and LMM (deficit irrigation) treatments when compared to the HHH (full irrigation) treatment because the soil water content in the early stages of crop growth was much less with the LHM, LMH, and LMM treatments when compared to the HHH treatment. Among the deficit irrigation strategies, simulated yield with the LMM treatment was consistently lower for all irrigation termination dates (fig. 2). In normal and wet years, simulated yield with the LHM treatment was higher than that with the LMH treatment when irrigation was terminated on or before 5 September, and thereafter the difference in yield between both treatments became small (figs. 2 and 3). This is consistent with the findings of several other studies, which reported that water deficit imposed during peak bloom stage significantly affected physiological processes and caused severe damage to crop development, thereby reducing yield (Simao et al., 2013; Snowden et al., 2014; Bordovsky et al., 2015; Zonta et al., 2017). In contrast, in dry years, simulated yield with the LMH treatment was consistently higher than that with the LHM treatment, except for the first two termi-

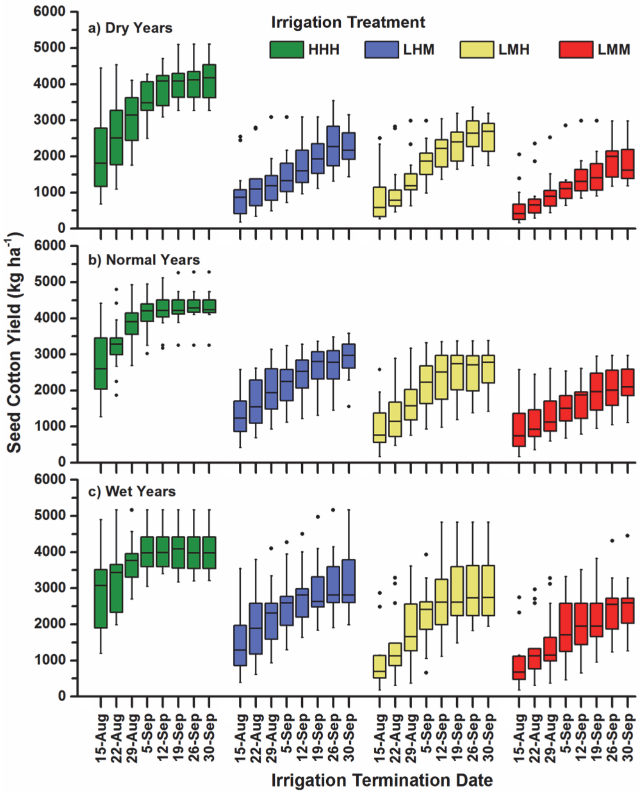

Figure 2. Effect of irrigation termination date on simulated seed cotton yield under four irrigation treatments (HHH, LHM, LMH, and LMM) during (a) dry, (b) normal, and (c) wet years. Horizontal lines inside boxes are medians, and ends of boxes are 25th and 75th percentiles. Dots outside the boxes are outliers or values greater than 1.5 interquartile ranges away from the 25th or 75th percentiles.

nation dates. This was because the higher amount of irrigation water applied during P3 (maturation stage) was beneficial for increasing seed cotton yield in dry years.

IRRIGATION WATER USE WITH SIMULATED IRRIGATION TERMINATION PERIODS

Simulated average irrigation water use under the LHM, LMH, and LMM treatments among all categories of years and all irrigation termination dates was less than the annual groundwater pumping limit of 460 mm (18 in.) specified by the HPWD (fig. 4), indicating that irrigating cotton according to one of these three deficit irrigation treatments could enable producers to be compliant with the HPWD regulation. Producers in the THP apply pre-plant and/or at-plant irrigations of up to 80 mm in most years to establish a plant stand (Bordovsky et al., 2015), but that application was not considered in these simulations due to wide variability in the amount of pre-plant irrigation applied in each year, which depends on the precipitation received during the spring months. Instead, a uniform initial soil water content was assumed in the soil profile at the beginning of each simulation year for all treatments. Even if the highest pre-plant irrigation amount of 80 mm was added to the simulated irrigation water use, the total annual irrigation water use under the three deficit irrigation treatments would still be less than the annual groundwater pumping limit of 460 mm (fig. 4). However, for the HHH treatment, the simulated median irrigation water use exceeded the HPWD's pumping limit when irrigation was terminated after 5 September (118 DAP) in dry years and after 12 September (125 DAP) in normal and wet years. When pre-plant irrigation is also accounted for, irrigation water applications in the HHH treatment may exceed the HPWD pumping limit earlier than 5 (or 12) September. Therefore, it may not be possible to maximize seed cotton yield under the HHH treatment without exceeding the HPWD's annual pumping limit. However, the HPWD provides an option to bank unused irrigation water in one year for use in a subsequent year; hence, with careful irrigation planning, producers can comply with the HPWD pumping limit.

IDEAL IRRIGATION TERMINATION PERIODS BASED ON IRRIGATION WATER USE EFFICIENCY

Interestingly, simulated IWUE was highest under the LMM treatment, followed by the other two deficit irrigation treatments (LHM and LMH) in most cases, and it was the

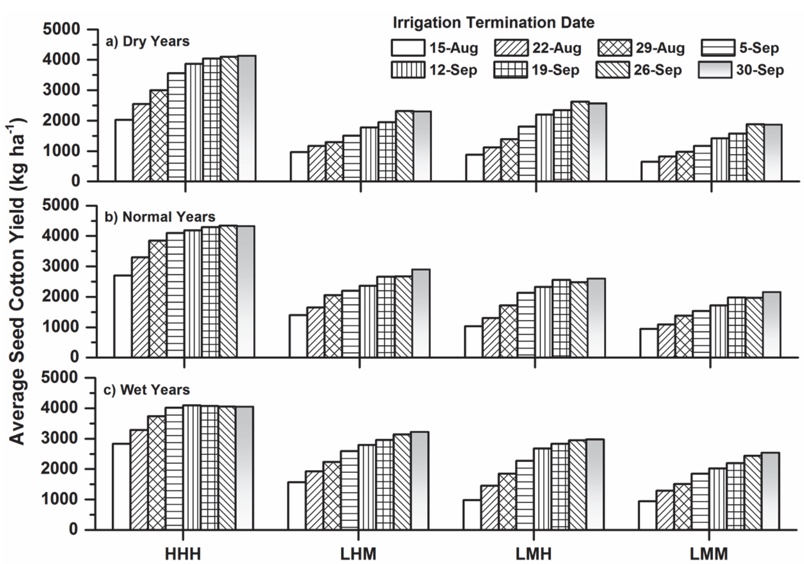

Figure 3. Effect of irrigation termination date on simulated average seed cotton yield under four irrigation treatments (HHH, LHM, LMH, and LMM) during (a) dry, (b) normal, and (c) wet years.

Table 3. Suggested irrigation termination periods for HHH, LHM, LMH, and LMM treatments in dry, normal, and wet years.

Climate Condition	Criteria	Irrigation Treatment			
		HHH	LHM	LMH	LMM
Dry years	Ideal irrigation termination period based on simulated average seed cotton yield[a]	Sept. 12 (3871)	Sept. 26 (2317)	Sept. 26 (2623)	Sept. 26 (1879)
	Ideal irrigation termination period based on simulated average IWUE[b]	Sept. 5 (0.78)	Sept. 12 (0.78)	Sept. 12 (0.85)	Sept. 12 (0.87)
	Suggested optimum irrigation termination period	Sept. 12	Sept. 19	Sept. 19	Sept. 19
Normal years	Ideal irrigation termination period based on simulated average seed cotton yield[a]	Sept. 5 (4097)	Sept. 19 (2662)	Sept. 19 (2559)	Sep. 19 (1983)
	Ideal irrigation termination period based on simulated average IWUE[b]	Aug. 29 (0.93)	Aug. 29 (1.10)	Aug. 29 (1.07)	Aug. 29 (1.16)
	Suggested optimum irrigation termination period	Sept. 5	Sept. 12	Sept. 5	Sept. 12
Wet years	Ideal irrigation termination period based on simulated average seed cotton yield[a]	Sept. 5 (4015)	Sept. 19 (2961)	Sept. 19 (2833)	Sept. 26 (2441)
	Ideal irrigation termination period based on simulated average IWUE[b]	Aug. 15 (0.82)	Aug. 15 (1.10)	Aug. 15 (1.10)	Aug. 15 (1.10)
	Suggested optimum irrigation termination period	Aug. 29	Sept. 5	Sept. 5	Sept. 5

[a] Values in parentheses are average seed cotton yield in kg ha^{-1}.
[b] Values in parentheses are average IWUE in kg m^{-3}.

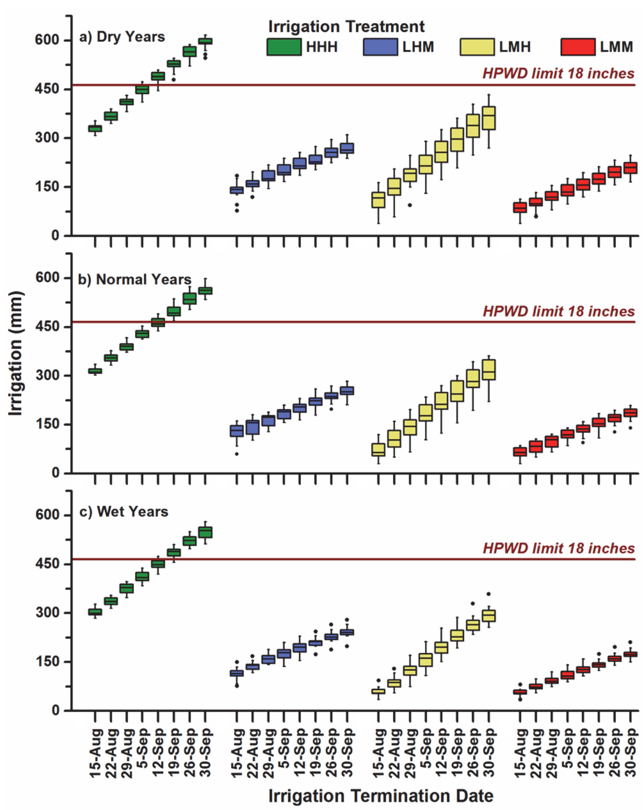

Figure 4. Effect of irrigation termination date on irrigation water use under four irrigation treatments (HHH, LHM, LMH, and LMM) during dry, normal, and wet years. Horizontal lines inside boxes are medians, and ends of boxes are 25th and 75th percentiles. Dots outside the boxes are outliers or values greater than 1.5 interquartile ranges away from the 25th or 75th percentiles.

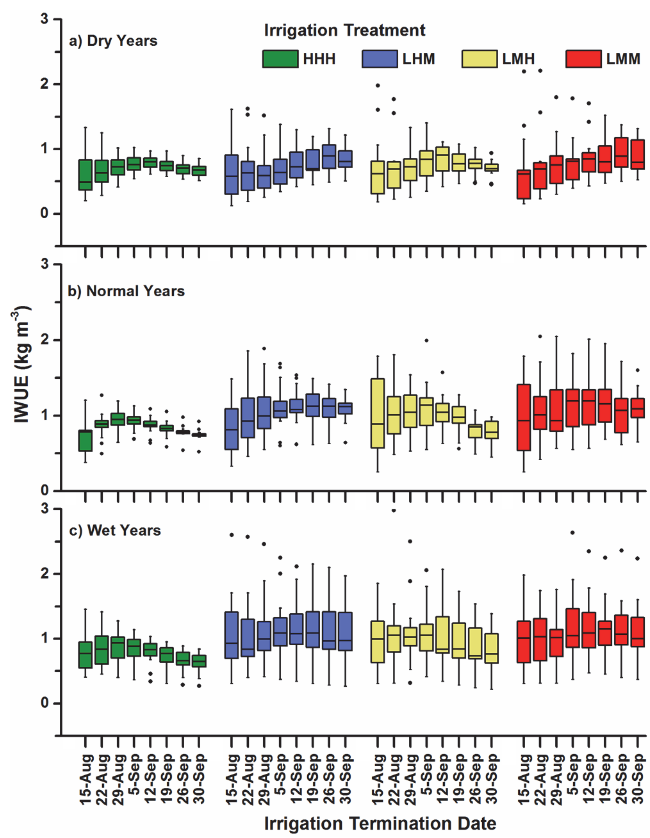

Figure 5. Effect of irrigation termination date on simulated irrigation water use efficiency (IWUE) under four irrigation treatments (HHH, LHM, LMH, and LMM) during dry, normal, and wet years. Horizontal lines inside boxes are medians, and ends of boxes are 25th and 75th percentiles. Dots outside the boxes are outliers or values greater than 1.5 interquartile ranges away from the 25th or 75th percentiles.

lowest under the full irrigation (HHH) treatment for all irrigation termination dates (fig. 5). The simulated differences in IWUE under the four treatments were more distinguishable in normal and wet years than in dry years. These trends indicate that irrigating early in the growing season (P1) is not beneficial in terms of IWUE. This is consistent with the findings of Bordovsky et al. (2015), who reported that attempts to store water in the soil profile early in the growing season reduced seasonal IWUE. As the irrigation termination date moved later in the growing season, the simulated average IWUE increased until a certain termination date and then decreased for the later termination dates (fig. 5). Higher IWUE values occurred later in the season in the LHM and LMM treatments when compared to the HHH and LMH treatments, which indicated that applying higher amounts of irrigation during the post-peak-bloom stage did not contribute to increasing IWUE. Moderate amounts of irrigation during this stage would therefore be sufficient for optimizing IWUE. Like seed cotton yield, there was inconsistency in the simulated trends of median IWUE across the termination dates; hence, the average IWUE was used as a basis for identifying ideal irrigation termination periods for dry, normal, and wet years. Based on the simulated average IWUE, the ideal irrigation termination date in normal years was found to be 29 August (111 DAP) for all treatments (fig. 6; table 3). When compared to normal years, the ideal termination period in wet/dry years was found to be two weeks earlier/later for all treatments, except for HHH in dry years, in which case the ideal irrigation termination period was found to be a week later (fig. 6).

Suggested Optimum Irrigation Termination Periods for Full And Deficit Irrigation

The ideal irrigation termination periods identified for the HHH, LHM, LMH, and LMM treatments in dry, normal, and wet years based on the simulated average seed cotton yield and IWUE are summarized in table 3. When compared to the ideal irrigation termination periods identified based on average seed cotton yield, the ideal termination dates identified based on average IWUE were about one to three weeks earlier in normal years, one or two weeks earlier in dry years, and one to six weeks earlier in wet years. In view of the substantial differences between the ideal termination periods identified based on the two criteria, simulated seed cotton yield and IWUE values for all termination periods between the identified ideal termination dates were compared, and the optimum irrigation termination periods were finally determined as the dates at which both seed cotton yield and IWUE were optimized (i.e., higher seed cotton yield could be achieved while maintaining higher IWUE) (table 3). Based on this assessment, it is suggested to terminate irrigation in the last week of August (about 111 DAP), first week of September (118 DAP), and second week of September (125 DAP) in wet, normal, and dry years, respectively, for the HHH (full irrigation) treatment (table 3). For the LHM and LMM (deficit irrigation) treatments, it would be desirable to terminate irrigation in the first (118 DAP), second (125 DAP), and third week (132 DAP) of September in wet, normal, and dry years, respectively. The suggested optimum termination period for the LMH treatment was the same as that for the other deficit irrigation treatments in wet and dry years but a week earlier (first week of September) in normal years (table 3).

The simulated average seed cotton yield and IWUE corresponding to the suggested optimum irrigation termination periods are shown in figure 7. In general, simulated IWUE was higher in the deficit irrigation treatments as compared to

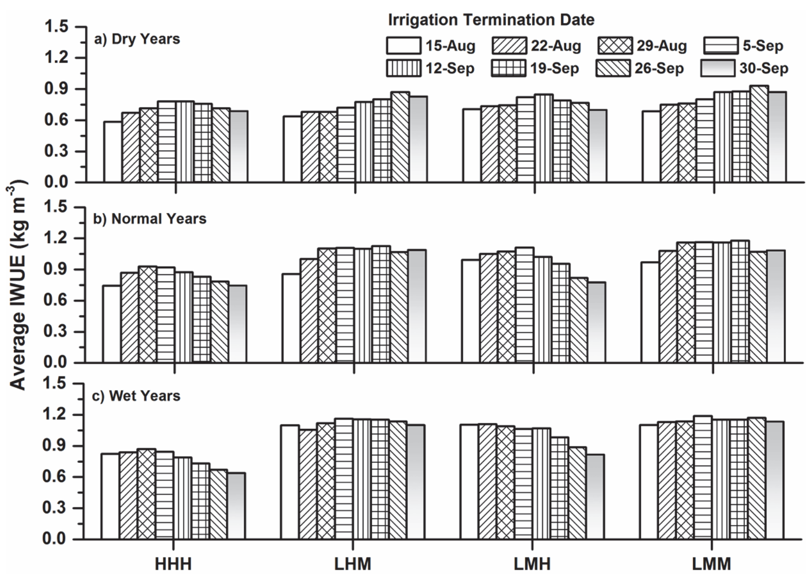

Figure 6. Effect of irrigation termination date on simulated average IWUE under four irrigation treatments (HHH, LHM, LMH, and LMM) during dry, normal, and wet years.

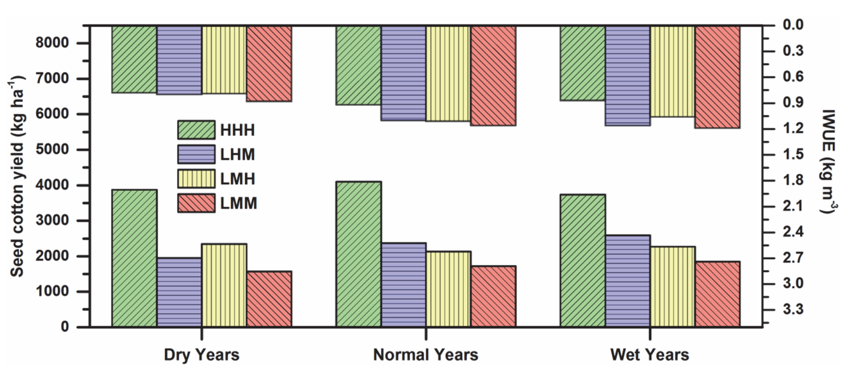

Figure 7. Simulated seed cotton yield and IWUE with the identified optimum irrigation termination periods under four irrigation treatments (HHH, LHM, LMH, and LMM) during dry, normal, and wet years.

the full irrigation (HHH) treatment, and the simulated seed cotton yield was the highest under full irrigation. Among the deficit irrigation treatments, simulated IWUE was highest in the LMM treatment, while simulated seed cotton yield was highest in the LHM treatment in normal and wet years and in the LMH treatment in dry years. Deficit irrigation per the LMH irrigation schedule in dry years and per the LHM schedule in normal and wet years is therefore desirable for optimizing yield and IWUE. In dry years, as expected, full irrigation led to the highest seed cotton yield while achieving an IWUE that was comparable to the deficit irrigation strategies. However, in normal and wet years, IWUE was substantially reduced under full irrigation when compared to the deficit irrigation strategies. These results suggest that implementing appropriate irrigation termination strategies along with deficit irrigation practices could potentially increase IWUE while maintaining high cotton yield. However, the effects of irrigation regimes on IWUE and seed cotton yield vary with cultivar characteristics, crop management (e.g., planting date, growth regulators), climate, late-season plant condition, available soil water, and near-term weather conditions; hence, the results of this study should be used as a general guide. Our future efforts will focus on determining ideal irrigation termination periods for commonly adopted deficit and excess irrigation strategies in the THP (e.g., 55%, 70%, 85%, 100%, and 115% ET replacement) in dry, normal, and wet years.

Implications of Suggested Cotton Irrigation Termination Strategies for Water Security

Producers in the THP region typically terminate irrigation between 25 August and 10 September. The optimum irrigation termination periods suggested in this study fell within this range in wet years but were slightly outside the range in normal years (only for the LHM and LMM treatments). In dry years, the suggested optimum termination dates were about one to two weeks later than the termination dates practiced in the THP. However, the results of this study indicate that producers in the THP could potentially achieve higher seed cotton yields by applying a little extra late-season irrigation without diminishing IWUE by adopting the suggested irrigation termination strategies in normal, wet, and dry years. In addition, adoption of the suggested irrigation termination strategies would enable producers in the THP to comply with the pumping restrictions imposed by groundwater conservation districts while maintaining their productivity goals. Optimizing irrigation efficiency while increasing crop water productivity is one of the important ways to contribute to global water security, and this study focused on this key priority area.

Conclusions

The DSSAT CSM CROPGRO-Cotton model was used in this study to assess the effects of irrigation termination dates on cotton IWUE and seed cotton yield under full and deficit irrigation conditions implemented in a field experiment at Halfway, Texas, in the THP. Results from the long-term (1978-2016) simulations indicated that the ideal irrigation termination periods varied according to the desired objective (maximize yield vs. IWUE) and the environmental conditions during the growing season (dry vs. normal vs. wet years per growing season precipitation until the irrigation termination date). Under the simulated conditions, the optimum irrigation termination periods for achieving higher seed cotton yield and IWUE were found to be the last week of August (about 111 DAP), first week of September (118 DAP), and second week of September (125 DAP) in wet, normal, and dry years, respectively, in the HHH (full irrigation) treatment. In the LHM and LMM (deficit irrigation) treatments, irrigation should be terminated in the first (about 118 DAP), second (125 DAP), and third week (132 DAP) of September in wet, normal, and dry years, respectively. The ideal irrigation termination period for the LMH treatment was the same as that for the other deficit irrigation treatments in wet and dry years but a week earlier (first week of September) in normal years.

The suggested optimum irrigation termination periods were within the range of termination dates practiced in the THP region (25 August to 10 September) in wet years but slightly outside that range in normal years (only in the LHM and LMM treatments) and dry years. However, producers in the THP region could potentially achieve higher seed cotton yields by applying a little extra late-season irrigation without diminishing IWUE by adopting the irrigation termination strategies suggested in this study. While the simulated irrigation water use was always less than the HPWD's annual pumping limit of 460 mm (18 in.) for the LHM, LMM, and LMH treatments, it exceeded the limit in the HHH treatment when irrigation was terminated after the first week of September (118 DAP). Our future efforts will focus on identifying ideal termination periods for commonly adopted deficit/excess irrigation strategies in the THP (e.g., 55%, 70%, 85%, 100%, and 115% ET replacement) in dry, normal, and wet years.

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