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Maximizing profits via irrigation timing for capacity-constrained cotton production

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ABSTRACT

Cotton producers on the southern High Plains of Texas face reduced seasonal irrigation capacities as groundwater resources from the Ogallala Aquifer decline. Technological advancements have allowed producers to achieve maximal water use efficiencies (> 95 %); however, new management strategies are necessary to sustain producer profitability. By determining the optimal timing of irrigation, producers may be able to conserve irrigation water and reduce their pumping expenses. In a field experiment conduced from 2010 to 2013, cotton (*Gossypium hirsutum* L.) lint yield and profitability were compared across 27 irrigation treatments using a LEPA irrigation system on Pullman Clay/Olton soils. Irrigation was applied during three growing periods determined by growing degree days ($GDD_{15.6}$), where P1 = emergence to 525 $GDD_{15.6}$, P2 = 525–750 $GDD_{15.6}$, and P3 > 750 $GDD_{15.6}$. Treatments for the experiment included three irrigation capacities of 0, 3.2, and 6.4 mm d^{-1} in a randomized block design with three replications. Profitability was assessed by calculating gross margin from economic budgets that included the management operations from each year. On average, treatments with an irrigation capacity of 0 mm d^{-1} in P1 made 6 % less yield, but saved 30 % more water and generated the same profitability as the IC treatments of 3.2 mm d^{-1}. Irrigation during P3 at the 6.4 mm d^{-1} irrigation capacity (IC) was the most critical for yield potential, generating 114 % more yield than the 0 mm d^{-1} IC and 27 % more than the 3.2 mm d^{-1} IC treatments, resulting in a 468 % and 110 % increase in profit, respectively.

1. Introduction

Increasing drought coupled with declining nonrenewable water levels threaten the economic viability of irrigated agriculture in the Ogallala Aquifer region of the southern Texas High Plains (THP). The Ogallala Aquifer region of Texas constitutes over 36,000 sq mi^2 that covers 48 counties, spanning the Texas panhandle to just north of the Midland-Odessa area. (McGuire, 2007; TWDB, 2011). Agriculture contributes approximately $7 billion annually in economic activity to the THP economy, producing 25 % of U.S. cotton production. Climate models indicate potential increases in average temperatures and the frequency, duration, and intensity of extreme events, making this region a hotspot for severe water stress (Kloesel et al., 2018). During 2011, scorching temperatures coupled with record low precipitation resulted in the worst drought the THP has seen since the 1930′s.

The variability of this semi-arid climate has increased the dependence for water resources, leading to the beginning of a transitional period from irrigated to rainfed agriculture. With the decline in irrigation capacities, producers are unable to meet crop water demand, resulting in reduced yield potential and profitability (Araya et al., 2019). Deficit irrigation is an adaptive solution to declining saturated thickness, making the timing and amount of irrigation crucial to maximize cotton boll development. Himanshu et al. (2019); Ritchie et al. (2009); Sharma et al. (2015), and Schaefer et al. (2018) found irrigation can be strategically applied during different crop growth stages to optimize water availability. However; researchers do not agree on which cotton growth stage is the most sensitive to irrigation (Snowden et al., 2014; Bordovsky et al., 2015; Buttar et al., 2007; Orgaz et al., 1992). A variety of best management practices are being adopted by producers to reduce yield loss and maintain profitability. Pre-plant irrigation has

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been a common strategy used by producers to build moisture in the soil profile to bank water in times of stress, but this can often result in inefficient use of water resources, ranging from 45 to 70% water loss due to the high winds and temperatures characteristic of the region (Mahan et al., 2012; Bordovsky and Porter, 2003).

Compounding these challenges are water management policies and institutions that have hindered adaptation to declining groundwater levels. Texas groundwater law is uniquely governed by a modified rule of capture which contributes to overexploitation of the aquifer. Desired Future Conditions (DFCs) were established by the groundwater management districts to address how the aquifer will be managed (Mace et al., 2008). To meet the DFCs, the High Plains Underground Water Conservation District adopted a 50/50 policy such that 50 % of current water in the Ogallala aquifer would remain in 50 years. This is enforced by restricting the amount of water applied for irrigation to an allowable production rate of 1.50 ac ft per contiguous ac, or 18 in per year (High Plains Water District (HPWD), 2015). Many producers in the region already face pumping capacities below this limit, and the number of irrigated acres facing such natural restrictions is increasing.

The objective of this paper is to evaluate the impact of irrigation timing on the yield and economic profitability of cotton production using various irrigation capacities in the southern High Plains of Texas to improve irrigation management strategies in the face of declining water resources.

2. Methods

2.1. Study Area

This study utilizes results from cotton irrigation experiments conducted by Bordovsky et al. (2015) from 2010 to 2013 at the Texas A&M AgriLife Research Center at Halfway, Texas (1075-m elev., 34° 10′N, 101° 56′ W). The soil types at this location transitioned from a Pullman clay loam (fine, mixed, superactive, thermic Torrertic Paleustolls) to an Olton loam (fine, mixed, superactive, thermic, Aridic Paleustolls) (USDA - NRCS, 2014). The climate of this region is characterized as semi-arid with hot and dry summers and cold winters. The average annual rainfall is 444 mm and average in-season rainfall of 280 mm occurring 1 May to 20 September. During this study, high rainfall was received in 2010, with low and ineffective rainfall in 2011 and 2012 and near average rainfall in 2013.

2.2. Irrigation experiments

Irrigation treatments were applied within three periods during the growing season (P1, P2, P3) for daily maximum irrigation capacities (IC) of 0 mm d^{-1} (**L**ow), 3.2 mm d^{-1} (**M**edium) and 6.4 mm d^{-1} (**H**igh). The periods were defined by growing degree day (GDD) accumulation from crop emergence at a threshold temperature of 15.6 °C (Peng et al., 1989; Mahan et al., 2014), which is also related to the cotton developmental periods of early vegetative/juvenile (P1 = 0–525 $GDD_{15.6}$), reproductive (P2 = 525–750 $GDD_{15.6}$) and maturation (P3 > 750 $GDD_{15.6}$). Combinations of the three irrigation capacities resulted in 27 irrigation treatments. For example, a treatment of **LLL** resulted in irrigation of 0 mm d^{-1} in all three periods and **LLM** resulted in 0 mm d^{-1} in periods one and two and 3.2 mm day in period three. If a rain event occurred, irrigation was reduced or terminated if the water profile was above the specified target for that day. Table 1 describes the maximum irrigation capacities during the three growing periods for each of the 27 irrigation treatments.

This study was designed as a randomized complete block with a nested-factorial treatment arrangement having three replicates in a 3.8 ha test area. A four-span center pivot system delivered water using the LEPA irrigation method. A variable rate irrigation (VRI) controller (7000 VRI, Farmscan AG Pty. Ltd., Toowooma, Australia) was used to create in-field changes in irrigation amounts based on each treatment and location within the field. The VRI system and installation was completed prior to the start of the 2010 field experiment and continued through the 2013 growing season. The treatment locations were left

Table 1
Maximum irrigation capacities (mm d^{-1})for cotton irrigation experiments at the Texas A&M AgriLife Research Center, Halfway, Texas, 2010–2013.

Treatment Name	P1 (0–525 GDD)	P2 (525–750 GDD)	P3 (> 750 GDD)
LLL	0	0	0
LLM	0	0	3.2
LLH	0	0	6.4
LML	0	3.2	0
LMM	0	3.2	3.2
LMH	0	3.2	6.4
LHL	0	6.4	0
LHM	0	6.4	3.2
LHH	0	6.4	6.4
MLL	3.2	0	0
MLM	3.2	0	3.2
MLH	3.2	0	6.4
MML	3.2	3.2	0
MMM	3.2	3.2	3.2
MMH	3.2	3.2	6.4
MHL	3.2	6.4	0
MHM	3.2	6.4	3.2
MHH	3.2	6.4	6.4
HLL	6.4	0	0
HLM	6.4	0	3.2
HLH	6.4	0	6.4
HML	6.4	3.2	0
HMM	6.4	3.2	3.2
HMH	6.4	3.2	6.4
HHL	6.4	6.4	0
HHM	6.4	6.4	3.2
HHH	6.4	6.4	6.4

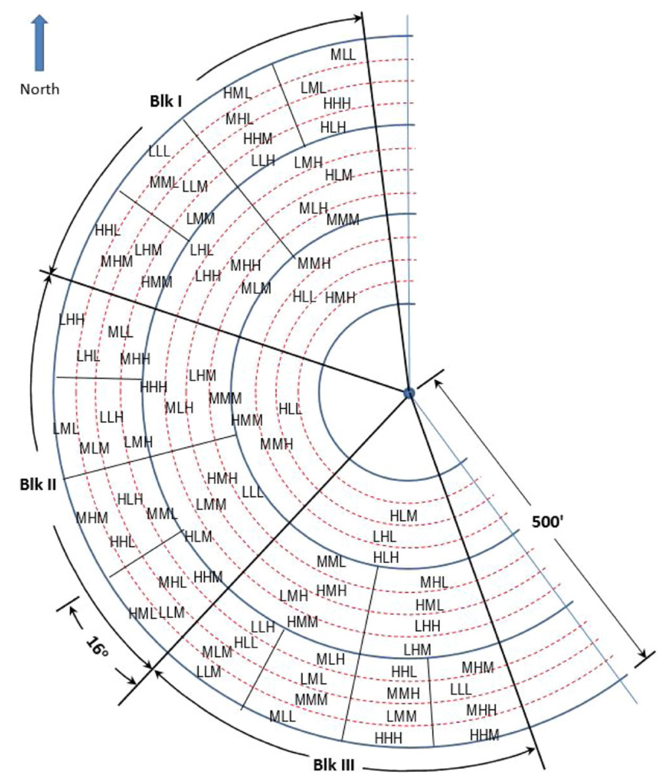

Fig. 1. Diagram of treatment areas for irrigation timing with variable rate irrigation capacity experiments at Texas A&M AgriLife Research Center, Halfway Texas, 2010–2013. The position of letters in treatment names indicate the 1st, 2nd, and 3rd irrigation periods with the letters representing the maximum irrigation capacity in each period. Source: Bordovsky et al. (2015).

Table 2
Agronomic and management data for the cotton irrigation experiments conducted at the Texas A&M AgriLife Research Center, Halfway, Texas, 2010–2013.

Agronomic Data	2010		2011		2012		2013	
Operation/Material Applied/Variety:	Date	Amount	Date	Amount	Date	Amount	Date	Amount
Tillage								
Shred Stalks	29-Mar				6-Dec		29-Nov	
Tandem Disk					6-Dec			
Ripper					6-Jan			
Field Cultivator					9-Jan			
List			23-Nov		9-Jan			
Paratill							24-Jan	
Pull Stalks	29-Mar		18-Nov				30-Nov	
Rolling Cultivator	1-Apr		20-Apr		10-Jan		13-Mar	
Rolling Cultivator							8-Mar	
Bed Roller	11-May		28-Apr				5-Apr	
Rotery Hoe	19-May		20-May		14-May			
Rotery Hoe	21-May		26-May		25-May			
Rotery Hoe					9-Jun			
Rotery Hoe					15-Jun			
Rotery Hoe					18-Jun			
Furrow Dike	10-Jun		14-Mar		2-Apr		18-Mar	
Furrow Dike			28-Apr		19-Jun		4-Jun	
Furrow Dike			13-Jun				25-Jun	
Herbicides (applied in a 112 L ha^{-1} solution								
Pendimethalin 3.3 (mL m^{-2}) & Glyphosate 5.5 (mL m^{-2})	29-Mar	0.18 & 0.24						
Trifluralin 4.0 (mL m^{-2})			20-Apr	0.19				
Glyphosate 6.4 (mL m^{-2})							13-Mar	0.24
Glyphosate 4.0 (mL m^{-2})			12-May	0.24			24-Jun	0.24
Glyphosate 5.5 (mL m^{-2})	4-May	0.17						
Glyphosate 5.5 (mL m^{-2})							8-Jul	0.24
Prometryn 4.0 (mL m^{-2})	12-May	0.36	12-May	0.36	9-May	0.36	22-Jul	0.24
Glyphosate 4.0 (mL m^{-2})	7-Jul	0.24	13-Jun	0.22	13-Jun	0.24		
Glyphosate 5.5 (mL m^{-2})			11-Jul	0.36				
Glyphosate 4.0 (mL m^{-2})			10-Aug	0.3	11-Jul	0.24		
Glyphosate 4.0 (mL m^{-2})					28-Aug	0.24		
Growth Regulator								
Mepiquat Pentaborate 0.82 (mL m^{-2})	13-Jul	0.07						
Mepiquat Chloride 0.35 (mL m^{-2})	21-Jul	0.11	13-Jul	0.05	11-Jul	0.05	6-Jul	0.06
Mepiquat Chloride 0.35 (mL m^{-2})	3-Aug	0.09					22-Jul	0.08
Mepiquat Chloride 0.35 (mL m^{-2})							29-Jul	0.12
Insecticides (applied at 122 L ha^{-1} solution)								
Aldicarb 15 G (g m^{-2})	11-May	0.34	11-May	0.34				
Acephate 90 % (mL m^{-2})							29-May	0.0024
Orthene 75 % (banded, g m^{-2})			13-Jun	0.14	1-Jun	0.028		
Harvest aids (applied at 122 L ha^{-1} solution)								
Etheophon phosphoric acid 6.0 & pyraflufen ethyl 0.208 (mL m^{-2})							2-Oct	0.18 & 0.54
S,S,S-Tribytyl phosphorotrithioate 6.0 & Ethephon Phos Acid 6.0 (mL m^{-2})	19-Sep	0.17 & 0.06	23-Sep	0.09 & 0.24				
Carfentrazone-ethyl 2.0 & Etheophon phosphoric acid 6.0 (mL m^{-2})					24-Sep	0.01 & 0.18		
Paraquat Dichloride 3.0 (mL m^{-2})	7-Oct	0.12	3-Oct	0.18			17-Oct	0.18
Paraquat Dichloride 3.0 (mL m^{-2}) & pyraflufen ethyl 0.208 (mL m^{-2})					8-Oct	0.18 & 0.02		
Nutrients								
10-34-0 Urea, all plots	26-May	1.7-5.6-0-0-0	11-Mar	3.5–8.2-0-.8-0			18-Feb	.7-2.5-0-0-0-0
10-34-0 Urea, Medium Irrigation					23-Feb	1.1–3.9-0-0-.1		
10-34-0 Urea, High Irrigation					24-Feb	2.4–7.7-0-0-.1		
32-0-0 Urea:								
Low irrigation treatments	10-Jun	12.3-0-0-0-0	18-Apr	11.2-0-0-0-0			18-Feb	6.3-0-0-0-0
Medium irrigation treatments	10-Jun	12.3-0-0-0-0	18-Apr	16.8-0-0-0-0	23-Feb	7.1-0-0-0-0	19-Feb	3.9-0-0-0-0
High irrigation treatments	10-Jun	12.3-0-0-0-0	18-Apr	16.8-0-0-0-0	23-Feb	7.1-0-0-0-0	19-Feb	7.8-0-0-0-0
Planting								
Fibermax 9680B2RF (seed ha^{-1})	11-May	128,000	11-May	115,000	9-May	122,000	13-May	138,000

unchanged over the four year field experiment (Fig. 1).

2.3. Economic analysis

An economic analysis was conducted to assess the profitability of each irrigation treatment using the management practices described in Table 2, which follow the commonly accepted guidelines for the region. Economic budgets were created by calculating crop revenue and expenses. Total crop revenue was calculated using the yield at harvest multiplied by the 2010–2013 average price for lint and cottonseed of \$0.34/kg and \$240/ton, respectively (NASS, 2010-2013). Prices were held constant to make consistent comparisons across years. Due to a lack of spatial and temporal changes in fixed costs, the cost of production was calculated using only variable expenses. Variable costs were defined by pre-harvest and harvest expenses. Total pre-harvest expenses included planting, seed, tillage, herbicides, growth regulators,

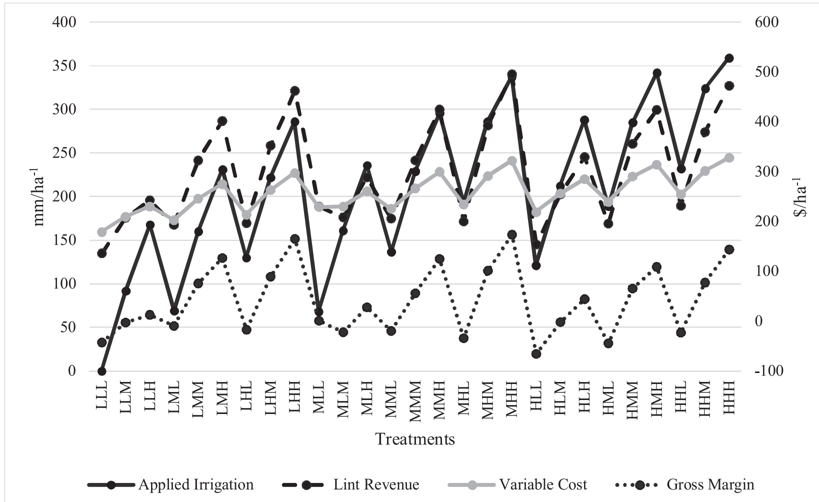

Fig. 2. Average irrigation applied, revenue, variable cost, and gross margin across all irrigation experiments at the Texas A&M AgriLife Research Center, Halfway, Texas.2010–2013.

and fertilizers. Fibermax 9680 B2RF Cotton was planted in May of each year at 115,000–138,000 seed ha^{-1}. Tillage practices included shredding and pulling stalks, tandem disk, ripper, field cultivator, listing, paratill, rolling cultivators, rotary hoe, and furrow diking. Prices for each tillage activity was averaged from the 2011 and 2013 Texas A&M Custom Rate Survey (Klose, 2011; 2013). Chemical and fertilizer prices were used from the Texas Alliance for Water Conservation budgets (TAWC, 2010; 2011; 2012, 2013). Fertilizer expenses varied according to the irrigation amounts and the growth regulators were only used in the high irrigation treatments. Harvest expenses included the use of harvest aids, stripping, ginning, bagging, and tying. The economic value and cost of production varied with each irrigation treatment due to the differences in yield and pumping cost. (Fig. 2)

Gross margin was used as the measure of profitability and was calculated as:

$$GM_{i,t} = EV_{i,t} - VE_{i,t} \tag{1}$$

where $EV_{i,t}$ is the economic value of the cotton lint and seed for each of the 27 irrigation treatments across each year of the study and $VE_{i,t}$ are the variable expenses incurred from the management operations that were unique to each crop year (Table 2). An assessment of the economic productivity of the applied irrigation will determine the per ha^{-1} profitability of the volume of irrigation water applied. This is calculated as:

$$EWP_{i,t} = \frac{GM_{i,t}}{AI_{i,t}} \tag{2}$$

where $EWP_{i,t}$ is the economic water productivity for each irrigation treatment across all years in the study, $GM_{i,t}$ is the gross margin calculated in Eq. (1), and $AI_{i,t}$ is the water applied during each irrigation treatment.

3. Results

3.1. Environmental and crop conditions

3.1.1. Rainfall and irrigation

The growing conditions of the four-year study were highly varied. The 2010 crop year was a wet year, with annual rainfall of 557 mm, exceeding the long-term averages at the Halfway experiment station, with more than double the amount of monthly rainfall from January to April and July. In-season rainfall received was 161 mm from May through September. Temperatures in 2010 followed closely with the long-term average. The 2011 growing season was plagued by hot and dry weather, with annual rainfall of 137 mm with only 23 mm occurring through the growing season. Temperatures were well above the long-term average. Another dry year occurred in 2012, with temperatures slightly higher than the long-term average. In 2012, annual rainfall returned closer to the long-term average at 348 mm, but only 40 mm was received during the growing season. The 2013 growing season was more representative of average weather and rainfall for the region. Rainfall was still below the long-term average, but it was received at the right time from June to September. For graphical representation of monthly rainfall and daily high air temperature, see Figure 4 of Bordovsky et al. (2015).

In-season irrigation was initiated after planting with varied dates from year-to-year because of differences in planting dates and rainfall amounts. On average, irrigation amounts varied from 0 mm to 359 mm with 151 mm applied across the **L–** treatments, 216 mm across the **M–** treatments, and 261 mm across the **H–** treatments. In 2010, the irrigation amounts varied from 0 mm in the **LLL** scenario to 232 mm in the **HHH** scenario, and from 0 to 446 mm in 2011, 0–369 mm in 2012, and 0–359 in 2013.

3.1.2. Yield

Cotton yield results are shown in Tables 4 and 5. Mean lint yield for each year was 1424 in 2010, 374 in 2011, 491 in 2012 and 1245 kg ha^{-1} in 2013. The highest average yields occurred in 2010, with yields ranging from 960 kg ha^{-1}in the **MLL** and **HLL** treatments to 1820 kg ha^{-1} in the **MHH** treatment. The lowest average yields of this study was reported in 2011 with a range of 40 in the **LLL** treatment to 1020 kg ha^{-1} in the **MHH** treatment. Lint yields in 2012 were also low, with yields ranging from 20 kg ha^{-1}in the **LLL** to 1250 in the **MHH** treatment. In 2013, yields ranged from 560 in the **LLL** and **MLL** treatments to 1900 kg ha^{-1} in the **MMH** treatment (Table 4).

Averages across years of all 27 experiments ranged from 408 kg ha^{-1} in the **LLL** treatment (0 mm irrigation) to 1480 kg ha^{-1} in the **MHH** treatment (337 mm irrigation). The **HHH** treatment had the highest irrigation amount of 359 mm and generated a yield of 1410 kg ha^{-1}, which was 5 % less yield than the **MHH** treatment.

Eliminating P1 irrigation (**L–**) resulted in 30 % and 42 % less water applied compared to the **M–** and **H–** treatments and 6 % and a 10 % decline in yield, respectively. The **LMM** and **MMM** treatments generated the same average yield, but **LMM** resulted in 30 % less water applied. The **LHH** used 20 % less irrigation than the **HHH**, but only had a decline in yield of 2 %. In 2010, the average **L–** treatments yielded 19 kg ha more than **M–** and 8 kg ha less than the **H–**. In 2011, the drought year, eliminating the P1 irrigation (**L–** treatments) had a 19 %

Table 3
Seasonal irrigation applications (mm) for each irrigation experiment at the Texas A&M AgriLife Research Center, Halfway, Texas, 2010–2013.

Treatment Name	2010	2011	2012	2013	Average
LLL	0	0	0	0	0
LLM	76	86	95	110	92
LLH	146	160	171	195	168
LML	64	76	67	67	69
LMM	140	162	162	177	160
LMH	191	233	238	262	231
LHL	102	152	133	134	130
LHM	178	238	228	244	222
LHH	202	307	304	329	286
MLL	32	89	76	76	68
MLM	108	178	171	186	161
MLH	178	249	247	271	236
MML	96	165	143	143	137
MMM	172	254	238	253	229
MMH	210	322	314	338	296
MHL	113	241	209	210	193
MHM	189	330	304	320	286
MHH	213	396	368	371	337
HLL	51	165	114	152	121
HLM	127	251	209	262	212
HLH	197	322	285	347	288
HML	115	241	181	219	189
HMM	191	327	276	346	285
HMH	229	398	352	388	342
HHL	132	305	236	253	232
HHM	208	394	331	363	324
HHH	232	446	369	388	359
Average L–	122	157	155	169	151
Average M–	146	247	230	241	216
Average H–	165	317	261	302	261
Average -L-	102	167	152	178	150
Average -M-	156	242	219	244	215
Average -H-	174	312	276	290	263
Average –L	78	159	129	139	127
Average –M	154	247	224	251	219
Average –H	200	315	294	321	283

and 27 % decline in yield from the average **M–** and **H–** treatments, respectively. In an average production year like 2013, eliminating P1 irrigation had a 7 % and 13 % decline in yield.

Regardless of the year or the P1 and P2 irrigation amounts, **–H** irrigation in P3 produced the highest amount of cotton yield. Comparing the **LMM** to the **MMM** treatments in 2011, yield was 470 and 450 kg ha^{-1}, and 1300 and 1330 kg ha^{-1}, respectively in 2013. In the higher IC treatments, yields in the **LHH** to **MHH** to **HHH** in 2011 were 760, 1020, and 990 kg ha^{-1}, respectively. In 2013, the high IC treatments were 1810, 1830, and 1750 kg ha^{-1}. Across all years, the **MHH** treatments outperformed the **HHH** and the differences between **LHH** and **HHH** were 20 kg ha^{-1} less in 2010, 230 kg ha^{-1} less in 2011, 70 kg ha^{-1} more in 2012, and 60 kg ha^{-1} more in 2013. Results from from a statistical analysis of irrigation period effects on cotton lint yield, SIWUE, and loan value during each year of the experiments is reported in Bordovsky et al. (2015).

3.2. Economic results

Table 6 presents the revenue, variable cost, and gross margin for each of the 27 irrigation treatments from 2010 to 2013. Gross margin in 2010 all exceeded \$100 ha^{-1}In this wet year, the rainfed treatment (**LLL**) performed better than the **HLL**, **HML**, **MLL**, **MHL**, and **MML** treatments. The **MHH**, **LHH**, and **HHH** treatments generated the greatest revenue and had the greatest profit. Due to the intensity of the 2011 drought and the significant reduction in crop yield, all treatments had negative gross margin except for **MHH** and **HHH**. In 2012, 11 of the 27 treatments had positive gross margin with the LHH, MHH, and HHH treatments generating the highest profit. In 2013, the **LLL**, **MLL**, and **HLL** treatments had negative profitability. The highest yielding treatments mostly achieved the highest gross margin, although there were minimal differences between the profitability of **H–** and **M—**IC during the first and second growing periods. In the third irrigation period, **–H** irrigation capacity treatments made 85 % more profit than **–M** treatments. The **MHH**, **HHH**, and **LHH** treatments were the most profitable in 2011 and **MMH**, **LMH**, and **MHH** were the most profitable in 2013.

Eliminating the P1 irrigation, had a \$32 (13 %) and \$47 (18 %) reduction in variable cost compared to the **M–** and **H–** IC treatments in 2011. The water applied in the **M–** and **H–** IC treatments were 90 and 160 mm more than the **L–** IC. In 2013, there was a \$13 (4 %) and \$40 (12 %) reduction in variable cost compared to the **M–** and **H–** IC treatments, respectively, where the irrigation water applied was 72 and 133 mm more than the **L–** IC. The **LLL** treatment had a yield of 40 and 560 kg ha^{-1} (Table 5) in 2011 and 2013, respectively.

The **–H** irrigation treatments in P3 had the greatest yield response and generated the most revenue, but also lead to the most variable cost (due to pumping), which impacted profitability. Across the average **L–**, **M–**, and **H–** IC, **LMH** and **LHH**, **MHH** and **MMH**, and **HMH** and **HHH**, generated the highest gross margin, respectively. The **H–** treatments had the highest revenue, highest variable cost and lowest gross margin. Profitability was comparable between the **LMH** and **LHH** and **MHH** and **MMH** treatments.

Economic productivity of the applied irrigation is shown in Table 7. Results for the **LLL** treatment were left blank since no water was applied. The economic productivity of water in 2010 was very high compared to the other years in the study. On average, the **L–** capacity treatments had the highest return on water applied. In 2010, the **MLL**, **LLM**, and **LML** treatments had the highest value of water. The 2011 and 2012 crop years were very low due to increased irrigation and poor yields. In 2013, the **LMH**, **MMH**, and **LMM, and LHH** generated the most return per mm of water used.

4. Discussion

4.1. Impact of reduced irrigation in the early growing season

In the face of water use restrictions or expected decline in yield due to drought, forgoing irrigation during the first growth stage can help reduce water use and mitigate expenses. On average, treatments with no irrigation (**L–**) from germination to $GDD_{15.6}$ = 525 generated only 6 % and 10 % less yield than medium to high irrigation and used 30 % and 42 % less water, respectively (Tables 3 and 5). Medium capacity irrigations (**M–**) of 3.2 mm d^{-1} generated 2 % more profit than capacity irrigations of 0 mm d^{-1}, but the return per mm of water applied per ha^{-1} was 28 % less (Tables 6 and 7). High capacity irrigation (**H–**) of 6.4 mm d^{-1} generated 29 % less profit than capacity irrigations of 0 mm d^{-1} and 55 % less return per mm of water applied per ha^{-1}(Tables 6 and 7). Although the high irrigation capacities generated the most yield, the cost of pumping increased variables expenses. The **MHH** treatment generated the highest yield across all treatments of 1480 kg ha^{-1} on average followed by 1410 kg ha^{-1} in the **HHH** treatment

Table 4
Descriptive statistics of cotton lint yield across all irrigation experiments at the Texas A&M AgriLife Research Center, Halfway, Texas, 2010–2013.

Yield Statistics	2010	2011	2012	2013
Mean Yield (kg ha^{-1})	1424	374	491	1245
Standard Error	57	59	75	81
Median	1540	200	260	1300
Standard Deviation	296	305	390	421
Sample Variance	87687	92848	152315	177357
Range	860	980	1230	1340
Minimum	960	40	20	560
Maximum	1820	1020	1250	1900

Table 5
Cotton lint yield means (kg ha^{-1}) of irrigation treatments at Texas A&M AgriLife Research Center, Halfway, Texas, 2010–2013.

Treatment	2010	2011	2012	2013	Average
LLL	1010	40	20	560	408
LLM	1540	60	110	770	620
LLH	1620	80	140	1060	725
LML	1090	130	200	890	578
LMM	1540	470	540	1300	963
LMH	1680	620	680	1820	1200
LHL	1090	150	250	860	588
LHM	1510	500	870	1330	1053
LHH	1770	760	1180	1810	1380
MLL	960	50	70	560	410
MLM	1390	80	110	910	623
MLH	1740	160	180	1370	863
MML	1030	190	390	850	615
MMM	1540	450	530	1330	963
MMH	1590	660	920	1900	1268
MHL	1030	200	260	900	598
MHM	1580	640	920	1550	1173
MHH	1820	1020	1250	1830	1480
HLL	960	110	90	680	460
HLM	1450	140	190	1260	760
HLH	1750	200	230	1760	985
HML	1010	170	220	940	585
HMM	1610	500	680	1460	1063
HMH	1660	820	940	1640	1265
HHL	1190	240	260	1080	693
HHM	1500	670	910	1450	1133
HHH	1790	990	1110	1750	1410
Average L–	1428	312	443	1156	835
Average M–	1409	383	514	1244	888
Average H–	1436	427	514	1336	928
Average –L-	1380	102	127	992	650
Average –M-	1417	446	567	1348	944
Average –H-	1476	574	779	1396	1056
Average –L	1041	142	196	813	548
Average –M	1518	390	540	1262	928
Average –H	1713	590	737	1660	1175

Table 6
Economic value of water productivity (gross margin in $/ha/mm water applied) across irrigation experiments at the Texas A&M AgriLife Research Center, Halfway, Texas, 2011 and 2013.

Treatment	2010	2011	2012	2013	Average
LLL	N/A	N/A	N/A	N/A	N/A
LLM	$3.32	-$1.94	-$1.02	$0.02	-$0.02
LLH	$1.79	-$1.09	-$0.59	$0.33	$0.08
LML	$2.13	-$1.93	-$1.02	$0.62	-$0.14
LMM	$1.73	-$0.44	$0.03	$0.74	$0.48
LMH	$1.41	-$0.19	$0.12	$0.97	$0.55
LHL	$1.27	-$1.01	-$0.50	$0.17	-$0.13
LHM	$1.28	-$0.32	$0.35	$0.52	$0.40
LHH	$1.44	-$0.06	$0.49	$0.73	$0.58
MLL	$3.35	-$2.04	$1.59	-$0.55	$0.02
MLM	$1.92	-$1.06	-$0.81	$0.17	-$0.14
MLH	$1.62	-$0.72	-$0.53	$0.51	$0.12
MML	$1.20	-$0.96	-$0.42	$0.16	-$0.14
MMM	$1.37	-$0.41	-$0.16	$0.52	$0.24
MMH	$1.16	-$0.19	$0.16	$0.79	$0.42
MHL	$0.99	-$0.70	-$0.50	$0.12	-$0.18
MHM	$1.29	-$0.20	$0.17	$0.55	$0.36
MHH	$1.42	$0.05	$0.35	$0.65	$0.52
HLL	$1.99	-$1.09	-$1.31	-$0.22	-$0.54
HLM	$1.71	-$0.74	-$0.66	$0.38	-$0.01
HLH	$1.44	-$0.56	-$0.50	$0.63	$0.16
HML	$0.90	-$0.73	-$0.70	$0.11	-$0.23
HMM	$1.30	-$0.32	-$0.08	$0.40	$0.23
HMH	$1.12	-$0.08	$0.10	$0.46	$0.32
HHL	$1.12	-$0.55	-$0.53	$0.22	-$0.10
HHM	$1.04	-$0.18	$0.09	$0.37	$0.24
HHH	$1.25	$0.01	$0.21	$0.54	$0.40
Average L–	$1.80	-$0.87	-$0.27	$0.51	$0.22
Average M–	$1.59	-$0.69	-$0.02	$0.33	$0.14
Average H–	$1.32	-$0.47	-$0.38	$0.32	$0.05
Average –L-	$2.14	-$1.15	-$0.48	$0.16	-$0.04
Average –M-	$1.37	-$0.58	-$0.22	$0.53	$0.19
Average –H-	$1.23	-$0.33	$0.01	$0.43	$0.23
Average –L	$1.62	-$1.13	-$0.42	$0.08	-$0.18
Average –M	$1.66	-$0.62	-$0.23	$0.41	$0.20
Average –H	$1.41	-$0.31	-$0.02	$0.62	$0.35

and 1380 kg ha^{-1} in the **LHH** treatment (Table 5). Water use was 337, 359, and 286 mm ha^{-1}, respectively (Table 3). The gross margin generated for the **MHH**, **HHH**, and **LHH** was $174, $144, and $165 ha^{-1}(Tables 6). Treatments that generated the highest return per mm of water applied were **LHH** ($0.58), **LMH** ($0.55), **MHH** ($0.52), and **HHH** ($0.40) (Table 7). Forgoing irrigation in the first growing period only resulted in a profit loss of $9 per ha^{-1}, and used 51 mm less water (Tables 6 and 3).

In a wet year like 2010, yield, water use, and profitability were less variable. Treatments with no irrigation (**L–**) from germination to $GDD_{15.6}$ = 525 generated average yields of 19 kg ha^{-1} more than the medium capacity irrigations and 8 kg ha^{-1} less than the high capacity irrigations using 122, 146, and 165 mm per ha^{-1} of water applied, respectively (Tables 3 and 5). Average profitability per ha was $215.08, $206.23, and $207.23 and return based on water applied was $1.80, $1.59, and $1.32 for the **L–**, **M–**, and **H–** capacity treatments, respectively (Tables 6 and 7). The **MHH** treatment achieved the highest gross margin, followed by the LHH, and **HHH**. The **LMH** and **LLH** treatments were very comparable (Table 6). In a drought year such as 2011, treatments with no irrigation (**L–**) from $GDD_{15.6}$ = 525 generated 18.5 % and 27 % less yield on average than medium (**M–**) to high (**H–**) irrigation capacities and used 36 % and 50 % less water, respectively (Tables 3 and 5). Profitability across the **L–**, **M–**, and **H–** capacities was -$112.31, -$120.72 and -$121.31 per ha^{-1} with returns per mm of -$0.87, -$0.69, and -$0.47 (Tables 6 and 7), respectively. Only the **MHH** and **HHH** treatments had positive gross margin. In 2013, an average production year, treatments with no irrigation (**L–**) from germination to $GDD_{15.6}$ = 525 generated average yields of 7 % and 13 % less yield than the medium and high capacity irrigations using 30 % and 44 % less irrigation water, respectively (Tables 3 and 5). The loss of irrigation in 2013 during the first part of the growing season resulted in a 15 % decline in profitability compared to the average across all medium irrigation capacity treatments of 3.2 mm d^{-1} (Table 6)There was a $4 per ha difference in the average profit between the medium and high irrigation capacity treatments. The **MMH**, **LMH**, and **MHH** treatments generated the highest gross margin (Table 6).

4.2. Impact of increased irrigation later in the growing season

Irrigation in the last growing stage where $GDD_{15.6} > 750$ generated far more profit potential than irrigation in the first stage with irrigation of **-M-** to **-H-** in period 2. This implies that irrigations can be delayed until it is needed in the future, rather than trying to bank water in the soil profile during pre-season irrigation. On average, treatments with high amounts of irrigation (**–H**) after $GDD_{15.6} > 750$, generated 114 % and 27 % more yield than low (0 mm d^{-1}) and medium (3.2 mm d^{-1}) irrigation capacities and used 122 % and 29 % more water, respectively (Tables 3 and 5). Low capacity irrigations (–**L**) of 0 mm d^{-1} generated 127 % less profit than capacity irrigations of 6.4 mm d^{-1}, and a 151 % decrease on the return per mm of water applied per ha^{-1}(Tables 6 and 7). Medium capacity irrigations (**–M**) of 3.2 mm d^{-1} generated 127 % less profit than capacity irrigations of 6.4 mm d^{-1} and a 43 % decline on the return per mm of water applied per ha^{-1}(Tables 6 and 7).

During 2010, the average **–L**, **–M**, and **–H** irrigation capacities had yields of 1041, 1517, and 1713 kg ha^{-1} and used 78, 154, and 200 mm ha^{-1}, respectively (Tables 3 and 5). Gross margin was $119.96, $232.43 and $276.15 per ha^{-1} (Table 6). Across the **–H** capacity irrigations, the

Table 7
Gross Margin for each study year across treatments ($/ha^{-1}).

Treatment	2010 Revenue	2010 Variable Cost	2010 Gross Margin	2011 Revenue	2011 Variable Cost	2011 Gross Margin	2012 Revenue	2012 Variable Cost	2012 Gross Margin	2013 Revenue	2013 Variable Cost	2013 Gross Margin	Average Revenue	Average Variable Cost	Average Gross Margin
LLL	$338.38	$212.53	$125.84	$13.52	$170.92	-$157.40	$6.76	$111.17	-$104.41	$187.78	$221.67	-$33.89	$136.61	$179.08	-$42.47
LLM	$516.01	$263.71	$252.31	$20.28	$186.82	-$166.54	$36.80	$133.56	-$96.76	$258.01	$255.27	$2.74	$207.78	$209.84	-$2.06
LLH	$542.68	$281.20	$261.48	$26.66	$200.52	-$173.85	$46.94	$148.45	-$101.50	$355.28	$290.56	$64.72	$242.89	$230.18	$12.71
LML	$365.04	$229.01	$136.03	$43.56	$190.13	-$146.56	$66.85	$135.40	-$68.55	$298.19	$256.80	$41.40	$193.41	$202.83	-$9.42
LMM	$516.01	$274.41	$241.61	$157.36	$229.17	-$71.81	$181.02	$176.01	$5.01	$435.65	$304.95	$130.69	$322.51	$246.13	$76.38
LMH	$562.96	$293.11	$269.85	$207.68	$251.91	-$44.23	$227.96	$198.87	$29.09	$609.90	$356.92	$252.98	$402.13	$275.20	$126.92
LHL	$365.04	$235.33	$129.71	$50.32	$204.28	-$153.96	$83.75	$150.10	-$66.35	$288.05	$265.81	$22.25	$196.79	$213.88	-$17.09
LHM	$505.87	$278.53	$227.34	$167.50	$244.06	-$76.56	$291.43	$210.96	$80.47	$445.79	$318.31	$127.47	$352.65	$262.97	$89.68
LHH	$593.00	$301.44	$291.56	$254.63	$274.48	-$19.85	$395.46	$246.19	$149.27	$606.52	$367.36	$239.17	$462.40	$297.37	$165.04
MLL	$321.48	$214.22	$107.25	$16.90	$198.55	-$181.65	$395.46	$274.51	$120.95	$187.78	$229.22	-$41.44	$230.40	$229.13	$1.28
MLM	$465.69	$258.15	$207.54	$26.66	$215.57	-$188.90	$36.80	$174.57	-$137.77	$304.95	$272.98	$31.97	$208.53	$230.32	-$21.79
MLH	$582.86	$295.25	$287.61	$53.70	$233.27	-$179.57	$60.46	$192.39	-$131.93	$458.93	$320.56	$138.37	$288.99	$260.37	$28.62
MML	$345.14	$230.04	$115.09	$63.84	$221.46	-$157.61	$130.69	$190.24	-$59.55	$284.67	$261.42	$23.26	$206.09	$225.79	-$19.70
MMM	$516.01	$279.75	$236.26	$150.60	$255.11	-$104.51	$177.64	$216.29	-$38.65	$445.79	$314.70	$131.09	$322.51	$266.46	$56.05
MMH	$532.91	$289.78	$243.13	$221.20	$281.78	-$60.58	$308.33	$257.29	$51.04	$636.57	$370.25	$266.32	$424.75	$299.78	$124.98
MHL	$345.14	$232.89	$112.25	$66.85	$234.80	-$167.95	$87.13	$191.84	-$104.71	$301.57	$276.28	$25.29	$200.17	$233.95	-$33.78
MHM	$529.53	$285.53	$244.01	$214.44	$281.63	-$67.19	$308.33	$255.64	$52.70	$519.39	$341.85	$177.54	$392.93	$291.16	$101.76
MHH	$609.90	$306.97	$302.93	$341.76	$320.29	$21.46	$418.75	$290.21	$128.54	$613.28	$370.68	$242.60	$495.92	$322.04	$173.88
HLL	$321.48	$220.19	$101.29	$36.80	$215.96	-$179.15	$30.04	$179.44	-$149.40	$227.96	$260.82	-$32.86	$154.07	$219.10	-$65.03
HLM	$485.97	$268.51	$217.46	$46.91	$232.49	-$185.58	$63.84	$202.60	-$138.76	$422.13	$321.31	$100.82	$254.71	$256.23	-$1.52
HLH	$586.24	$301.95	$284.29	$66.85	$248.70	-$181.85	$76.99	$218.18	-$141.19	$589.62	$371.77	$217.85	$329.93	$285.15	$44.77
HML	$338.38	$234.55	$103.83	$57.08	$233.09	-$176.00	$73.61	$200.09	-$126.48	$315.09	$290.90	$24.19	$196.04	$239.66	-$43.62
HMM	$539.30	$290.76	$248.54	$167.50	$271.31	-$103.81	$227.96	$249.40	-$21.44	$489.35	$349.88	$139.47	$356.03	$290.34	$65.69
HMH	$556.20	$300.79	$255.41	$274.91	$306.46	-$31.56	$315.09	$280.97	$34.12	$549.44	$369.94	$179.50	$423.91	$314.54	$109.37
HHL	$398.84	$250.49	$148.35	$80.37	$248.79	-$168.42	$87.13	$212.19	-$125.06	$362.04	$306.76	$55.28	$232.09	$254.56	-$22.46
HHM	$502.49	$285.64	$216.86	$224.58	$294.88	-$70.30	$304.95	$275.17	$29.79	$485.97	$351.99	$133.98	$379.50	$301.92	$77.58
HHH	$599.76	$310.70	$289.07	$331.62	$326.77	$4.84	$371.80	$296.10	$75.70	$586.24	$377.91	$208.33	$472.36	$327.87	$144.49
Average L–	$478.33	$263.25	$215.08	$104.61	$216.92	-$112.31	$148.55	$167.86	-$19.30	$387.24	$293.07	$94.17	$279.69	$235.28	$44.41
Average M–	$472.07	$265.84	$206.23	$128.44	$249.16	-$120.72	$213.73	$227.00	-$13.26	$416.99	$306.44	$110.56	$307.81	$262.11	$45.70
Average H–	$480.96	$273.73	$207.23	$142.96	$264.27	-$121.31	$172.38	$234.90	-$62.52	$447.54	$333.48	$114.06	$310.96	$276.60	$34.36
Average –L-	$462.31	$257.30	$205.01	$34.26	$211.42	-$177.17	$83.79	$181.65	-$97.86	$332.49	$282.68	$49.81	$228.21	$233.27	-$5.05
Average –M-	$474.66	$269.13	$205.53	$149.30	$248.94	-$99.63	$189.91	$211.62	-$21.71	$451.63	$319.53	$132.10	$316.38	$262.30	$54.07
Average –H-	$494.40	$276.39	$218.01	$192.45	$270.00	-$77.55	$260.97	$236.49	$24.48	$467.65	$330.77	$136.88	$353.87	$278.41	$75.46
Average –L	$348.77	$228.81	$119.96	$47.70	$213.11	-$165.41	$106.82	$182.78	-$75.95	$272.57	$263.30	$9.27	$193.96	$222.00	-$28.03
Average –M	$508.55	$276.11	$232.43	$130.65	$245.67	-$115.02	$180.98	$210.47	-$29.49	$423.00	$314.58	$108.42	$310.79	$261.71	$49.09
Average –H	$574.06	$297.91	$276.15	$197.67	$271.58	-$73.91	$246.87	$236.52	$10.35	$556.20	$355.11	$201.09	$393.70	$290.28	$103.42

MHH treatment had the highest gross margin of $302.93 with a $1.42 per mm return on water applied (Tables 6 and 7). The **LLH** treatment had comparable gross margins of $261.48 and generated the most return on water applied of $1.79 per mm (Tables 6 and 7). In 2013, there was a $191.82 difference between the **–H** and **–L** irrigation capacitates and a $92.67 difference between the **–H** and **–M** treatments (Table 6).

5. Conclusions

This four-year experiment analyzed the impact of irrigation timing and capacity on 27 cotton treatments conducted at the Texas A&M Research Center in Halfway, Texas using a low energy precision application irrigation system under extreme weather conditions. Across all years of the study, results indicate that early season irrigation that attempted to bank moisture in the soil did not significantly increase yield and decreased profitability; however, treatments with high irrigation capacities during the crop maturation period achieved the highest yield, gross margin, and return on water applied. On average, the high irrigation capacity treatments generated the most revenue and also had the highest variable cost, due to increased pumping, making it comparable to the gross margin on the medium capacity treatments, suggesting that water can be saved and producers can be profitable while conserving resources. In years of reduced rainfall such as 2012, high amounts of irrigation could be used to minimize profit losses, however; in an extreme drought year like 2011 where losses were incurred across all treatments, conserving water for use in the next cropping season may be the best irrigation management strategy.

Declaration of Competing Interest

The authors declare they have no conflict of interest.

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