Evaluation of crop-growth-stage-based deficit irrigation strategies for cotton production in the Southern High Plains

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ABSTRACT
Identification of efficient crop-growth-stage-based deficit irrigation strategies for cotton (Gossypium hirsutum L.) can play a pivotal role in optimizing the use of available irrigation water in the Southern High Plains (SHP) region, which is facing severe challenges from rapidly declining groundwater levels in the underlying Ogallala Aquifer. The objective of this study was to suggest efficient crop-growth-stage-based deficit irrigation strategies for cotton under nine different climate variability classes using the CROPGRO-Cotton module available in the Decision Support System for Agrotechnology Transfer (DSSAT) Cropping System Model (CSM). Cotton growth stages considered in this study include: i) germination and seedling emergence (GS1), ii) squaring (GS2), iii) flower initiation/early bloom (GS3), iv) peak bloom (GS4), and v) cutout, late bloom and boll opening stage (GS5). The amount of seasonal irrigation water applied was varied from 120 to 540 mm under eight different irrigation scheduling scenarios with four irrigation application rates of 3, 6, 8 and 9 mm d−1 using the subsurface drip irrigation method. Under each scenario, six growth-stage-based irrigation treatments were adopted, resulting in a total of 48 irrigation strategies. Results indicated that imposing water deficit in the initial (GS1 to GS2) or final (GS5) growth stages had little effect on seed cotton yield. The peak bloom growth stage (GS4) was found to be the most sensitive stage to water stress, and imposing water deficit during this stage resulted in the lowest irrigation water use efficiency (IWUE) and seed cotton yield under most climate variability classes. Application of higher than 420 mm irrigation did not significantly contribute to an increase in seed cotton yield and resulted in a decline in IWUE. The results from this study are useful for the SHP producers to make appropriate crop-growth-stage-based deficit irrigation management decisions for achieving higher seed cotton yield while conserving precious irrigation water resources from the Ogallala Aquifer.

1. Introduction
About 40% of the world’s population experience water shortages (Hamdy et al., 2003; Steduto et al., 2017), and the misuse and mismanagement of available water resources pose serious threats to sustainable development (Kummu et al., 2016). Since about 70% of the world’s freshwater resources are consumed for agricultural production (Schloesser et al., 2014; FAO, 2016), improving irrigation water use efficiency (IWUE) can lead to conservation of limited water resources while achieving optimum economic crop productivity (AbdelGadir et al., 2012; Himanshu et al., 2013). Cotton is the most important fiber crop for the textile industry, and it is grown under irrigated conditions in many parts of the world. Out of worldwide production of about 25.8 million metric tons of cotton lint, about 4.0 million metric tons were produced in the United States (USA) in the year 2018 (Dohman et al., 2019). The USA is the leading exporter of raw cotton, covering about one-third of the global trade (MacDonald, 2000). A rapid growth in global population and changes in land use and climate have been affecting irrigation water availability and sustainability of cotton production.

The Southern High Plains (SHP) region consisting of the eastern New Mexico and northwestern Texas is one of the major cotton producing regions of the USA (Mauget et al., 2017). However, cotton production in the SHP faces a major challenge due to the region’s summer climate, which is water-limited relative to the needs of cotton (Mauget et al., 2013, 2017). Semi-arid climate along with low levels of soil nitrogen and phosphorus are also leading factors affecting cotton production in the SHP (Peng et al., 1989; Morrow and Krieg, 1990). These unfavorable conditions led to dependency of cotton production on irrigation from the underlying Ogallala Aquifer. More than 90% of

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the irrigation water used in this region is pumped from the Ogallala Aquifer (Allen et al., 2008). However, due to increase in irrigated crop production, groundwater in the Ogallala Aquifer was depleted by more than 50% since the starting of large-scale irrigation in 1950s (Konikow, 2015). This rapid decline of ground water levels has reduced irrigation capacities that supply irrigation for cotton production in the SHP (Torell et al., 1990; Colaizzi et al., 2009; Scanlon et al., 2012; Chaudhuri and Ale, 2014a, b), and increased risk of irrigation non-availability during the growing season. In order to prolong the usable lifetime of the Ogallala aquifer, Groundwater Conservation Districts in this region have started imposing restrictions on groundwater pumping for irrigation purposes (HPWD, 2015). For example, the High Plains Water District set the limit for annual allowable groundwater pumping for irrigation at 460 mm (18 in.) of depth. Declining groundwater levels and proposed restrictions on use of ground water for irrigation make it crucial to implement efficient irrigation water management practices in the SHP to optimize the use of available irrigation water.

Scheduling irrigation with appropriate deficits during crop growing season is a feasible practice that facilitates improvements in IWUE (Kirda et al., 2007; Greaves and Wang, 2017). Several field studies have been carried out in the SHP region to assess the impacts of water deficit on cotton growth and yield (Howell et al., 2004; Snowden et al., 2013; Bordovsky et al., 2015). Stress due to water deficit is the most common and quantifiable problem in cotton production and it affects biomass accumulation, node and boll development, and crop maturity (Ritchie et al., 2009). The size and number of bolls are affected by the amount and timing of irrigation (Dumka et al., 2004; Ritchie et al., 2009; Snowden et al., 2013; Sharma et al., 2015; Pokhrel et al., 2018; Schaefer et al., 2018). Many other field studies suggested that in case of limited availability of irrigation water, the efficiency of its allocation can be increased by optimally allocating water among different critical growth stages (Snowden et al., 2014; Bordovsky et al., 2015; Zonta et al., 2017). Some of these studies reported large yield reduction when water deficit occurred during peak flowering period compared to earlier or later in the growing season (Butter et al., 2007; Snowden et al., 2014; Bordovsky et al., 2015; Zonta et al., 2017).

Weather is also one of the most important factors affecting cotton growth and yield, but limited attempts have been made to relate crop response to available irrigation and long-term weather (Reddy et al., 1996, 1997; Logan and Gwathmey, 2002; Kothari et al., 2019). Cotton growth and yield is highly affected by the amount and distribution of rainfall throughout the growing season, because average daily water requirement during different cotton growth stages varies within a range of 2–8 mm (Fisher and Udeigwe, 2012). On the other hand, air temperature determines the duration of a crop growing season and it controls crop water requirement (Reddy et al., 1997). Assessing the impacts of growing season precipitation and average air temperature on seed cotton yield and IWUE under different crop-growth-stage-based deficit irrigation management practices could enable identification of efficient irrigation management strategies for the SHP region.

Identification of efficient irrigation strategies for productive use of irrigation water can be achieved through field experiments or use of crop growth simulation models. However, field experimentation is limited by the cost and time to examine a comprehensive number of potential irrigation strategies. Crop models are complementary to field experiments, and after a thorough testing based on field data, they allow a conjunctive evaluation of various crop growing environments and their long-term effects on crop production (Geerts et al., 2010; Thorp et al., 2014; Attia et al., 2016). Crop models are also useful for identifying ideal irrigation management strategies in terms of timing and amount of irrigation application under different climatic conditions (Liu et al., 2007; Geerts et al., 2016; Greaves and Wang, 2017). In addition, crop growth simulation models provide valuable information about different irrigation scenarios in terms of crop productivity and IWUE, and thus serve as decision support tools for irrigation management (Greaves and Wang, 2017). Several cotton simulation models such as GOSSYM, COTCO2, Cotton2K, OZCOT, CSM-CROPGRO-Cotton etc. are available for effectively simulating cotton growth and development under different crop and irrigation management plans (Nair et al., 2013; Thorp et al., 2014; Attia et al., 2016). These models differ in their scales of application, complexity, input variables and outputs. Among the cotton growth simulation models, the CROPGRO-Cotton module within the Decision Support System for Agrotechnology Transfer (DSSAT) Cropping system Model (CSM) has been increasingly used by researchers worldwide for various applications (Butter et al., 2007; Pathak et al., 2007; Ortiz et al., 2009; Pereira et al., 2009; Thorp et al., 2014; Modala et al., 2015; Adhikari et al., 2016, 2017; Mauget et al., 2017; Loison et al., 2017; Amin et al., 2018; Kothari et al., 2019; Li et al., 2019). In this study, the DSSAT-CSM-CROPGRO-Cotton model that was evaluated for the study site in a prior study (Adhikari et al., 2016) was used to address three main objectives: i) assess the sensitivity of cotton crop to water stress during different growth stages and identify critical growth stages for irrigation application, ii) suggest efficient crop-growth-stage-based deficit irrigation strategies for cotton under limited irrigation water availability, and iii) assess the impact of climate variability on suggested efficient crop-growth-stage-based deficit irrigation strategies.

2. Material and methods

2.1. Study area/experimental site

The SHP region consists of 43 counties in northwest Texas and 5 counties in eastern New Mexico (Fig. 1). This semi-arid, windy and flat region is one of the most intensively irrigated agricultural areas in the USA. Very dry conditions prevail in the SHP during the winter from October to April, and peak rainfall is generally received in the months of May and September (Allen et al., 2008). Cotton, winter wheat (Triticum aestivum L.), corn (Zea mays L.) and sorghum (Sorghum bicolor L.) are the major crops grown in this region. Common soil types found in the SHP region are sandy loams and clay loams. The Ogallala Aquifer, which underlies all SHP counties, is a major source of irrigation water for this region. Center pivot irrigation is the most commonly used irrigation method in this region. However, subsurface drip irrigation (SDI) systems are gaining popularity in this region due to multiple advantages such as higher irrigation efficiency (Camp, 1998; Ayars et al., 1999; Bordovsky et al., 2001; Thompson et al., 2009; Zaccaria et al., 2017), 10–25% higher lint yield compared to the low energy precision application (LEPA)/ low elevation spray (LESA) systems (Cowie et al., 2011), negligible evaporation and runoff losses (Enciso et al., 2017).

Fig. 1. The Southern High Plains (SHP) region of Texas and New Mexico.
and less labor requirement. There are about 14,284 center pivot systems and 5,798 SDI systems in operation within the High Plains Water District, and they irrigate about 739,682 and 181,472 hectares, respectively (HPWD, 2018). This study is focused on suggesting efficient crop-growth-stage based irrigation strategies for cotton fields irrigated with SDI systems.

Measured data used for building DSSAT projects for this study and for evaluating the DSSAT CROPGRO-Cotton model in a prior study (Adhikari et al., 2016) were obtained from the cotton IWUE experiments conducted at the Texas A&M AgriLife Research Station at Halfway (34° 10′ N, 101° 56′ W; elevation 1075 m; Fig. 1) in the SHP during 2010–2013 growing seasons (Bordovsky et al., 2015). The mean (1977–2018) annual and growing season (May–October) rainfall at the study site was 463 mm and 344 mm, respectively. The months of March, April and May are the windiest, and the months from October to February are generally dry at Halfway (Adhikari et al., 2016). Additional details about planting and harvesting dates, tillage management, fertilizers applied, and irrigation management followed in these experiments can be found in Bordovsky et al. (2015).

2.2. Weather data classification

Daily weather data of precipitation (mm), minimum and maximum air temperature (°C), wind speed (m s⁻¹), solar radiation (MJ m⁻²) and relative humidity (%) for this study were obtained from weather measurements at the Texas A&M AgriLife Research Center, Halfway, TX for the period from 1977 to 2018. A summary of annual and growing season (May–October) rainfall, and average of daily high and low growing season air temperature is presented in Fig. 2. Based on the growing season precipitation and average air temperature, simulation period from 1977 to 2018 was divided into nine climate variability classes (Table 1) for climate variability impact assessment. The years with growing season precipitation below 277 mm (33rd percentile) were considered as ‘dry’ years, and those years with precipitation above 366 mm (66th percentile) were considered as ‘wet’ years. Similarly, the years with average growing season temperature below 21.2 °C (33rd percentile) and above 21.8 °C (66th percentile) were classified as ‘cold’ and ‘warm’ years, respectively (Table 1). The years that did not fall under any of the above classified categories were considered as ‘normal’ years. The thresholds chosen for classification of years in this study were the same as those used in Kothari et al. (2019). Similar criteria of percentiles were also adopted by other researchers to classify climatic variables. For example, Auer and Böhm (1994) used the 40th and 60th percentile criteria, whereas, Chmielewski and Potts (1995) used the 25th and 75th percentile criteria for classification of simulation years into different climate variability classes.

2.3. The crop simulation model used

The CSM-CROPGRO-Cotton module distributed with the DSSAT model was used to assess the response of cotton crop to water stress at different growth stages under different climate variability classes. DSSAT 4.7 version was used in this study. The CSM-CROPGRO-Cotton model predicts cotton growth and yield, soil water, and carbon and nitrogen processes over time based on weather, soil, cultivar and crop management information (Jones et al., 2003; Thorp et al., 2014;
The model can expand the information gathered from field experiments by simulating crop responses under extensive experimental conditions.

The model requires soil parameters, and crop management, environment and cultivar related information as inputs. Required crop management parameters include tillage type, tillage depth and dates, cultivar characteristics, planting date and method, seeding depth, plant population, row spacing, fertilizer application method, fertilizer amount and application dates, method of irrigation, irrigation dates and amounts, and harvesting method and date. The required soil parameters include soil texture, color, slope, albedo, bulk density, drainage, hydraulic conductivity, saturated water content, drained upper limit, drained lower limit, organic carbon content, and total soil nitrogen. Environmental variables such as daily precipitation, maximum and minimum temperature and incoming solar radiation are also required inputs, while wind speed and dew point temperature are optional inputs.

### 2.4. Model evaluation

The CSM-CROPGRO-Cotton model was evaluated for the study site, Halfway, TX in a prior study (Adhikari et al., 2016) using the observed data from cotton IWUE experiment over a period of four years from 2010 to 2013. The field experiment consisted of 27 irrigation treatments (Bordovsky et al., 2015), and observed data from four high irrigation treatments (a total of 16 treatment-years) were used for model calibration, while observed data from the remaining 23 medium and low irrigation treatments (a total of 92 treatment-years) were used for model evaluation. A good agreement between the measured and simulated seed cotton yields and dates of onset of various cotton phenological stages were achieved during model calibration and evaluation as indicated by good model performance statistics (Adhikari et al., 2016). The coefficient of determination, average percent error and index of agreement were 0.94, 0.1% and 0.90 during calibration and 0.94, 6.5% and 0.83 during evaluation, respectively for seed cotton yield prediction (Adhikari et al., 2016). The evaluated model did an excellent job in responding well to various irrigation strategies implemented in 27 treatments over 4 growing seasons with varying amounts and distribution patterns of precipitation. More details about the model evaluation can be found in Adhikari et al. (2016).

### 2.5. Simulation of crop-growth-stage-based deficit irrigation strategies

Long-term simulations were run using weather data for the period from 1977 to 2018 to assess the impacts of crop-growth-stage-based deficit irrigation strategies on seed cotton yield and IWUE. Based on the planting dates adopted in the field experiment at Halfway during 2010–2013 growing seasons (Bordovsky et al., 2015), planting date was assumed as May 11 for each year in the simulation period. Five critical cotton growth stages were considered for irrigation based on the recommendations made by various researchers (Oosterhuis, 1990; Ritchie et al., 2007; Perry and Barnes, 2012) (Table 2). The total amount of irrigation water applied during the growing season under eight different irrigation scenarios simulated in this study varied from 120 to 540 mm with four different irrigation application rates of 3, 6, 8 and 9 mm d$^{-1}$ as shown in Table 3.

In general, water use pattern of cotton varies widely between planting and harvesting, and the daily water use ranges from < 2.5 mm during the emergence to as high as 14 mm during the peak bloom period under extreme water stress (Boman and Warren, 2014). Therefore, depending on the water requirement (low/moderate/high) during the selected growth stages (Table 2), the total number of irrigation days (Table 3) were split proportionately among five growth stages and irrigation was then applied within the days after planting (DAP) specified for each growth stage in Table 2. For example, the highest number of irrigation days were scheduled during the peak bloom stage because plants require the highest amount of water during this stage and water stress during this period could have a pronounced negative effect on cotton yield. On rainy days (when rainfall amount ≥ 1 mm), irrigation was eliminated, but the number of irrigation days specified for each growth stage were maintained the same by extending irrigation period. Each year’s simulation was carried out independent of the previous years and soil initial conditions were reinitialized prior to planting. This was done to evaluate the sensitivity of treatments to precipitation and temperature variability independently of any residual effects the treatments might have (Tovihoudji et al., 2019).

Under each irrigation scenario, six crop-growth-stage-based irrigation strategies (referred to as treatments) were adopted (Table 4). Among these six irrigation treatments, irrigation was skipped in each of the identified five critical crop growth stages in five treatments, and irrigation was applied in all growth stages in the sixth treatment as shown in Table 4. However, the same amount of irrigation water was applied for treatments T1 through T6 in each scenario and irrigation regimes were established in such a way that more irrigation water was applied during those growth stages in which water requirement was higher (Table 2).

Suggestions on efficient irrigation strategies for cotton production in the SHP under different climate variability classes were finally made based on the simulated average seed cotton yield and IWUE while

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### Table 2

<table>
<thead>
<tr>
<th>Growth stages of cotton considered as critical for irrigation.</th>
<th>Code</th>
<th>Days after planting (DAP)</th>
<th>Water requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germination and seedling emergence</td>
<td>GS1</td>
<td>3 to 17</td>
<td>Low</td>
</tr>
<tr>
<td>Squaring</td>
<td>GS2</td>
<td>23 to 47</td>
<td>Low</td>
</tr>
<tr>
<td>Flower initiation/ early bloom</td>
<td>GS3</td>
<td>48 to 72</td>
<td>Moderate</td>
</tr>
<tr>
<td>Peak Bloom</td>
<td>GS4</td>
<td>72 to 102</td>
<td>High</td>
</tr>
<tr>
<td>Cutout, late bloom and boll opening</td>
<td>GS5</td>
<td>103 to 130</td>
<td>Moderate</td>
</tr>
</tbody>
</table>

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### Table 3

<table>
<thead>
<tr>
<th>Irrigation Scenario</th>
<th>Code</th>
<th>Irrigation application rate (mm d$^{-1}$)</th>
<th>No. of days irrigation applied</th>
<th>Seasonal irrigation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>S1</td>
<td>3</td>
<td>40</td>
<td>120</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>S2</td>
<td>2</td>
<td>60</td>
<td>180</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>S3</td>
<td>6</td>
<td>40</td>
<td>240</td>
</tr>
<tr>
<td>Scenario 4</td>
<td>S4</td>
<td>4</td>
<td>50</td>
<td>300</td>
</tr>
<tr>
<td>Scenario 5</td>
<td>S5</td>
<td>6</td>
<td>60</td>
<td>360</td>
</tr>
<tr>
<td>Scenario 6</td>
<td>S6</td>
<td>6</td>
<td>70</td>
<td>420</td>
</tr>
<tr>
<td>Scenario 7</td>
<td>S7</td>
<td>8</td>
<td>60</td>
<td>480</td>
</tr>
<tr>
<td>Scenario 8</td>
<td>S8</td>
<td>9</td>
<td>60</td>
<td>540</td>
</tr>
</tbody>
</table>

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### Table 4

<table>
<thead>
<tr>
<th>Irrigation Treatment</th>
<th>Code</th>
<th>Crop growth stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment 1</td>
<td>T1</td>
<td>GS1 GS2 GS3 GS4 GS5</td>
</tr>
<tr>
<td>Treatment 2</td>
<td>T2</td>
<td>N Y Y Y Y</td>
</tr>
<tr>
<td>Treatment 3</td>
<td>T3</td>
<td>Y N Y Y Y</td>
</tr>
<tr>
<td>Treatment 4</td>
<td>T4</td>
<td>Y Y Y N Y</td>
</tr>
<tr>
<td>Treatment 5</td>
<td>T5</td>
<td>Y Y Y Y N</td>
</tr>
<tr>
<td>Treatment 6</td>
<td>T6</td>
<td>Y Y Y Y Y</td>
</tr>
</tbody>
</table>

Y: Irrigation applied during crop growth stage; N: Irrigation not applied during crop growth stage.
keeping in view the HPWD annual groundwater pumping limits for irrigation (460 mm). Initially, the irrigation treatment (e.g. T1) that simulated the highest average seed cotton yield was identified for each irrigation scenario (e.g. S6) under each climate variability class (e.g. dry-normal) and that “irrigation scenario-irrigation treatment” combination (S6-T1) was designated as an “efficient irrigation strategy” for that irrigation scenario (S6 in this example) under that climate variability class (dry-normal in this example). Ideal irrigation strategy for each climate variability class was then identified using a criterion. An irrigation strategy was considered as ideal for a climate variability class if the increase in average seed cotton yield from that irrigation strategy to the next higher irrigation-water-use strategy in that climate variability class was less than 5%. For example, if the percent increase in average seed cotton yield from an irrigation strategy S6-T1 to S7-T1 under dry-normal class was less than 5%, then S6-T1 was considered as an ideal irrigation strategy for a dry-normal climate. In this study, the IWUE (kg m−3) was estimated using the following equation:

\[
IWUE = \frac{(\text{Yield}_{\text{irr}} - \text{Yield}_{\text{dry}})}{\text{Irrigation}}
\]

(1)

where

- \(\text{Yield}_{\text{irr}}\) = Irrigated seed cotton yield (kg ha\(^{-1}\))
- \(\text{Yield}_{\text{dry}}\) = Dryland seed cotton yield (kg ha\(^{-1}\))
- Irrigation = Total amount of irrigation water applied (seasonal plus preplant irrigation) (m\(^3\))

3. Results and discussion

3.1. Impact of crop-growth-stage-based deficit irrigation strategies on seed cotton yield and IWUE

Simulated seed cotton yield and IWUE under different crop-growth-stage-based irrigation strategies are presented in Figs. 3 and 4, respectively. A substantial difference in simulated seed cotton yield and IWUE was found under different irrigation strategies due to varying responses of cotton to water stress during different crop growth stages (Figs. 3 and 4). Water stress during certain critical cotton growth stages caused severe effect on physiological processes, with consequent loss in yield and IWUE (Snowden et al., 2014; Bordovsky et al., 2015; Zonta et al., 2017). The reduction in seed cotton yield was not significant when water deficit was imposed in the initial (GS1 to GS2) or final (GS5) growth stages. Early season irrigation water applications during germination and seedling emergence stages can be lost via evaporation or result in undesirable excessive plant growth and diseases, and hence they did not contribute towards increasing IWUE and/or cotton yield. Reduction in early season irrigation potentially increased cotton root growth and thereby enhanced water uptake and resilience to water shortage during the reproductive stage and resulted in an increase in IWUE and seed cotton yield (Thorpe et al., 2017). Similarly, elimination of irrigation during the cutout, late bloom and boll opening growth stage (GS5) has also caused less effect on seed cotton yield and IWUE.

The peak bloom growth stage (GS4) was found to be the most sensitive stage for imposing water deficits resulted in the lowest seed cotton yield (Fig. 3) and IWUE (Fig. 4). The growth and development of most of the reproductive structures occur during the peak bloom stage and hence plants require more water during this stage (Ritchie et al., 2007; Perry and Barnes, 2012). Water stress during peak bloom stage, in general, increases shedding (dropping of flower buds), reduces boll retention and flowering rate. The results of the simulations are consistent with several other studies, which reported that water deficit imposed during peak bloom stage has significantly affected physiological processes and caused severe damage to crop development, and thereby reduction in yield (Simao et al., 2013; Snowden et al., 2014; Bordovsky et al., 2015; Zonta et al., 2017). However, skipping irrigation during the peak bloom stage in case of high irrigation water scenarios (S6, S7 and S8) had less effect on seed cotton yield (Fig. 3) and IWUE (Fig. 4) possibly due to residual soil moisture from irrigation in the preceding growth stages.

As the amount of irrigation water applied during the growing season increased, simulated seed cotton yield increased gradually until the
irrigation amount reached 420 mm (scenario 6) with additional irrigation resulting in stable or minor yield increases (Fig. 3). In contrast, as the amount of applied irrigation water increased, simulated IWUE increased until 300 mm irrigation had been applied (scenario 4) and then decreased for the remaining irrigation scenarios (Fig. 4). Applying higher than 420 mm irrigation water during the growing season (scenarios S7 and S8) did not improve seed cotton yield much when compared to S6 scenario and resulted in a decline in IWUE. These results reinforce the findings of other studies (Snowden et al., 2014; Bordovsky et al., 2015; Zonta et al., 2017) and indicate that the producers in the SHP could potentially achieve higher seed cotton yields without exceeding the HPWD’s annual pumping limit of 460 mm by adopting appropriate crop-growth-stage-based irrigation strategies.

Within an irrigation scenario, the trend in simulated IWUE under different irrigation treatments was the same as that of simulated seed cotton yield because same amount of irrigation water was applied for all treatments (Fig. 4). Interestingly, as the amount of applied irrigation water during the growing season increased, variability in simulated seed cotton yield, and hence IWUE, decreased (Figs. 3 and 4). This was assumed to be caused by reduced water stress with the increase in seasonal applied irrigation water. In order to better understand the impact of climate variability on seed cotton yield and IWUE under crop-growth-stage-based deficit irrigation strategies, simulated results were further analyzed among nine different climate variability classes defined earlier.

3.2. Impacts of crop-growth-stage-based deficit irrigation strategies on seed cotton yield under different climate variability classes

Simulated average (1977–2018) seed cotton yield varied substantially under different climate variability classes (Fig. 5). Similar to the trends noticed in case of the entire simulation period (Fig. 3), the peak bloom growth stage (GS4) was found to be the most sensitive growth stage for water stress, whereas, growth stages GS1, GS2 and GS5 were found to be least sensitive stages to water stress under most climate variability classes (Fig. 5). In addition, under all climate variability classes, as the amount of applied irrigation water during the growing season increased, simulated seed cotton yield increased until a certain amounts (e.g. until 360 mm (scenario S5) in wet-warm years; Fig. 5g) and then became almost stable (Fig. 5). However, the impact of crop-growth-stage-based irrigation strategies on seed cotton yield was found to be minimal in case of higher irrigation water scenarios, especially in wet years. When moderate to high irrigation water was applied, irrigation treatment T1 was found to be the best irrigation strategy for maximizing seed cotton yield under different climate variability classes, except in dry-cold and wet-normal climatic conditions under which irrigation treatments T2 and T5, respectively were found to be the best irrigation treatments. Cooler temperatures resulted in fewer heat units and less time for crop development and hence there was either reduction in yield or no yield gain from late season irrigation. Irrigation treatment T4 resulted in comparatively lower yields in any irrigation scenario under all climate variability classes.

As expected, simulated seed cotton yield was consistently higher under wet weather conditions than dry and normal weather conditions in case of low to moderate irrigation scenarios (S1 through S5). However, in case of high irrigation scenarios (S6 through S8), simulated seed cotton yield did not vary much among dry, normal and wet years (Fig. 5). Also, maximum seed cotton yield was achieved with lesser amounts of irrigation water in wet years when compared to dry and normal years.

Simulated seed cotton yield was found to be higher in warm weather than that under cold weather conditions, especially in case of high irrigation scenarios (S6, S7 and S8). Simulated seed cotton yield was much less under wet-normal (Fig. 5h) and wet-cold (Fig. 5i)
conditions than under wet-warm (Fig. 5g) conditions among all irrigation-scheduling scenarios. The highest seed cotton yield was simulated under wet-warm climatic conditions among all climate variability classes (Figs. 5). These results are consistent with the findings of other researchers, who reported that warm and humid climate is favorable for cotton production and hence most of the cotton farming is limited to warm and humid climatic conditions prevalent in countries such as China, India, USA, Pakistan, Brazil, Uzbekistan (Reddy et al., 1996, 1997; Logan and Gwathmey, 2002).

3.3. Impacts of crop-growth-stage-based deficit irrigation strategies on IWUE under different climate variability classes

Simulated average (1978–2018) IWUEs for different crop-growth-stage-based deficit irrigation strategies under different climate variability classes are shown in Fig. 6. Like seed cotton yield, a substantial difference in simulated IWUE was found among different irrigation strategies and climate variability classes, due to varying responses of cotton to water availability during different stages of crop growth (Snowden et al., 2014; Zonta et al., 2017). Once again, simulated IWUE was found to be the lowest in all irrigation treatments when irrigation was eliminated during the peak bloom growth stage (GS4). Conversely, elimination of irrigation during the early and late season growth stages (GS1, GS2 and GS5) did not greatly reduce IWUE among the treatments (Fig. 6). As the amount of applied irrigation water increased, the differences in simulated IWUE among different irrigation treatments within an irrigation scenario decreased substantially under all climate variability classes (Fig. 6). For example, in wet-warm years, substantial differences in simulated IWUE were found among different treatments (T1 through T6) under scenario S1. These differences decreased as the applied irrigation water increased (from S1 to S8) and finally resulted in the minimum/negligible difference in IWUE among treatments under scenario S8 (Fig. 6g). Like seed cotton yield, in general, irrigation treatments T1 and T4 were found to be the most and least efficient strategies, respectively, for maximizing IWUE. However, under some climate variability classes, in case of irrigation greater than 360 mm (scenario S5), treatments T2 (in dry-cold years) and T5 (in wet-normal years) were found to be more efficient strategies for maximizing IWUE.

As the applied seasonal irrigation water amount increased, simulated IWUE increased until a certain irrigation amount (e.g. until 420 mm (scenario S6) in dry-warm years; Fig. 6a) and then decreased for the higher irrigation scenarios, except in wet weather conditions (Fig. 6). Decline in simulated IWUE with increasing irrigation was more rapid in wet years as compared to normal and dry years. In case of wet years, simulated IWUE was the highest under S1 scenario (120 mm seasonal irrigation) and then it decreased continuously with increase in the amount of applied irrigation water. Seasonal rainfall received during the wet years was very high (649.2 mm, 450.8 mm and 443.4 mm in wet-warm, wet-normal and wet-cold climatic conditions, respectively) (Table 1), and this has resulted in a very high IWUE under S1 scenario in spite of applying lower amounts of irrigation water. These results are also supported by earlier findings that warm and humid climate is favorable for cotton production (Reddy et al., 1996, 1997; Logan and Gwathmey, 2002).

In case of low irrigation water scenarios (S1, S2 and S3), simulated IWUE was consistently lower in dry and normal years as compared to wet years (Fig. 6). In contrast, under moderate irrigation water scenarios (S4 and S5), simulated IWUE was higher in normal years as compared to dry and wet years. In case of high irrigation scenarios (S6, S7 and S8), simulated IWUE in normal years was comparable to that in dry years, but it was lower in wet years (Fig. 6). Overall, applying moderate amounts of irrigation water (scenarios S4 and S5) could potentially increase IWUE while maintaining higher seed cotton yields as compared to applying lower (scenarios S1, S2 and S3) and higher (scenarios S6, S7 and S8) amounts of irrigation water. However, the effects of irrigation regimes/deficits on IWUE and seed cotton yield
3.4. Efficient crop-growth-stage-based irrigation strategies under different levels of irrigation water availability

One of the goals of this simulation study was to answer a hypothetical question, “if annual irrigation depths are limited by policy to 120, 180, 240, 360, or 420 mm, at what cotton growth stage(s) should water be applied in order to maximize seed cotton yield/IWUE and how does that compare to more limited field studies?” In case of limited availability of irrigation water, it is important to enhance irrigation efficiency by optimally allocating water among different growth stages (Snowden et al., 2014; Bordovsky et al., 2015; Zonta et al., 2017). It could be inferred from the discussion in preceding sections and from previous studies that for a given level of annual irrigation, some crop-growth-stage-based irrigation strategies are better than others. In addition, as discussed earlier, higher seasonal irrigation amounts (> 420 mm) have not contributed to substantial increases in seed cotton yield and have decreased IWUE.

For each of the simulated scenarios with 420 mm or less seasonal irrigation water (S1 to S6), identified efficient irrigation strategies along with growth-stage-wise distribution of irrigation water that maximized seed cotton yield and IWUE under different climate variability classes are presented in Fig. 7. Irrigation treatment T1 was found to be the best irrigation treatment for maximizing seed cotton yield/IWUE under most of the irrigation scenarios followed by T3, T2 and T5 treatments (Fig. 7). Irrigation treatment T4 was found to be the worst in any irrigation scenario under any climate variability class. Therefore, it is recommended to ensure irrigation application at the peak bloom growth stage of cotton (GS4), even if there is a limited availability of irrigation water. Results from this study reinforce some of the outcomes from earlier studies (Butter et al., 2007; Snowden et al., 2014; Bordovsky et al., 2015; Zonta et al., 2017), and these recommendations should be used with caution as producers in the SHP apply pre-plant and/or at-plant irrigations in some years to establish a good plant stand (Bordovsky et al., 2015), which were not considered in these simulations.

3.5. Suggested ideal irrigation strategies under different climate variability classes

Ideal cotton irrigation strategies identified for different climate variability classes based on the criterion adopted in this study (an irrigation strategy was considered as ideal if the increase in average seed cotton yield from that irrigation strategy to the next higher irrigation-water-use strategy was less than 5%) are presented in Fig. 8. Seasonal irrigation water application under the suggested efficient irrigation strategies under different climate variability classes was less than the annual groundwater pumping limit of 460 mm (18 in. specified by the HPWD, except in dry-warm years (Fig. 8) indicating that irrigating cotton according to these suggested crop-growth-stage-based irrigation strategies enables producers to be compliant with the HPWD regulations. In case of dry-warm years, it may not be possible to achieve the potential highest seed cotton yield without exceeding the HPWD’s annual pumping limit. However, the HPWD allows producers to establish a conservation reserve and hence producers can save irrigation water in wet/cold years and use it in subsequent dry/warm years, and thereby manage to comply with the HPWD pumping limits with careful irrigation planning. Adoption of suggested crop-growth-stage-based irrigation strategies under different climate variability classes based on forecasted weather could potentially save considerable amount of irrigation water. However, depending on the changes in actual weather as the growing season progresses, switching from one strategy to another strategy may be necessary.
4. Conclusion

The DSSAT-CSM CROPGRO-Cotton model was used to assess the effects of crop-growth-stage-based irrigation strategies on seed cotton yield and IWUE under different climate variability classes and suggest efficient irrigation strategies for the SHP region. The results from this study indicated that the amount and distribution of irrigation water among different cotton growth stages had substantial effect on the seed cotton yield and IWUE. While elimination of irrigation during peak bloom stage (GS4) resulted in the lowest seed cotton yield and IWUE, irrigation elimination during the initial (GS1 to GS2) or final (GS5) growth stages caused minimum effect on seed cotton yield and IWUE in most of the climate variability classes. Wet-warm climatic conditions were found to be most favorable among all climate variability classes for cotton growth, and resulted in maximum seed cotton yield and IWUE.

Overall, application of moderate amounts of irrigation water (300 to 360 mm) in wet years, and moderate to high amounts of irrigation water (360 to 420 mm) in dry and normal years through appropriate crop-growth-stage-based deficit irrigation strategies could enable achieving higher IWUEs while maintaining higher seed cotton yields. Application of more than 420 mm of irrigation water (scenarios S7 and S8) was found to be least efficient.

Fig. 7. Suggested irrigation water application during different cotton growth stages for each of the identified efficient irrigation strategies (indicated on the top of vertical bar; T stands for treatment) under different levels of irrigation water availability.

Fig. 8. Suggested ideal irrigation strategies for cotton under different climate variability classes (indicated on the right-hand side of horizontal bar; S stands for scenario and T stands for treatment) and irrigation water application during different crop growth stages under each strategy.
S8) during the growing season resulted in a decline in IWUE and provided minimal, if any, increases in seed cotton yield. Suggestions were finally made on efficient crop-growth-stage-based deficit irrigation strategies under different climate variability classes and different levels of irrigation water availability. The results from the present study are useful for SHP producers to optimize the application of limited available irrigation water in achieving higher seed cotton yields without exceeding the HPWDD’s annual pumping limits. Future efforts will focus on considering larger number of irrigation scenarios that are representative of reducing irrigation capacities in the SHR region for identifying efficient crop-growth-stage-based irrigation strategies.

Declaration of Competing Interest

The authors hereby declare that there is no conflict of interest regarding the publication of this paper.

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