Modeling Cotton Growth and Yield Response to Irrigation Practices for Thermally Limited Growing Seasons in Kansas

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Highlights

- Later planting and greater site elevation or latitude decreased seasonal growing degree days and cotton yield in Kansas.
- Higher irrigation capacity (rate) usually increased lint yield, which was probably due to increased early boll load.
- Strategies for splitting land allocations between high irrigation rates and dryland did not increase production.
- Cotton may reduce irrigation withdrawals from the Ogallala aquifer, but the Kansas growing season limits production.

Abstract. *Precipitation in the western Great Plains averages about 450 mm, varying little with latitude and providing 40% to 80% of potential crop evapotranspiration (ET_c). Supplemental irrigation is required to fully meet crop water demand, but the Ogallala or High Plains aquifer is essentially non-recharging south of Nebraska. Pumping water from this aquifer draws down water tables, leading to reduced water availability and deficit irrigation to produce an alternate crop such as cotton (*Gossypium hirsutum *L.) with a lower peak water demand than corn (*Zea mays *L.). Our objective was to compare simulated cotton yield response to emergence date, irrigation capacity, and application period at three western Kansas locations (Colby, Tribune, and Garden City) with varying seasonal energy or cumulative growing degree days (CGDD) and compare split center pivot deficit irrigation strategies with a fixed water supply (i.e., where portions of the center pivot land area are managed with different irrigation strategies). We used actual 1961-2000 location weather records with the GOSSYM simulation model to estimate yields of cotton planted into soil at 50% plant-available water for three emergence dates (DOY 145, 152, and 159) and all combinations of irrigation period (0, 4, 6, 8, and 10 weeks beginning at first square) and capacity (2.5, 3.75, and 5.0 mm d^{-1}). Simulated lint yield and its ratio to ET_c, or water use efficiency (WUE), consistently decreased with delayed planting (emergence) as location elevation or latitude increased due to effects on growing season CGDD. Depending on location, simulated cotton lint consistently increased ($p = 0.05$) for scenarios with increasing irrigation capacity, which promoted greater early season boll load, but not for durations exceeding 4 to 6 weeks, probably because later irrigation and fruiting did not complete maturation during the short growing season. Cotton WUE generally increased, with greater yields resulting from earlier emergence and early high-capacity irrigation. We calculated lower WUE where irrigation promoted vigorous growth with added fruiting forms that delayed maturation and reduced the fraction of open bolls. The irrigation strategy of focusing water at higher capacities on a portion of the center pivot in combination with the dryland balance did not increase net yields significantly at any location because the available seasonal energy limited potential crop growth and yield response to irrigation. However, the overall net lint yield was numerically larger for focused irrigation strategies at the southwest Kansas location (Garden City). Based on lint yields simulated under uniform or split center pivot deficit irrigation, we conclude that cotton is poorly suited as an alternative crop for central western and northwestern Kansas because of limited growing season CGDD.*

Keywords. *Cotton, Crop simulation, Deficit irrigation, Evapotranspiration, Irrigation capacity, Split center pivot irrigation, Water use efficiency, Yield limiting factors.*

The semiarid U.S. High Plains physiographic region, extending from Texas to South Dakota, receives mean annual precipitation of approximately 450 mm, which provides 40% to 80% of the corresponding potential crop water demand for evapotranspiration (ET_c) (Follett et al., 2012). To meet the balance of ET_c, irrigation from the High Plains aquifer was developed

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during the 1950s with groundwater withdrawals that generally exceeded the negligible recharge (Stewart, 2003). The spatially weighted water-level change in the High Plains aquifer since pre-development (ca. 1950) averages -4.8 m overall and -8 m in Kansas (McGuire, 2017), in contrast to the limited variable changes of alluvial aquifers along the Colorado-Kansas border or central Kansas (Woods et al., 2000). In western Kansas, the annual groundwater declines for the Ogallala region of the High Plains aquifer averaged 0.16 to 0.51 m over the past 20 years, with an average recommended pumping reduction of 30% to achieve irrigation sustainability, i.e., no change in the water table (Whittemore et al., 2018). The declining water table has triggered a growing concern for the eventual depletion of the aquifer and reduction of irrigated areas in the central and southern High Plains by the year 2100, as estimated by Haacker et al. (2016).

The irrigated production levels in the southern and central Great Plains have been sustained, in part, by the development of additional wells to compensate for declining saturated thickness and reduced pumping capacities. However, extending the longevity of the aquifer will require reduction in irrigated land area or some combination of increased irrigation efficiency and alternative crops. Improved irrigation scheduling and application technologies that increase irrigation efficiency (Howell, 2001) have produced corresponding water savings of 1.96% and 3.91%, calculated as a fraction of the total irrigation demand, in the Texas High Plains (Colaizzi et al., 2009). Additional water savings averaging 8.26% of the irrigation demand could be achieved through the production of alternate crops that exhibit greater tolerance of water deficit stress. For western Kansas, alternative crops gaining interest include grain sorghum (*Sorghum bicolor* (L.) Moench.) and cotton (*Gossypium hirsutum* L.), a potentially more profitable crop. The median seasonal ET_c estimated for the Texas High Plains with a calibrated Soil and Water Assessment Tool (SWAT) model was 450 mm for cotton, or approximately 30% less than the ET_c for corn (*Zea mays* L.) of 635 mm (Marek et al., 2017). On the merit of potential water savings when growing cotton rather than corn in the Ogallala region of Kansas, Gowda et al. (2007) evaluated cotton production using the growing season energy expressed as cumulative growing degree days (CGDD) calculated as the sum of the daily average of the minimum and maximum air temperatures minus a base temperature of 15.6°C. Their model used growing season energy to determine cotton growth and estimate lint yield assuming a typical plant density. Gowda et al. (2007) determined that cotton was a suitable alternative crop for conserving groundwater irrigation in the southwest Kansas Ogallala region despite any growing season energy limitations. They also concluded that some irrigation strategies may be managed to extend cotton production to higher elevations and more northern U.S. latitudes. For example, by imposing water stress, Baumhardt et al. (2017) induced cotton cutout and further flowering, which significantly reduced the number of green bolls while not reducing either the number of open bolls or lint yield.

Converting production of corn to cotton in western Kansas must confront challenges to identify suitable production practices for the alternative crop while promoting profitability and desirable yields under deficit irrigation. Computer crop growth simulation has long been recognized as an efficient means of evaluating cultural practices (Whisler et al., 1986; McKinion et al., 1989) and evaluating some dryland cropping systems (Staggenborg and Vanderlip, 2005). Cotton simulation has experienced increasing use by nontraditional crop modelers to gain production insights related to economics and climate issues (Thorp et al., 2014). Crop growth model guidance for improved management response to environmental factors increased growing season irrigation efficiency (Thorp et al., 2017). Modeling cotton growth, as concluded by Modala et al. (2015) for the Texas Rolling Plains, may identify successful deficit irrigation strategies for producing a relatively new crop in western Kansas. Using the GOSSYM cotton model, Baumhardt et al. (2009) confirmed that cotton lint yield and water use efficiency (WUE), or the ratio of lint yield to ET_c, represented functionally as:

$$\text{WUE} = \frac{\text{Lint yield}}{\text{ET}_c} \tag{1}$$

increased with increasing initial soil water or greater irrigation capacity. Application of a fixed water resource to a center pivot split 2:1 between irrigation at 3.75 mm d^{-1} and dryland and split 1:1 between dryland and 5.0 mm d^{-1} irrigated areas (Baumhardt et al., 2009) or multiple spatial combinations (Nair et al., 2013) produced greater net cotton yields compared with uniform irrigation at 2.50 mm d^{-1}. Although reducing irrigation duration from 8 weeks to 4 weeks decreased modeled yield of cotton irrigated at 2.5 mm d^{-1} by 14% at Bushland, Texas, increasing the irrigation capacity to 3.75 and 5.0 mm d^{-1} in 2:1 and 1:1 split center pivot applications increased the net yield after 4 weeks to 95% of the 8-week uniform irrigation that received double the water (Baumhardt et al., 2009).

Grower-managed water availability for irrigation is often dictated by economic returns of competing crops and by well pumping capacity, which has led to cropping alternatives such as cotton. While the CGDD analysis reported by Gowda et al. (2007) demonstrated the impact of limited growing season energy to decrease the yield potential of full ET_c irrigated cotton, the effect of deficit irrigation strategies to reduce applications or advance maturation (Baumhardt et al., 2017) is not known for western Kansas. The objective of this study was to develop irrigated cotton production information for the limited growing season energy conditions of western Kansas that improves water conservation through more efficient water application. To achieve this goal, we compared simulated cotton yields having different emergence dates under various irrigation duration and pumping capacity combinations and evaluated net yields for applied split pivot irrigation strategies.

Materials and Methods

Study Sites

Irrigation capacity and duration effects on the growth and yield of cotton with normal emergence (DOY 145) and two progressively later emergence dates (DOY 152 and DOY 159) were evaluated for locations in southwest, west central, and northwest Kansas (fig. 1) with specific site locations and

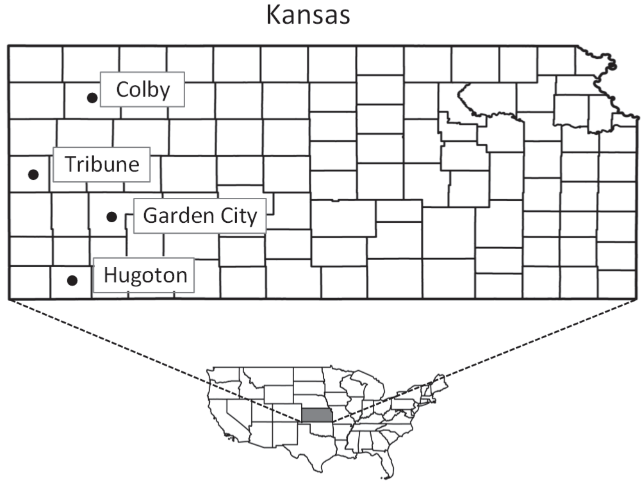

Figure 1. Southwest, west central, and northwest Kansas sites used for modeling cotton response to irrigation application capacity and period.

elevations listed in table 1. To do this, we used the mechanistic cotton growth simulation model GOSSYM (Baker et al., 1983) version 4, which simulates C, N, and water processes subject to stresses due to solar radiation, temperature, rainfall, wind, and soil conditions (Liang et al., 2012). Related models (CALGOS and Cotton2K) were developed without equating dewpoint and daily minimum temperatures, which led GOSSYM to underestimate ET_c in arid climates (Marani et al., 1992; Marani, 2004). However, Staggenborg et al. (1996) concluded that leaf area index (LAI) caused more errors in calculated ET_c for semiarid climates. CROPGRO-Cotton is another process-oriented model that simulates daily crop development and carbon, N, and soil water balances (Jones, 2003; Pathak et al., 2007), but modeled yields did not consistently agree with observed 2005 and 2006 lint yields (Pachta, 2007). GOSSYM requires site-specific climate input data, including observed daily solar irradiance (MJ m^{-2}), maximum and minimum air temperatures (°C), precipitation (mm), and wind run (km). These climate data were supplied from 1961-2000 weather records that predate the period when observed global warming was no longer indistinguishable from human-induced warming, according to the IPCC (Allen et al., 2018). By confining weather data to a period with only random climate variability or a stationary series (Haan, 1977), the simulated cotton response to scenario emergence and the irrigation rate and duration were not confounded by climate change effects that biased the seasonal energy.

Although not the dominant soil at any site, we selected a nearly level (~1.0% slope) Ulysses silt loam (fine-silty, mixed, superactive, mesic Torriorthentic Haplustoll) for the simulations because it covers 11% to 25% of the county at all three locations (NRCS, 2016, 2018a, 2018b). Using a common soil eliminated any soil × location interaction and simplified interpretation of location crop performance differences due to irrigation rate and duration. The Ulysses 1.9 m deep profile was divided into two layers that included a mollic epipedon (0.0 to 0.38 m) and underlying cambic horizons (0.38 to 1.88 m) with measured bulk density, texture, N, and hydrologic properties adapted from pedon ID 89P0734 (KSSL, 1989). Each simulation began with an assumed initial soil water content of 50% plant-available water (~182 mm) uniformly distributed within the profile, although greater water would likely increase yield. That amount of moisture is close to the ~170 mm of soil water measured for 0 to 1.9 m by Schlegel et al. (2016) at the time of planting for deficit-irrigated (127 mm) corn, sorghum, and soybean crops in western Kansas. Modeled maximum rooting depth was unrestricted within the 1.9 m Ulysses soil profile and consistent with water extraction patterns to depths of 1.6 to 1.9 m reported for cotton grown in 2.2 m deep lysimeters at Bushland, Texas (Tolk and Evett, 2012).

Table 1. Georeferenced location, elevation (m ASL), and mean growing season (CGDD) of the modeled sites.

Modeled Site	Georeferenced Location	Elevation (m ASL)	Mean Thermal Energy (CGDD)
Colby	39° 23′ N, 101° 2′ W	962	832
Tribune	38° 28′ N, 101° 45′ W	1100	859
Garden City	37° 58′ N, 100° 51′ W	865	945
Hugoton	37° 18′ N, 101° 15′ W	940	1170[a]

[a] Mean CGDD for the 2005-2012 Hugoton trials excludes 2008 and 2010 due to auxin herbicide damage.

Cotton simulations were based on typical 0.76 m row spacing at 13 plants m^{-2} population using a stripper-type cultivar with a growth habit similar to All-Tex Atlas (Levelland, Tex.), as described in the variety file ST1 supplied with GOSSYM (Staggenborg et al., 1996; Baumhardt et al., 2009, 2015, 2018). The variety files contain numerous parameters that modify the modeled plant growth and development through carbohydrate partitioning to reflect dry matter governing height, nodes, squares, bolls, and yield (Landivar et al., 2010). Sufficient N to maximize lint yield for available water up to 700 mm (Morrow and Krieg, 1990) or a yield equal to the variety trial 1200 kg ha^{-1} mean for desirable CGDD (Duncan et al., 1993) was provided by Ulysses soil profile N of ~33 kg N ha^{-1} (KSSL, 1989) plus 110 kg N ha^{-1} fertilizer. No other nutrient fertilizers were specified because GOSSYM does not simulate their effects on cotton growth. Adequate infiltration of rain and irrigation into the Ulysses soil typically results in negligible runoff (Klocke et al., 2014) and was not simulated. All simulations began two weeks before the scenario emergence 10 d after a 15 May target planting date (DOY 145) plus sequential emergence delays of 1 and 2 weeks to DOY 152 and 159 (Baumhardt et al., 2009). Growing season simulations continued from the prescribed emergence until plants reached physiological maturity (100% open bolls) or the first freeze, when lint yield and growing season ET were determined.

Model Validation

Because cotton has been recognized as an alternative crop for Kansas (Duncan et al., 1993), ongoing variety trials were conducted in southern Kansas, including about 15 km northeast of Hugoton (37° 18′ N, 101° 15′ W; 955 m ASL) in southwest Kansas (fig. 1). At that site, irrigated cotton variety trials following irrigated corn provided lint yield performance data from 2005 to 2012, excluding 2008 and 2010 due to auxin-type herbicide injury (Staggenborg and Duncan, 2007, 2009, 2010; Staggenborg and Heer, 2011; Haag et al., 2012, 2013). The annual variety trials, planted in 0.76 m row spacing at 13 plants m^{-2} population on DOY 144 ±2, varied in number of entries from 14 to 49, with few repeated >3 years. We used the overall observed yield means from one dryland and six irrigated trials in assessing model performance independently of compared location, emergence, or irrigation duration and pumping capacity. Cotton received customary crop protection chemicals and non-limiting irrigation and fertility applications from the cooperating producers who hosted these trials. Cotton was sampled at maturity or following a killing freeze for lint yield and fiber quality at the Texas Tech Fiber and Biopolymer Research Institute, Lubbock, Texas (Staggenborg and Duncan, 2000).

Cotton yield was estimated by GOSSYM simulations for a stripper-type cultivar described in the variety file ST1 planted in 0.76 m row spacing at 13 plants m^{-2} population on DOY 145. The model-required soil bulk density, texture, N, and hydrologic properties were specified for a 1.9 m Ulysses soil profile at a uniformly distributed initial soil water content of 50% plant-available soil water. Nutrients specified for GOSSYM included the Ulysses profile 33 kg N ha^{-1} (KSSL, 1989) and 110 kg N ha^{-1} fertilizer, or roughly double that recommended for irrigated cotton by Duncan et al. (1993). Modeled lint yield was determined at plant physiological maturity (100% open bolls) or the first freeze.

CROP SIMULATION DESIGN

Cotton growth, lint yield, and water use were simulated under dryland conditions (precipitation only) or with decreasing deficit irrigation. That is, irrigation, applied independently of crop growth stage, included three rates of 2.5, 3.75, and 5.0 mm d^{-1} that typify the variation in regional irrigation capacities of ~0.29, 0.43, and 0.58 L s^{-1} ha^{-1} and correspond to weak, declining, and strong producing irrigation wells (Schlegel et al., 2012). Irrigation applications to supplement rainfall were on a 7 d interval beginning 37 d after emergence, or around first square, and continuing for incrementally increasing durations of 4, 6, 8, and 10 weeks to characterize cotton response to progressively later applications. The cumulative irrigation depth resulting from the different combinations of irrigation capacity and period simulated over the growing season are shown in figure 2. A total of 13 scenarios comprised of dryland, 0.0 mm d^{-1}, plus all possible combinations of irrigation capacity (three levels) and duration (four levels) for applications from 70 to 350 mm were evaluated for each of three emergence dates during 40 years of weather records at each of the three sites, amounting to 4,680 simulations.

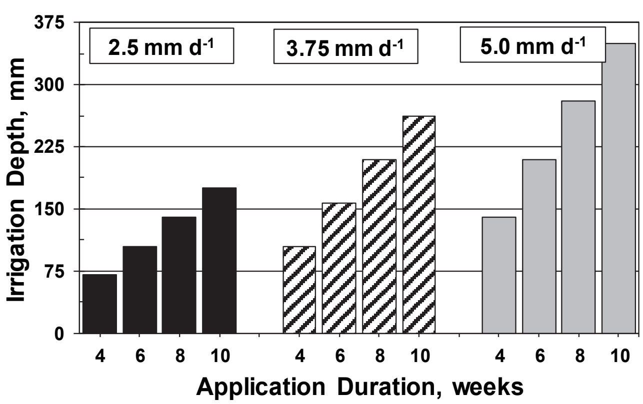

Figure 2. Depth of irrigation applied using rates of 2.5, 3.75, and 5.0 mm d^{-1} for periods of 4 to 10 weeks showing incrementally greater application with increasing duration and similar or common amounts applied earlier in the growing season for higher irrigation rates.

STATISTICAL ANALYSIS

Cotton growth, lint yield, and ET_c were simulated and WUE was calculated for each scenario emergence date by irrigation capacity and duration combination under the unique input weather conditions from 40 growing seasons at each location. Normal climatic variability from the weather conditions, e.g., rainfall and temperature, unique for each growing season (1961-2000) supplied, as 40 replicates, the random experimental variability for comparing GOSSYM projected cotton performance. We plotted by declining rank all growing season CGDD and yield values from the combined scenarios of irrigation practices and emergence dates at each location as a function of the nontransformed probability of being exceeded (exceedance probability) according to Barfield et al. (1981). We then compared the emergence date by irrigation capacity and duration fixed effects at each location according to a factorial arrangement of a completely randomized design replicated by years as random effects using the SAS mixed model ANOVA procedures (SAS, 2014). Again using years as random effects, we subsequently isolated simulated cotton water use, growth, and lint yield at each location to compare scenario emergence date and irrigation capacity by duration fixed effects by location. Unless otherwise specified, all statistical analysis effects were declared significant at the 0.05 probability level.

RESULTS AND DISCUSSION

MODEL UNCERTAINTY

Any cotton production insight using crop growth simulation largely depends on the validity of the simulation model to calculate plant performance under variable growing conditions. For GOSSYM, previous model validation by Staggenborg et al. (1996) demonstrated that the calculated daily water use was within one standard deviation of measured values and seasonal totals differed by ~10% for irrigated cotton under semiarid southern High Plains conditions. Similarly, the observed and modeled dryland lint yields at Bushland, Texas, about 180 km north agreed well with observations, achieving an RMSE that was ~20% of the mean yield (Baumhardt, 2002; Baumhardt et al., 2018). For Kansas, GOSSYM-estimated yields are plotted in figure 3 across overall means of as many as 49 cultivars from ongoing variety trials conducted near Hugoton, Kansas, 228 km NNE of Bushland. Observed varietal mean yields ± standard error generally agreed with the corresponding model-simulated yields and appear along the 1:1 line up to modeled yield estimates exceeding 1400 kg ha^{-1}, where the observed yields averaged about 1700 kg ha^{-1}. Regressing observed on simulated yields through a 0.0 intercept produced $R^2 = 0.93$ and a slope of 1.11 due to model underestimation of the higher 1600 to 1800 kg ha^{-1} observed yields. We suggest that this yield underestimation was possibly because the N specified to meet crop needs for the expected 1200 kg ha^{-1} yield was insufficient compared with the 33% to 50% higher actual

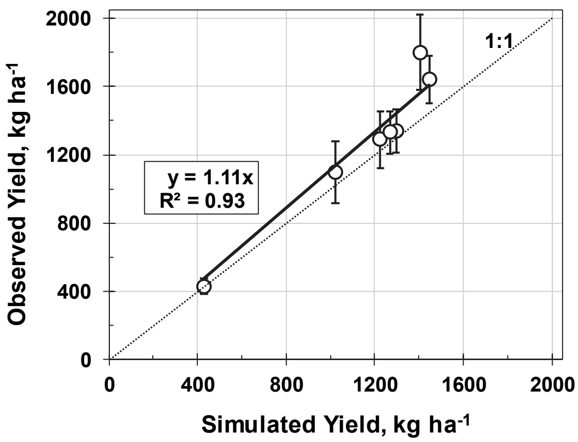

Figure 3. Mean lint yields of cotton cultivar trials in southwest Kansas from 2005 to 2012 plotted in relation to GOSSYM-simulated yields for corresponding emergence and irrigation conditions. Error bars represent standard errors of mean observations and are plotted with both 1:1 and regression lines that intercept the origin.

yields. Despite the possible N deficit, GOSSYM-simulated lint yields averaged ~90% of the mean observed yields of multiple cultivars, suggesting robust model performance that, taken in aggregate, shows reliable calculated yields. Validation of GOSSYM using local soil parameters and weather has been consistently successful at sites spanning a ~400 km distance from Lubbock to Bushland (Staggenborg et al., 1996; Baumhardt et al., 2018) and on to Hugoton. This suggests that model application for an additional ~250 km distance north from Hugoton to Colby can provide reasonable management inferences despite no further validation in lieu of variety performance data.

Growing Season CGDD and Lint Yield

Growing season accumulated GDD beginning with emergence and continuing until first freeze often governs cotton performance and varies with elevation, latitude, and regional weather patterns. For our three Kansas locations, the greatest CGDD averaged across all emergence dates was 945 GDD °C at Garden City and ranged from a minimum of 753 GDD °C to a maximum of 1288 GDD °C (graph C in fig. 4). In contrast, the corresponding CGDD averaged 859 GDD °C for Tribune, ranging from 571 to 1116 GDD °C, and averaged 832 GDD °C for Colby, ranging from 598 to 1086 GDD °C. Each week of emergence delay decreased the CGDD by approximately 28 GDD °C at Garden City, by 23 GDD °C at Tribune, and by 22 GDD °C at Colby, which reflected the declining seasonal CGDD accrual due to increasing elevation and, to a lesser extent, more northern U.S. latitude. The seasonal CGDD minimum of 750 GDD °C at Garden City was, in fact, greater than that observed at Tribune for nearly 20% of the years and greater than that observed at Colby for about 25% of the years. Although the median CGDD at Garden City exceeded 85% of the observations at Tribune and 69% of the observations at Colby, the corresponding energy maximums of about 1100 GDD °C at Tribune and Colby exceeded all observed CGDD except the largest 7% to 10% of the growing seasons at Garden City. To put growing season CGDD in perspective, Gowda et al. (2007) specified crop failures when growing season CGDD did not exceed 800 GDD °C, which compares with the median growing season CGDD of 803 GDD °C at Colby and 832 GDD °C at Tribune. Thorp et al. (2014) noted that many crop models, including GOSSYM, use a growing degree day concept based on air temperature to simulate crop processes and development, which makes CGDD critical to yield.

The corresponding simulated lint yields for fully irrigated (5 mm d^{-1}) cotton are plotted as a function of exceedance probability in graphs D to F in figure 4 for the three emergence dates at Colby, Tribune, and Garden City. Median yield at all locations was greatest for the early emergence date (DOY 145) and decreased by 20% to 25% with each week of delayed emergence. In Kansas, the cotton lint yield, like growing season CGDD, was greatest for Garden City at 604 kg ha^{-1} and decreased to 365 kg ha^{-1} at Tribune and 314 kg ha^{-1} at Colby with increasing latitude or elevation, which was similar to modeled dryland cotton yield trends in the Texas High Plains (Mauget et al., 2017). That is, Garden City lies at an elevation 235 m below and 55 km east of Tribune and 97 m below and 158 km south of Colby, thus contributing to the median lint yield at Garden City that exceeded 85% to 95% of the simulated lint yields at Tribune and Colby. The minimum simulated lint yields at Garden City, which ranged from 145 to 445 kg ha^{-1}, exceeded 30% to 40% of the simulated lint yields at Tribune and Colby for the corresponding planting dates. Frequent 0.0 kg ha^{-1} lint yield estimates reflect the risk of crop failure and indicate the unsuitability of cotton as an alternate crop. Gowda et al. (2007) estimated crop failure for three out of four years in seven of eight northwestern counties from around Tribune, Kansas, to north of Colby, Kansas. Our calculated yields of less than 100 kg ha^{-1} for Colby and Tribune likewise comprised 10% to 30% of simulated lint yields and may represent an undesirably large fraction for risk-averse producers.

Using a simple linear regression of growing season CGDD on simulated lint yield for the combined locations and emergence dates (data not shown), we determined that a growing season CGDD not exceeding 700 GDD °C was insufficient to produce minimal (100 kg ha^{-1}) lint yield, essentially a crop failure. An overall simulated target lint yield of 500 kg ha^{-1} was correlated (r^2 = 0.63) to a minimum CGDD of 900 GDD °C, although yield increased by 100 kg ha^{-1} incrementally with each 50 GDD °C additional CGDD during the growing season. Our simulated yield conversion rate for accumulating growing season energy was very similar to the 42 GDD °C used when estimating potential cotton yield for the southern and central High Plains (Gowda et al., 2007). For example, early (DOY 145) emergence cotton at Garden City had sufficient growing season CGDD for simulated lint yields exceeding 500 kg ha^{-1} during 85% of the years, as compared with 75% and 65% when emergence was delayed by 7 and 14 days, respectively. Likewise, simulated lint yield of 500 kg ha^{-1} for irrigated cotton at Tribune and Colby decreased by ~20% after a 14-day emergence delay during more than one-third of the 40 growing seasons. These cotton yields under full ET replacement irrigation revealed poor production with limited growing season CGDD in west central (Tribune) or northwestern (Colby) Kansas. However, the potential risk of growing cotton with insufficient growing season CGDD on a Ulysses soil has been shown to be

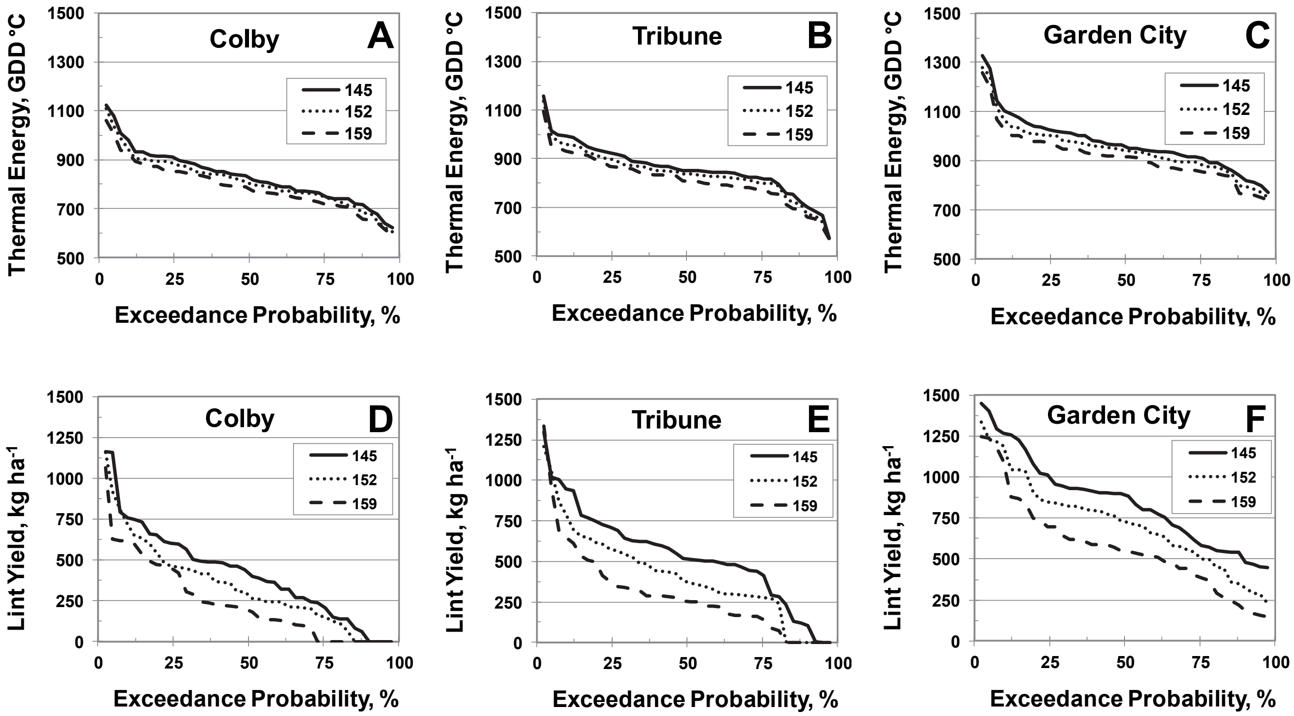

Figure 4. CGDD for the period 1961-2000 at the three locations considered (A, B, C) and simulated cotton lint yield (D, E, F) plotted as a function of exceedance probability for cotton emerging on day-of-year (DOY) 145, 152, and 159 (25 May, 1 June, and 8 June).

manageable with deficit irrigation that limited water use to promote fruit maturation (Baumhardt et al., 2018).

Effects of Emergence, Irrigation Capacity, and Duration on Cotton Lint Yield

Simulated mean cotton lint yields for the scenario irrigation capacities, durations, and emergence date combinations are summarized for main effects by location in table 2. The overall average yield decreased significantly ($p < 0.01$) from 604 kg ha^{-1} at Garden City to 365 kg ha^{-1} at Tribune and 314 kg ha^{-1} at Colby because of location limited growing season CGDD that failed to mature bolls compared with Garden City. Progressively later emergence dates likewise decreased both growing season length and, consequently, yield at all three locations (table 2) again due to reduced boll maturation. Irrigation capacity and duration together determine the cumulative irrigation amounts that regulate potential yield depending on growing season CGDD. As irrigation capacity increased from dryland or 0.0 mm d^{-1} to 5.0 mm d^{-1}, cotton lint yield increased significantly from 229 to 697 kg ha^{-1} at Garden City, with a modest increase of ~250 kg ha^{-1} at Tribune and Colby but no yield differences between the 3.75 and 5.0 mm d^{-1} irrigation capacities. The diminished irrigation capacity yield benefit for later crop emergence and resulting lower CGDD (data not shown) was a significant interaction, although increasing irrigation capacity is a significant and logical benefit to yield. Greater irrigation duration translates into increased water application and consequently larger plants and a greater boll load; however, our simulated yields never differed significantly for irrigation durations >8 weeks for any location. While irrigation durations of 4, 6, and 8 weeks incrementally increased lint yield ($p = 0.05$) at Garden City, simulated cotton yields for Tribune increased as irrigation duration increased above 4 weeks or increased from 6 to 10 weeks, suggesting that growing season CGDD limited crop response to irrigation (table 2). This limited growing season CGDD effect on yield response to irrigation was further demonstrated at Colby by a non-significant 15 kg ha^{-1} lint yield increase as the irrigation season duration increased from 4 to 10 weeks.

Earlier crop emergence combined with both decreased latitude and elevation limits growing season CGDD to interact with crop yield response to irrigation capacity and duration, as revealed in preliminary analyses and shown in figure 5. That is, greater irrigation duration or capacity typically increased lint yield to a smaller extent as location elevation or latitude increased and as plant emergence was delayed. The desirable incremental lint yield increases for the progressively longer 4 to 10 week durations of 2.5 mm d^{-1} irrigation diminished after the irrigation capacity increased to 5.0 mm d^{-1}, and yields did not differ for durations greater than 6 weeks.

Location-specific mean cotton water use ranged from 450 mm at Tribune up to 465 mm at Garden City with an overall average of ~460 mm, indicating that crop water use was largely independent of location, unlike either growing season energy for the dependent yield. Not surprisingly, our simulated water use at all locations increased for the progressively earlier emergence dates due to the resulting longer growing season for maturing bolls (table 2). The incrementally greater irrigation capacities, increasing from 0.0 to 5.0 mm d^{-1}, also significantly increased simulated water use at Garden City and Colby, but water use at Tribune for the 3.75 and 5.0 mm d^{-1} irrigation capacities did not differ significantly. Our calculated water use also increased ($p < 0.01$) as irrigation duration increased incrementally from 4 to 10 weeks regardless of location. For scenarios with either greater irrigation capacity or

Table 2. Main effects of emergence dates (E), irrigation capacity (C), and duration (D) on simulated cotton lint yield, ET, and WUE along with ANOVA test results. Effect means within columns followed by the same letter are not significantly different (p = 0.05).

	Lint Yield ($kg\ ha^{-1}$)			Water Use (mm)			Water Use Efficiency ($kg\ m^{-3}$)			Fraction of Open Bolls (%)		
Effect	Garden City	Tribune	Colby	Garden City	Tribune	Colby	Garden City	Tribune	Colby	Garden City	Tribune	Colby
Emergence (DOY)												
145	710 a	465 a	397 a	480 a	463 a	481 a	0.147 a	0.099 a	0.083 a	67 a	46 a	38 a
152	609 b	367 b	317 b	466 b	452 b	464 b	0.131 b	0.079 b	0.068 b	58 b	36 b	30 b
159	493 c	263 c	227 c	448 c	436 c	440 c	0.111 c	0.060 c	0.051 c	46 c	25 c	20 c
Irrigation capacity ($mm\ d^{-1}$)												
0.0 (dryland)	229 d	149 c	180 c	278 d	271 c	305 d	0.070 c	0.049 c	0.055 c	66 a	49 a	37 a
2.5	480 c	305 b	285 b	415 c	405 b	428 c	0.114 b	0.073 b	0.066 b	64 b	41 b	32 b
3.75	634 b	380 a	323 a	470 b	456 a	468 b	0.137 a	0.083 a	0.069 a	55 c	34 c	28 c
5.0	697 a	409 a	334 a	509 a	490 a	490 a	0.139 a	0.082 a	0.067 ab	53 d	32 c	28 c
Irrigation duration (weeks)												
4	544 c	335 c	304 a	404 d	394 d	414 d	0.134 a	0.083 a	0.073 a	60 a	38 a	30 a
6	603 b	364 b	314 a	447 c	434 c	449 c	0.135 a	0.082 a	0.069 b	57 b	36 b	29 a
8	631 a	378 ab	319 a	485 b	469 b	479 b	0.130 b	0.078 b	0.066 c	56 b	35 b	29 a
10	638 a	382 a	319 a	522 a	504 a	506 a	0.121 c	0.073 c	0.062 d	56 b	34 b	29 a
	Significance (p > F)			Significance (p > F)			Significance (p > F)			Significance (p > F)		
Emergence (E)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Irrig. capacity (C)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.02	<0.01	<0.01	<0.01
E × C	<0.01	<0.01	0.67	0.77	0.23	0.97	<0.01	0.17	0.99	0.41	0.01	0.57
Irrig. duration (D)	<0.01	<0.01	<0.06	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.06
D × E	0.70	0.43	0.99	>0.99	0.99	0.99	0.98	0.98	0.88	0.99	0.99	0.99
D × C	0.06	0.06	0.53	<0.01	<0.01	0.02	<0.01	<0.01	0.02	0.01	0.70	0.33
D × C × E	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99

duration, the increased water available to the crop probably promoted greater evaporative losses and more vigorous plant growth that, consequently, increased cumulative water use. The simulated water use means for the drought-tolerant alternative crop of cotton are comparatively lower than the reported ~650 mm ET for fully irrigated corn currently grown at these locations (Stone et al., 1996; Schlegel et al., 2016), the range of 635 to 677 mm for three different tillage systems and three plant densities in a four-year field study at Colby (Lamm et al., 2009), and the 679 mm simulated for automatically irrigated corn at Garden City (Araya et al., 2019).

Although cotton water use for all locations typically increased with the earlier emergence and greater irrigation capacity and duration main effects, one significant interaction between irrigation capacity and duration was identified (table 2). To illustrate this interaction, we plot simulated cotton water use at Garden City for each of the non-zero irrigation capacities and duration combinations within the three emergence dates, as shown in figure 6. The simulated cotton water use for any emergence date incrementally increased with each additional 2-week water application up to 10 weeks, and the water use increment varied with irrigation capacity. For example, simulated water use for the 2.5 $mm\ d^{-1}$ irrigation capacity consistently increased by about 32 ±2.5 mm with each 2-week, 35 mm irrigation increment ending on weeks 6, 8, and 10. Cotton water use for the 3.75 $mm\ d^{-1}$ irrigation capacity similarly increased by a near-uniform 42 ±2.5 mm for each biweekly increment. In contrast, the 5.0 $mm\ d^{-1}$ irrigation capacity resulted in a declining water use from 52 mm during the initial 4 to 6 weeks, to 41 mm for the 6 to 8 weeks interval, and ended with 37 mm for weeks 8 to 10. The declining biweekly water use may be due to meeting crop demand for initial vigorous growth and fruiting form development during the early to mid-growing season for the 5.0 $mm\ d^{-1}$ irrigation capacity.

The WUE reflects both growing season CGDD and the effects of irrigation amount and timing on the cotton lint yield. Due to the combined effects of decreased elevation and latitude in increasing the growing season energy, both simulated yields and the dependent WUE were significantly ($p < 0.01$) greater for Garden City, averaging 0.13 $kg\ m^{-3}$, compared with Tribune at 0.079 $kg\ m^{-3}$ and Colby at 0.067 $kg\ m^{-3}$ (table 2). For all locations, WUE increased significantly ($p < 0.01$) with progressively earlier emergence dates as a predictable result of the corresponding higher growing season energy and yield, but emergence delays of only one week depressed WUE. Mean WUE under lower-yielding dryland conditions was significantly ($p = 0.05$) less than any simulation scenario with irrigation, regardless of location. In contrast to Colby, where WUE with irrigation ranged from 0.066 to 0.069 $kg\ m^{-3}$, WUE at Tribune and Garden City for the 2.5 $mm\ d^{-1}$ irrigation capacity increased with either the 3.75 or 5.0 $mm\ d^{-1}$ irrigation capacities that met crop water demand. Similarly, the calculated WUE at Colby ranged from 0.073 to 0.062 as irrigation duration increased from 4 to 10 weeks, while WUE at Tribune and Garden City was optimized by shorter duration irrigation periods of 4 to 6 weeks compared with irrigations for 8 weeks or longer that progressively decreased WUE.

The significant interacting effects of irrigation duration and capacity on WUE, as shown in figure 7, exemplify a conditional benefit of short-duration irrigation at higher capacity. That is, WUE was generally elevated at all locations and for all emergence dates as the number of weeks of irrigation at the 5.0 $mm\ d^{-1}$ capacity decreased from 10 weeks to a minimum of 4 weeks. Decreasing irrigation at the 3.75 $mm\ d^{-1}$ capacity from 10 weeks to a minimum of 6 weeks at Garden City or to a minimum of 4 to 6 weeks for Colby and Tribune met crop water demand sufficiently to elevate WUE. When irrigation capacity supplied 2.5 $mm\ d^{-1}$, the duration to meet crop demand for higher WUE increased to a

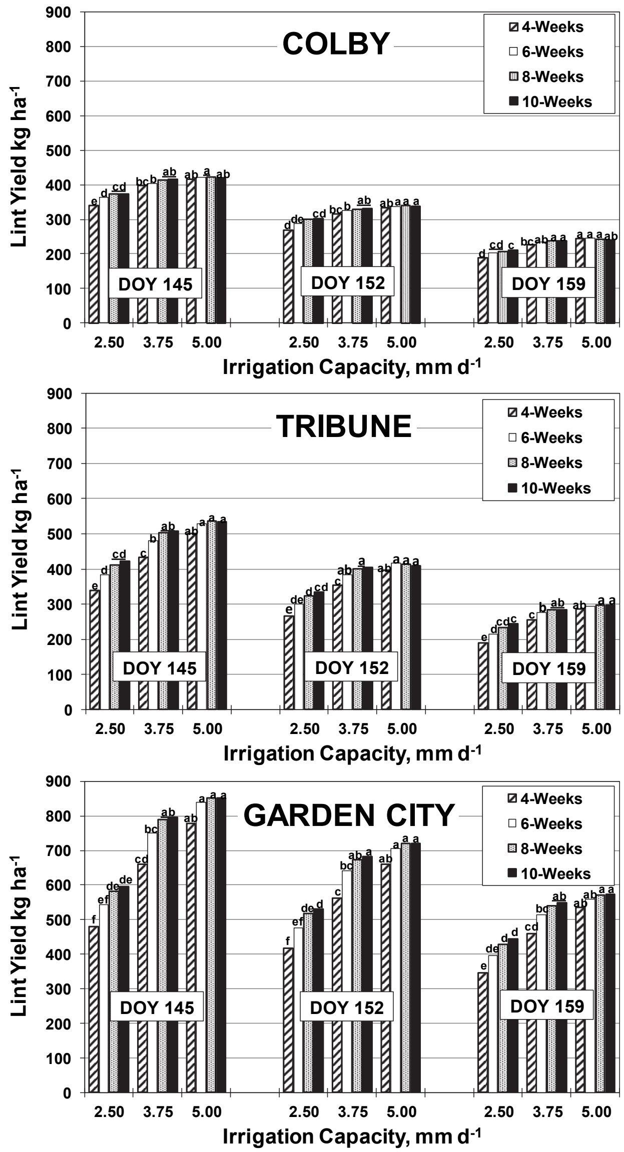

Figure 5. Simulated (1961-2000) lint yields for cotton that emerged on day-of-year (DOY) 145, 152, and 159 and was irrigated for 4, 6, 8, and 10 weeks at 2.5, 3.75, 5.0 mm d^{-1} in Garden City, Tribune, and Colby, Kansas. Columns for common locations and emergence dates with the same letter are not significantly different (p = 0.05) using Tukey.

minimum of 6 to 8 weeks at Tribune and Garden City, while the minimum 4-week duration maintained WUE at Colby. The cotton lint yield WUE values at Garden City were similar to experimental values measured with disk tillage at Bushland during growing seasons accumulating average monthly GDD (Baumhardt et al., 2013) but in the lower range reported by Zwart and Bastiaanssen (2004). Although simulated lint yields generally increased with irrigation amount, the calculated WUE values at Tribune and Colby were much lower by comparison because the limited CGDD was insufficient to mature the crop boll load acquired with the greater water use. The crop consumed water less efficiently to expand biomass resulting from increased leaf area, and fruiting forms did not directly contribute to lint yield that was proportionately lower. That is, in addition to adequately meeting crop water demand, longer duration and higher capacity irrigation scenarios promoted vigorous canopy growth and a greater simulated LAI, averaged across emergence dates, that exceeded 3.1. Similarly, robust fruiting resulted in an overall average of 88 green and open bolls m^{-2} at Colby, which increased to 95 and 114 bolls m^{-2} at Tribune and Garden City, but generally varied less than 10% with earlier emergence or higher irrigation capacity and was practically unaffected by application period (data not shown).

Our simulations revealed that the fraction of open bolls decreased as the location elevation and latitude increased, averaging 57% at Garden City while becoming significantly lower at Tribune and Colby (36% and 29%, respectively). For all locations, the percentage of open bolls also decreased significantly with the progressively later emergence due to the CGDD-limiting shorter growing season length, as well as decreasing when irrigation capacity increased to 5 mm d^{-1} at Garden City or to 3.75 mm d^{-1} at Tribune and Colby (table 2). Except for Colby, the open boll fraction was significantly greater for irrigations lasting 4 weeks compared with longer-duration scenarios with often larger fruit loads. The significant location, emergence, and irrigation capacity and duration main factor effects on the percentage of open bolls and location-specific interactions between emergence and irrigation capacity at Tribune and irrigation capacity and duration at Garden City are shown in figure 8. We observed a progressively larger fraction of open bolls at the more southerly

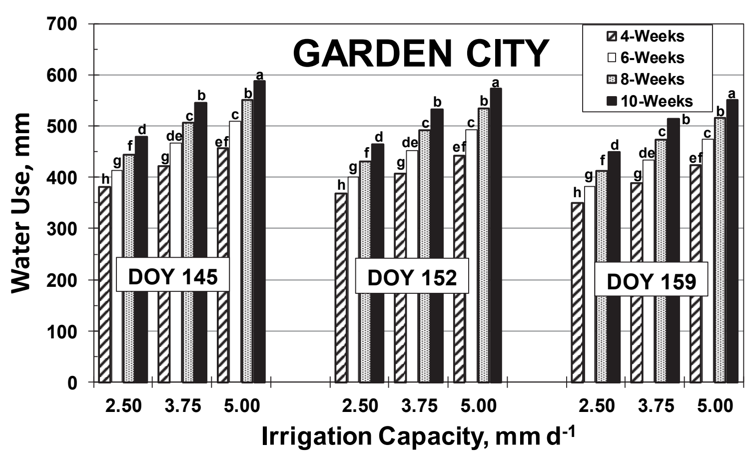

Figure 6. Simulated (1961-2000) water use of cotton emerging on day-of-year (DOY) 145, 152, and 159 and irrigated for 4, 6, 8, and 10 weeks at 2.5, 3.75, 5.0 mm d^{-1} in Garden City. Columns for common emergence dates with the same letters are not significantly different (p = 0.05) using Tukey.

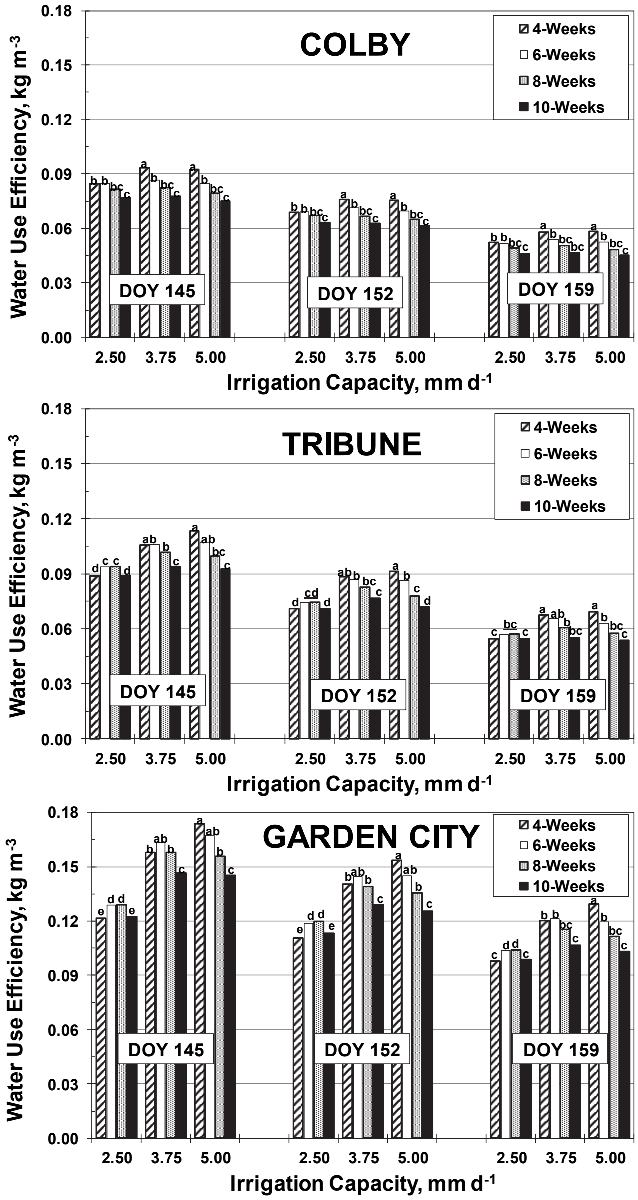

Figure 7. Mean calculated water use efficiency (WUE) of cotton emerging on day-of-year (DOY) 145, 152, and 159 that was irrigated for 4, 6, 8, and 10 weeks at capacities of 2.5, 3.75, 5.0 mm d^{-1} in Garden City, Tribune, and Colby, Kansas. Columns for a specific location and emergence date with the same letter are not different (p = 0.05) using Tukey.

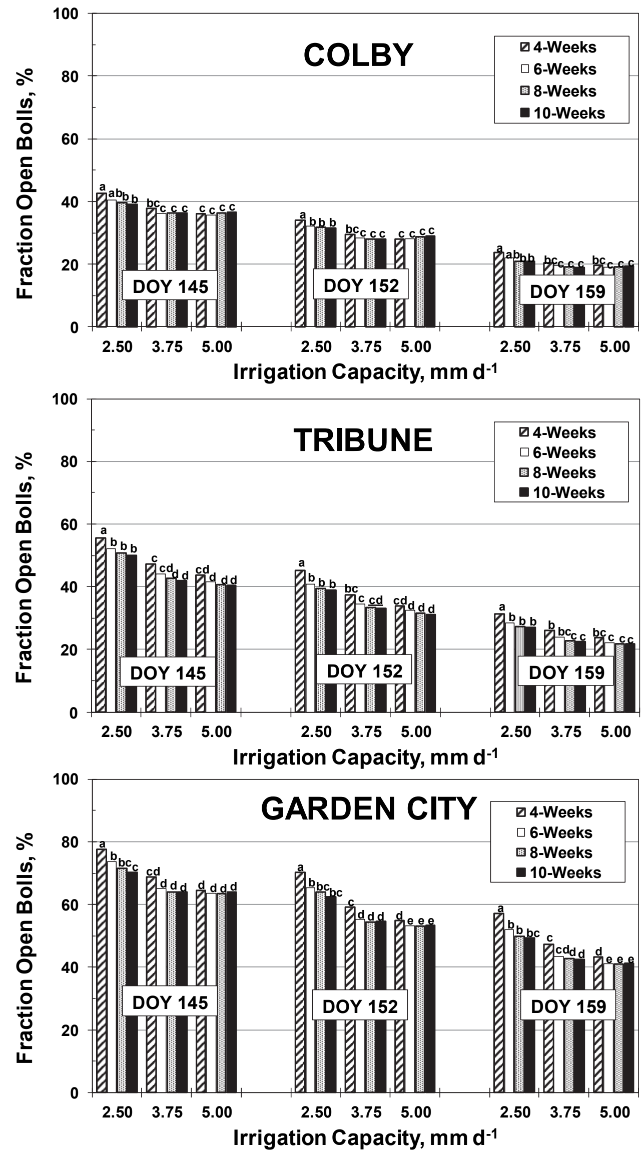

Figure 8. Fraction of open bolls for cotton emerging on day-of-year (DOY) 145, 152, and 159 that was irrigated for 4, 6, 8, and 10 weeks at capacities of 2.5, 3.75, 5.0 mm d^{-1} in Garden City, Tribune, and Colby, Kansas. Columns for a specific location and emergence date with the same letter are not different (p = 0.05) using Tukey.

locations of Tribune and Garden City with greater irrigation capacity and duration combinations. Increasing irrigation capacity combined with duration or emergence produced a declining but small difference in the percentage of open bolls because the impacts of both factors overlap at locations with limited growing season energy. These results suggest that WUE was governed more by factors limiting boll maturation, specifically seasonal CGDD, than the availability of water to support overall plant growth and fruiting.

Irrigation Strategies

Using modeled lint yield results for the Garden City, Tribune, and Colby locations, we compared three fixed water resource irrigation management strategies for the early emergence cotton that extends the growing season (table 3). Strategies included: (1) uniform full pivot deficit irrigation at 2.5 mm d^{-1}, (2) splitting the center pivot at a 2:1 ratio with irrigation at 3.75 mm d^{-1} on the larger fraction and an unirrigated balance, and (3) evenly divided split-pivot irrigation at a 1:1 ratio with 5.0 mm d^{-1} on half and no irrigation on the balance. Dryland lint yields were ~50% of the uniform 2.5 mm d^{-1} irrigation capacity with yields that averaged 550 kg ha^{-1} at Garden City and 389 kg ha^{-1} at Tribune. As a result of diminished crop response to irrigation at Colby due to limited growing season energy, the dryland yields averaged 65% of the uniformly irrigated (2.5 mm d^{-1}) yield of 363 kg ha^{-1}. Likewise, simulated lint yields increased by 36% to 51% over those for 2.5 mm d^{-1} irrigation capacity to 748 to 831 kg ha^{-1} for irrigation capacities of 3.75 and 5.0 mm d^{-1} at Garden City. In contrast, the corresponding lint yields for

Table 3. Garden City, Tribune, and Colby, Kansas, 40-year mean simulated lint yield for DOY 145 emergence cotton under dryland and uniform irrigation at 2.5, 3.75, and 5.0 mm d^{-1} capacities applied for 10 weeks and calculated weighted-average yields of split pivot irrigation strategies compared with uniform 2.5 mm d^{-1} irrigation capacity. Split pivot application strategies used irrigated to dryland ratios of 2:1 at 3.75 mm d^{-1} and 1:1 at 5.0 mm d^{-1}.

Location	Application Strategy	Irrigation Capacity (mm d^{-1})	Corresponding Mean Yield[a] (kg ha^{-1})	Fraction of 2.5 mm d^{-1} Yield (%)	Weighted Yield by Application Strategy[a] (kg ha^{-1})	Yield Fraction of Uniform Application (%)
Garden City	Uniform	2.50	550 c	100	550 c	100
	2:1	3.75	748 b	136	590 c	107
		Dryland	273 d	50		
	1:1	5.00	831 a	151	552 c	100
		Dryland	273 d	50		
Tribune	Uniform	2.50	389 b	100	389 b	100
	2:1	3.75	481 a	124	381 b	98
		Dryland	183 c	47		
	1:1	5.00	525 a	135	354 b	91
		Dryland	183 c	47		
Colby	Uniform	2.50	363 b	100	363 b	100
	2:1	3.75	408 a	112	350 b	96
		Dryland	235 c	65		
	1:1	5.00	420 a	116	328 b	90
		Dryland	235 c	65		

[a] Location-specific yield means followed by the same letter are not significantly different (p = 0.05).

higher irrigation capacities increased by modest amounts at Tribune and Colby, possibly due to the higher elevation effects at Tribune and more northern latitude at Colby. That is, the increasingly limited growing season energy at Tribune and Colby decreased cotton lint yield response to the higher irrigation capacities, as corroborated by similar mean cotton yields for all emergence dates (data not shown).

The mean weighted yields of the uniform, 2:1, and 1:1 application strategies are listed together with the corresponding yield fraction of the uniform 2.5 mm d^{-1} irrigation in table 3 for each location. At Tribune and Colby, yield means for the 2:1 and 1:1 irrigation strategies were 2% to 10% less than their respective 389 and 363 kg ha^{-1} simulated yields with uniform irrigation, but they could not be differentiated at the $p = 0.05$ level. Although the 2:1 split pivot application yields were competitive with the 2.5 mm d^{-1} uniform irrigation at Colby and Tribune, fewer than 20% of years had any yield increase with split pivot irrigation (data not shown). Compared with yields for the 2:1 split pivot application, uniform 2.5 mm d^{-1} irrigation increased lint yield by >50 kg ha^{-1} for Colby in 30% of the years and for Tribune in 20% of the years. Fewer than 20% of the 1:1 split pivot application yields at Colby had any increase over the uniform 2.5 mm d^{-1} irrigation, while uniform irrigation increased yield by >50 kg ha^{-1} for about 33% of the years. Tribune similarly had few years (<10%) in which the 1:1 split pivot irrigation had any increased yield over the uniform 2.5 mm d^{-1} irrigation, in addition to reduced yields with the 1:1 split pivot application than with uniform irrigation in 50% of the years.

Compared with the 550 kg ha^{-1} lint yield for uniform irrigation at Garden City, the lint yields with the 2:1 and 1:1 application strategies were not different ($p = 0.05$). However, the 2:1 strategy improved the weighted average by ~7% to a numerically greater simulated yield of 590 kg ha^{-1}, which is a similar to the findings of Baumhardt et al. (2009, 2015). These findings contrast to net yield increases of 11% to 21% for similarly managed split center pivot irrigation of determinant crops such as grain sorghum (Baumhardt et al., 2007). For about half the years at Garden City, the 2:1 split pivot application resulted in numerically larger yields over the uniform 2.5 mm d^{-1} irrigation, with about 24% of lint yields being >50 kg ha^{-1} larger. As observed at Colby, the Garden City lint yields for uniform irrigation exceeded those for the 2:1 split pivot application by >50 kg ha^{-1} in about 30% of the years. Although 1:1 split pivot irrigation at Garden City had some yield increase over uniform 2.5 mm d^{-1} irrigation in one-third of the years, uniform irrigation increased lint yield by >50 kg ha^{-1} over split pivot irrigation 40% of time. Application strategies that resulted in greater irrigation amounts earlier in the growing season were beneficial, generally resulting in greater early boll formation and maturation that increased simulated lint yield.

Summary and Conclusion

We quantified the effects of irrigation capacity and duration plus split center pivot irrigation strategies on the simulated yield of cotton, an alternative crop with lower water use that may prolong irrigation from the non-recharging Ogallala aquifer in south, central, and northwestern Kansas. Crop emergence date and location governed the long-term available growing season CGDD, which generally determines potential lint yield, as constrained by water and nutrient availability to meet plant demands. Compared with Garden City, growing season CGDD decreased by an average of 10% for the increased elevation and latitude at Tribune and Colby, but the corresponding mean lint yield decreased by a more severe 44%. Although cotton may be produced throughout western Kansas, the simulated crop performance illustrates that the risk associated with cotton production, regardless of commodity price or program support, is considerably less at Garden City in southwest Kansas compared with central western or northwestern Kansas. Not surprisingly, the irrigation capacity and duration scenario elements that increased the amount of water applied also increased, at least numerically, both simulated ET_c and lint yield, although at a variable WUE. That is, simulated WUE was consistently lower at 2.5 mm d^{-1} than for the 3.75 and 5.0 mm d^{-1} irrigation capacities when application durations did not exceed 4 to 6 weeks, depending on the interactive effects of location and emergence date. In addition to the water savings expected by irrigating cotton instead of corn, we conclude that further savings may be possible at locations with higher WUE achieved by avoiding irrigations at 5.0 mm d^{-1} after 6 weeks in the limited growing season conditions of western Kansas. However, the overall net lint yield for focused irrigation strategies at the southwest Kansas location (Garden City) was numerically larger. Based on both uniform and split center pivot deficit-irrigated lint yields, we conclude that cotton appears to be poorly suited as an alternative crop for central western or northwestern Kansas because of limited growing season CGDD. Cotton appears better suited for southwestern Kansas and responded to irrigation strategies promoting early canopy development and fruiting.

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