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ECONOMICS & MARKETING

Profitability of Using Advanced Irrigation Scheduling Methods for Cotton Production

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ABSTRACT

As global demand for food and fiber rise with growing population, scarce resources such as water face significant challenges. Agricultural producers rely on irrigation to manage production variability, which intensifies the pressure on water resources. To address this, advanced irrigation scheduling techniques have been developed to improve water use efficiency and boost production. However, the adoption of these new technologies remains low due to uncertainties about their economic return. This study evaluated the economic efficiency of four advanced irrigation scheduling methods alongside a calendar-based method for cotton production. Field trials were conducted over five growing seasons from 2013 to 2017. We compared water usage and profitability between dryland production and advanced irrigation scheduling methods under conservation and conventional tillage practices. The advanced irrigation scheduling methods included the smart irrigation cotton app (Cotton App), University of Georgia smart sensor array, cotton water stress index, and Irrigator Pro. The calendar-based method used the University of Georgia Checkbook method (Checkbook). Results showed that irrigation improved cotton productivity and profitability during dry years. However, in wet years, irrigated cotton exhibited reduced yield and profitability compared to dryland production. Among the various irrigation methods, the Cotton App demonstrated the best performance in terms of yield and profit. The adoption of advanced irrigation scheduling techniques, particularly the Cotton App, appears promising for enhancing cotton productivity and profitability, while potentially reducing water usage compared to traditional calendar-based approaches like the Checkbook method.

Water security is increasingly threatened by population growth, urbanization, and advancements in agriculture, making it a critical global issue (Bogardi et al., 2012). By 2050, it is projected that approximately 66% of the world's population will face water scarcity (Wallace and Gregory, 2002). Agriculture, being the largest consumer of water (Rosengrant and Cai, 2001), will be particularly affected by this challenge. Water plays a crucial role in agricultural production, and producers use irrigation to mitigate risks associated with weather uncertainties.

Farmers worldwide rely on different irrigation sources, including water from rivers, lakes, and ponds. Groundwater is a major contributor, accounting for approximately 38% of total irrigated land (Siebert et al., 2010). Wells and pumps are used to extract groundwater. However, the expansion of irrigated land and the increasing use of pumps and wells have intensified the rate of groundwater extraction from the aquifers. If the extraction rate exceeds the recharging capacity of the aquifers, it can lead to permanent damage, resulting in diminished water quality and ground subsidence. To ensure water availability for future generations, it is imperative to focus on developing and adopting more efficient irrigation methods in agriculture.

As the most widely used fiber crop, cotton accounts for approximately one-third of global fiber consumption. In 2024, the U.S. ranks as the fourth largest cotton producer worldwide, following China India, and Brazil. In 2019, U.S. farmers planted 5.6 million hectares of cotton, generating an economic impact of 6 billion U.S. dollars (USDA, 2019). Georgia is the second largest cotton producing state in the U.S., after Texas. While cotton is generally drought tolerant and can endure water stress throughout most of its growing period, it requires approximately 45.7 cm of water from planting to har-

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vest to achieve optimal yield (Bednarz et al., 2002). The critical phases of flowering to boll maturation are particularly sensitive to water stress. Episodic drought during these vital phases can significantly lower cotton yield (Snowden et al., 2014; Zonta et al., 2017). In the humid southeast region of the U.S., where rainfall can be variable and episodic droughts are possible, irrigation becomes essential to manage yield variability.

Many cotton growers rely on traditional irrigation scheduling methods, such as observing plant stress, feeling the soil, using a calendar-based method, or following neighbor's irrigation practices (USDA, 2018b). These methods often fail to account for the existing soil moisture, leading to potential over- or under-irrigation. Excessive water can cause excessive vegetative growth and reduced photosynthate availability for flower development, thereby lowering yield potential (Karam et al., 2006; Wanjura et al., 2002). In regions with enough but unpredictable rainfall, simple irrigation scheduling methods can reduce yield, water use efficiency, and profit (Liu et al., 2022). Conversely, under-irrigation, especially during critical growth phases, can severely impact yield. Therefore, adopting more efficient irrigation practices could help conserve water resources and maintain high cotton yields (DeLaune et al., 2020).

Knowledge of the right timing and quantity for irrigation is essential for maintaining irrigation water use efficiency (Colaizzi et al., 2003). Several advanced irrigation scheduling methods have been developed to address the pressing issue of reduced water resources (Awan et al., 2012; Liang et al., 2016; Pereira et al., 2007). These methods account for soil moisture and crop water requirements at various growth stages to estimate when and how much to irrigate, thus preventing both over- and under-irrigation. Implementing advanced irrigation scheduling methods can enhance water use efficiency and contribute to mitigating water scarcity in agricultural production. Numerous studies have investigated the sustainability and efficiency of these advanced methods (Miller et al., 2018; Vellidis et al., 2016). Economic analysis of these systems in corn production has demonstrated that advanced irrigation scheduling systems can reduce both energy and water usage while improving profitability (Epperson et al., 1993; Kranz et al., 1992; Lecina, 2016; Spencer et al., 2019; Vatta et al., 2018).

The main objective of this study is to evaluate the economic efficiency of irrigation scheduling methods for cotton production under conservation and conventional tillage practices. Four advanced irrigation scheduling methods have been developed at the University of Georgia (UGA) to reduce water usage, enhance water use efficiency, and improve yield and overall sustainability. These methods include a smart irrigation cotton app (Cotton App), UGA smart sensor array (UGA SSA), cotton water stress index (CWSI), and Irrigator Pro. This research compares these advanced methods with a dryland control (Control) and the calendar-based UGA Checkbook method (Checkbook) to assess their economic and water use efficiency for cotton production.

MATERIALS AND METHODS

Irrigation Scheduling Methods. Most innovative irrigation scheduling methods are based on deficit irrigation, which has been shown to be more efficient than full irrigation scheduling systems (Grove and Oosthuizen, 2010). Research by Himanshu et al. (2019) indicated that irrigation can be reduced during certain cotton growth stages, such as germination, seedling emergence, and squaring. Deficit irrigation methods aim to mitigate water stress during drought periods, reduce the total amount of irrigation water used, improve water use efficiency, and increase crop productivity. However, inadequate irrigation during critical phases, such as flowering to boll maturation, can severely impact cotton yield. For better cotton yield, the water deficit should be moderate rather than extreme (Pereira et al., 2009). Efficient irrigation scheduling techniques that accurately deliver the necessary water to the cotton plant are essential for increasing cotton production. This study investigated four advanced irrigation scheduling techniques: Cotton App, UGA SSA, CWSI, and Irrigator Pro. These methods were compared with Control and Checkbook to evaluate the economic efficiency in cotton production.

The Checkbook method, developed by UGA Extension, is a calendar-based irrigation scheduling method that provides weekly irrigation guidelines for cotton production (Whitaker et al., 2019). Due to its simplicity, it is widely used by cotton producers in Georgia. The Checkbook method assumes that the cotton crop needs approximately 20 mm of water each week before flowering. After the first bloom, irrigation is applied based on the weekly water requirements specified in Table 1, and continues until the first open boll stage. Growers are required to

Table 1. Weekly water requirement for cotton production recommended by UGA Checkbook irrigation scheduling method

Crop Stage	Millimeters/Week	Millimeters/Day
Week beginning at 1st bloom	25.4	3.81
2nd week after 1st bloom	38.1	5.58
3rd week after 1st bloom	50.8	7.62
4th week after 1st bloom	50.8	7.62
5th week after 1st bloom	38.1	5.58
6th week after 1st bloom	38.1	5.58
7th week and beyond	25.4	3.81

record daily rainfall using rain gauges and subtract the weekly rainfall from the weekly water requirements to determine the necessary irrigation for that week. However, this method does not account for soil moisture levels, which can lead to over-irrigation.

The Cotton App is an interactive, evapotranspiration-based irrigation scheduling method using deficit irrigation (Vellidis et al., 2016). Available for free on smartphones, the app uses meteorological data, soil parameters, crop phenology, crop coefficients, and past irrigation events to estimate the moisture deficit in the cotton plant's effective root zone. Users input information such as location, soil type, and irrigation type into the app. It then uses meteorological data from the nearest weather station to estimate the amount of water and time to irrigate (Vellidis et al., 2016).

UGA SSA is a soil moisture sensor-based irrigation scheduling system that uses real-time soil moisture data to schedule irrigation (Liakos et al., 2017; Vellidis et al., 2013). Sensors are installed at different depths (0.2, 0.3, and 0.4 m) that transmit hourly soil moisture data to a base station. Soil moisture data are uploaded to a server that converts the data into volumetric water content and provides recommendations for the amount and timing of irrigation water needed by the plant.

The CWSI method assesses plant water stress on the leaves by measuring average canopy temperatures using infrared sensors (Chastain et al., 2016). Irrigation is applied when stress is detected based on CWSI values (Jensen et al., 1990). Stressed leaves, which have reduced transpiration cooling, exhibit higher temperature compared to non-stressed leaves. CWSI is calculated by comparing the temperature difference between the plant canopy and the air with the temperature difference between the plant canopy of non-transpiring crops and the air (Idso et al., 1981).

Irrigator Pro is a sensor-based irrigation scheduling method that estimates available soil water content. It uses soil water tension data collected by the sensors placed at two different depths (0.2 and 0.4 m). Irrigation is triggered when the soil water tension exceeds a predefined threshold. A web-based version of Irrigator Pro, known as Pro SSA, has been developed to enhance the accuracy of irrigation recommendations. This version integrates soil moisture data from the UGA SSA system to provide more precise irrigation guidance.

Experiment Description. Cotton irrigation field trials were conducted from 2013 to 2017 at the University of Georgia C. M. Stripling Irrigation Research Park in Camilla, GA (Latitude: 31.281632, Longitude: -84.294388). The field trials used a complete randomized block split-plot experimental design. In this design, irrigation treatment served as the whole-plot factor, whereas the cotton variety and tillage method were the split-plot factors. Detailed irrigation treatments for different years are outlined in Table 2. All treatments, except Control, which was conducted under conservation tillage, were tested under both conservation and conventional tillage practices. To ensure uniform stand establishment and active weed control programs, blanket irrigation was applied to all plots at the start of the growing season before imposing specific irrigation treatments. After this initial application, no supplemental irrigation was provided to Control plots, whereas all other treatments received additional irrigation based on their respective criteria. The study evaluated two variations of the UGA SSA system: UGA SSA with a constant threshold of 50 kPa (UGA SSA C) and UGA SSA with a variable threshold (UGA SSA V). For UGA SSA V, the threshold is adjusted according to the crop's growth stage, which is 50 kPa threshold before flowering and 40 kPa after flowering.

Except for 2013, seeds of four commercially available cotton cultivars were sown at one seed

Table 2. Irrigation treatments for each year from 2013 to 2017 for conservation and conventional tillage. Control is only in the conservation tillage

Treatment	2013	2014	2015	2016	2017
1	Control	Control	Control	Control	Control
2	Checkbook	Checkbook	Checkbook	Checkbook	Checkbook
3	Cotton App	Cotton App	Cotton App	Cotton App	Cotton App
4	-	UGA SSA C	UGA SSA C	UGA SSA C	UGA SSA C
5	-	-	UGA SSA V	UGA SSA V	-
6	Irrigator Pro	-	-	-	-
7	-	-	-	-	Pro SSA
8	CWSI	-	-	-	-

per 0.3 m with 0.91-m inter-row spacing at a depth of 0.019 m. In 2013, a single variety of cotton was planted. The plot size was 15.2 m in length and 1.8 m in width, with 18.2-m alleys separating the plots. Three replications were conducted for each irrigation, cultivar, and tillage treatment. The experimental design included 27 plots (5 Irrigation Treatments × 1 Cultivar × 2 Tillages × 3 Replicates, Control only in conservation tillage) for 2013, 84 plots (4 Irrigation Treatments × 4 Cultivars × 2 Tillages × 3 Replicates, Control only in conservation tillage) for 2014, and 108 plots (5 Irrigation Treatments × 4 Cultivars × 2 Tillages × 3 Replicates, Control only in conservation tillage) from 2015 to 2017. All other inputs, such as fertilizers and pesticides, were uniformly applied across all plots according to UGA Cooperative Extension Service recommendations. All plots were irrigated using a lateral variable rate irrigation system, which categorized plots into different irrigation management zones, enabling the application of varied irrigation rates across different plots.

Cotton from each plot was harvested using a two-row spindle cotton picker at the end of the season. Seed cotton weight was recorded on-site and then transported to the UGA Micro Gin to obtain the gin turnout ratio and lint yield for each plot. Additionally, samples were outsourced to obtain cotton fiber quality. In 2014, gin samples were analyzed at the Fiber and Biopolymer Research Institute of Texas Tech University in Lubbock, TX. For the remaining years, samples were analyzed in the U.S. Department of Agriculture cotton program classing office Macon, GA. Depending on fiber quality, producers can receive premiums or discounts relative to the base fiber quality price when selling their cotton.

Net Return. Economic analyses were conducted to evaluate the profitability of different irrigation treatments. Data from the field trial were used to calculate the net return per acre after accounting for irrigation, harvest, and ginning costs for each treatment. To determine the net return, gross revenue was first calculated for each replicate of the irrigation treatment, cultivar, and tillage system in each production season:

$$\text{Gross revenue} = \text{Lint yield} \times \text{Lint price} + \text{Seed yield} \times \text{Seed price}. \quad (1)$$

Cotton lint yield was obtained from the field trials from 2013 to 2017 for each replicate after the ginning of seed cotton. Cottonseed yield was estimated by using a conversion ratio of 1.412 units of seed per unit of lint (Falconer and Reeves, 2017). Market price for the base quality cotton lint and premium or discount schedules for each year was obtained from Cotton Price Statistics Annual Reports (USDA, 2014, 2015, 2016, 2017, 2018a). Based on the fiber quality data for each replicate, premiums were added to, and discounts were subtracted from the market price for the base fiber quality. Cottonseed price was obtained from the USDA National Agricultural Statistics Service (NASS) from 2013 to 2017 (USDA, 2019).

Costs for irrigation, harvesting, and ginning were estimated in this analysis. Harvesting and ginning costs were assumed to be proportional to cotton yields for each irrigation treatment (Falconer and Reeves, 2017). Ginning costs were derived from the annual UGA Cotton Enterprise Budgets (Shurley and Smith, 2013, 2015, 2016, 2017). UGA did not officially published the budget in 2014. Therefore, the annual ginning cost value for 2014 was obtained from the budgets of 2015 to 2017. Harvesting costs were obtained from Cotton Incorporated cotton loan calculators (Falconer and Reeves, 2017). Costs were calculated as:

$$\text{Costs} = \text{Irrigation cost} + \text{Harvesting cost} + \text{Ginning cost}. \quad (2)$$

The irrigation budget for a 160-acre electric powered center pivot, developed by UGA Extension, was used to estimate irrigation ownership and operating costs (Bhattarai et al., 2021d). Ownership costs are the annual fixed costs, which include depreciation, intermediate interest, tax, and insurance for the irrigation method. These costs encompass the purchase and installation of irrigation equipment, sensors, and additional components for each irrigation scheduling method. Operating costs, or variable costs, fluctuate with the amount of water used and include expenses for fuel or electricity, repairs and maintenance, and labor and management. The irrigation budgets estimate each irrigation scheduling method's costs based on the amount of water applied each year. For irrigation cost calculations, actual production expenses incurred by cotton producers were used. There are no irrigation costs for dryland production, so the cost of irrigation for the Control was assumed to be zero in our analysis. Blanket irrigation amounts applied to other irrigation treatments were subtracted from the total irrigation amount when calculating the irrigation costs. Blanket irrigation varied across years depending on soil moisture condition at planting but remained consistent across all irrigation systems in a given year. Finally, the net return for each irrigation treatment was determined by subtracting the total costs from the gross revenue as follows:

$$\text{Net return}=\text{Gross revenue}-\text{Costs}. \quad (3)$$

RStudioVersion 1.2.5001 was used to conduct the analysis of variance for net returns of each irrigation treatment. Tukey tests were performed to determine significant differences in mean values among the irrigation treatment at a 5% significance level. These tests were conducted within the same tillage practice but not between tillage practices for the irrigation scheduling methods.

RESULTS AND DISCUSSION

Precipitation and Irrigation. Table 3 presents the rainfall, irrigation amount, and irrigation cost for conservation tillage and conventional tillage. Rainfall amounts varied across the experimental years. The years 2013, 2015, 2016, and 2017 were considered wet years, as precipitation in these years exceeded the total optimum water requirement for cotton production (457 mm) throughout its growing season (Bednarz et al., 2002). In contrast, 2014 was considered a dry year for cotton production due to the reduced rainfall during the production season, totaling 285 mm.

Irrigation amounts varied among different irrigation scheduling treatments, which also influenced the total irrigation costs for each treatment. Blanket irrigations were applied to all plots. In 2013, blanket irrigation was 38 mm. In 2014, the blanket irrigation was increased to 97 mm due to dry conditions. Blanket irrigation amounts for 2015, 2016, and 2017 were 13, 19, and 13 mm, respectively. Except for UGA SSA C under conventional tillage in 2015, irrigation amounts were generally higher for the Checkbook method than all the advanced irrigation scheduling methods. Similarly, except for UGA SSA C under conventional tillage in 2015, irrigation costs were higher for the Checkbook method compared to the advanced irrigation scheduling methods. The higher irrigation cost for UGA SSA C under conservation tillage in 2014, compared to the Checkbook method, was primarily due to the additional costs associated with sensor purchase and installation.

Compared with the Checkbook method, the Cotton App resulted in water savings ranging from 25 to 87%, with an average of 52% for conservation tillage, and 18 to 86% with an average of 50% for conventional tillage. The UGA SSA C method achieved water savings of 5 to 86% with an average of 53% for conservation tillage. However, in 2015, UGA SSA C used 21% more water for irrigation than the Checkbook method under conventional tillage, though it saved up to 79% in other years, averaging 55% water savings. The UGA SSA V method saved 25 to 72% of water with an average of 49% for conservation tillage, and 46 to 76% with an average of 61% for conventional tillage. The Irrigator Pro method was able to save 94% of water for conservation tillage and 93% for conventional tillage. For the CWSI method, water savings reached 73% for conservation tillage, and 93% for conventional tillage. Pro SSA method saved 82% of water for conservation tillage and 78% for conventional tillage.

Lint Yield. Table 4 presents the cotton lint yield for each year under both conservation and conventional tillage practices. In the dry year of 2014, the Control yielded significantly less cotton than the irrigated treatments under conservation tillage, with the Cotton App producing the highest average cotton yield for both tillage options. Our findings align with Sorensen and Lamb (2019), who also observed that irrigation boosts cotton yield during dry years. This suggested that supplementing irrigating when pre-

Table 3. Rainfall, irrigation, and cost of irrigation for cotton grown near Camilla, GA, during the 2013 to 2017 growing season for conservation and conventional tillage

Year	Rainfall	Treatment	Conservation Tillage		Conventional Tillage	
			Irrigation	Irrigation Cost	Irrigation	Irrigation Cost
	- mm -		-- mm --	$ ha^-1^	-- mm --	$ ha^-1^
2013	696	Checkbook	285	451	272	448
		Cotton App	38	385	38	385
		Irrigator Pro	18	389	18	389
		CWSI	76	404	18	389
2014	285	Checkbook	290	453	291	453
		Cotton App	134	411	134	411
		UGA SSA C	275	457	218	442
2015	574	Checkbook	152	416	152	416
		Cotton App	114	405	124	409
		UGA SSA C	70	403	184	433
		UGA SSA V	114	414	82	406
2016	650	Checkbook	184	424	184	424
		Cotton App	114	402	114	406
		UGA SSA C	64	401	38	394
		UGA SSA V	51	398	45	398
2017	617	Checkbook	228	436	228	436
		Cotton App	101	402	101	402
		UGA SSA C	32	392	89	408
		Pro SSA	42	395	51	398

Table 4. Summary statistics of cotton lint yield for all irrigation treatments from 2013 to 2017 growing season under conservation and conventional tillage practices near Camilla, GA

Year	Treatment	Conservation Tillage				Conventional Tillage			
		Mean	S.D.	Min	Max	Mean	S.D.	Min	Max
		Kg ha^{-1}							
2013	Control	1659a	152	1519	1820	-	-	-	-
	Checkbook	1513a	176	1320	1666	1290a	131	1146	1402
	Cotton App	1666a	222	1417	1845	1413a	157	1305	1594
	Irrigator Pro	1678a	197	1551	1904	1359a	83	1280	1603
	CWSI	1618a	449	1263	2122	1511a	152	1336	1445
2014	Control	1243c	317	828	1742	-	-	-	-
	Checkbook	1931ab	474	1318	3019	1989a	416	1320	2847
	Cotton App	2040b	454	1466	2888	2112a	258	1804	2609
	UGA SSA C	1652a	261	1075	2062	2003a	246	1594	2346
2015	Control	1832b	212	1461	2099	-	-	-	-
	Checkbook	1656a	187	1258	1978	1657a	244	1358	1995
	Cotton App	1711ab	170	1470	2055	1794a	210	1455	2083
	UGA SSA C	1822ab	155	1661	2078	1727a	257	1321	2126
	UGA SSA V	1738b	162	1522	2018	1712a	188	1516	2158

Continued

Table 4. Continued

		Conservation Tillage				Conventional Tillage			
Year	Treatment	Mean	S.D.	Min	Max	Mean	S.D.	Min	Max
		---Kg ha^{-1}---							
2016	Control	1371b	127	1208	1599	-	-	-	-
	Checkbook	1017a	142	835	1406	812a	233	586	1176
	Cotton App	1196ab	153	938	1417	1098b	277	781	1589
	UGA SSA C	1237ab	175	886	1576	1381b	106	1139	1718
	UGA SSA V	1274ab	68	1111	1366	1316b	89	1125	1566
2017	Control	1471b	73	1327	1760	-	-	-	-
	Checkbook	1251a	87	1047	1629	1251a	161	899	1487
	Cotton App	1484b	97	1182	1642	1484a	112	1159	1807
	UGA SSA C	1423b	52	1321	1611	1388a	149	886	1556
	Pro SSA	1490b	106	1251	1628	1257a	240	1104	1861

Means not sharing a common letter within a given year and a given tillage practice are significantly different ($p < 0.05$).

cipitation is inadequate can effectively increase the cotton yield, and that advanced irrigation scheduling methods can further improve cotton yield during dry years.

During wet years (2013, 2015, 2016, 2017), for conservation tillage, irrigation did not improve the yield compared to dryland production, and the yield was reduced when excessive water was applied using the Checkbook method. This observation is consistent with Vellidis et al. (2016), who found that the rain-fed field resulted in a higher yield than irrigated fields during wet years. These results indicate that when sufficient rainfall is available throughout the growing season, it is more beneficial for farmers to refrain from irrigating cotton grown under conservation tillage.

However, for producers with irrigation already installed, it is challenging to predict whether precipitation will be adequate during the growing season, making it difficult to opt out of irrigation when needed. In such cases, cotton growers should consider adopting advanced irrigation scheduling methods rather than relying on the calendar-based Checkbook method. Advanced methods can provide more precise irrigation recommendations based on real-time data, helping optimize water use and potentially improve yield in variable weather conditions than the calendar-based method.

Under conservation tillage, except for the UGA SSA C in 2014, all advanced irrigation scheduling methods outperformed the conventional Checkbook method with higher average yields in all years. This result aligns with previous studies of deficit irrigation having higher water use efficiency (Fan et al., 2018; Jalota et al., 2008; Liang et al., 2016; Miller et al., 2018; Ünlü et al., 2011).

For conventional tillage, during wet years (2013, 2015, 2016, 2017), the Checkbook method resulted in lower average yields than the advanced irrigation scheduling methods. In 2016, a relatively wet and hot year with high daily evapotranspiration, all the advanced irrigation scheduling methods achieved significantly higher average yields compared to the Checkbook method. The advanced irrigation systems were better equipped to manage evapotranspiration effectively, whereas the Checkbook method struggled under these conditions, resulting in notably lower yields. This suggests that for conventional tillage during wet years, advanced irrigation scheduling methods can enhance cotton yield more effectively than the calendar-based Checkbook method.

Net Return. Table 5 and Fig. 1A display the average net returns per hectare above the irrigation, harvest, and ginning costs for each irrigation scheduling treatment (net return) from 2013 to 2017. Weather conditions each year influenced cotton yield and irrigation amounts, resulting in variations in economic performance across the irrigation treatments. In dry years, advanced irrigation scheduling methods, particularly the Cotton App, proved more profitable compared to the calendar-based Checkbook method and Control. In contrast, during wet years, Control often had higher average net returns than all irrigated treatments. This outcome is attributed to two major factors. First, in wet years, additional irrigation can lead to an overabundance of water, negatively im-

Table 5. Summary statistics of cotton net returns for all irrigation treatments from 2013 to 2017 growing season under conservation and conventional tillage practices near Camilla, GA

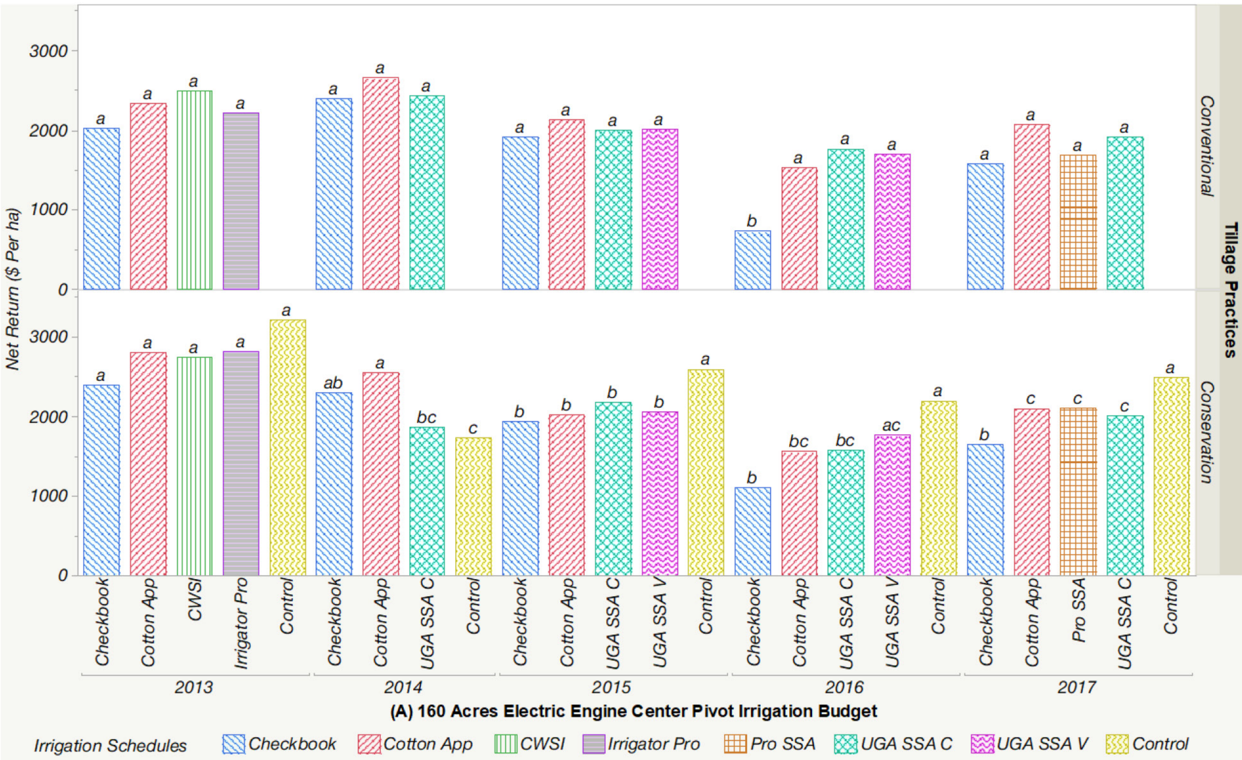
		Conservation Tillage				Conventional Tillage			
Year	Treatment	Mean	S.D.	Min	Max	Mean	S.D.	Min	Max
		--Kg ha^{-1}	--						
2013	Control	3199a	357	2851	3563				
	Checkbook	2379a	230	2121	2562	2011a	232	1745	2174
	Cotton App	2795a	467	2288	3208	2326a	255	2145	2617
	Irrigator Pro	2798a	443	2508	3308	2204a	155	2094	2381
	CWSI	2733a	896	2019	3739	2480a	412	2005	2734
2014	Control	1723c	433	1184	2365				
	Checkbook	2285ab	698	1364	3721	2388a	643	1361	3667
	Cotton App	2538a	680	1682	3819	2645a	385	2213	3409
	UGA SSA C	1857bc	403	1018	2362	2425a	334	1826	2872
2015	Control	2579a	311	2058	3010				
	Checkbook	1927b	269	1366	2391	1909a	351	1489	2428
	Cotton App	2009b	274	1566	2532	2123a	309	1628	2574
	UGA SSA C	2161b	226	1938	2554	1990a	347	1429	2452
	UGA SSA V	2049b	232	1718	2427	2004a	265	1716	2630
2016	Control	2182a	262	1908	2538				
	Checkbook	1091b	129	940	1256	719b	394	411	1291
	Cotton App	1546bc	380	1016	1836	1517a	447	1102	2140
	UGA SSA C	1563bc	469	983	2129	1752a	192	1528	1926
	UGA SSA V	1751ac	187	1626	2029	1690a	141	1478	1767
2017	Control	2475a	130	2323	2629				
	Checkbook	1636b	161	1521	1874	1564a	266	1264	1911
	Cotton App	2086c	181	1884	2324	2059a	200	1918	2355
	UGA SSA C	1995c	82	1923	2111	1908a	255	1624	2239
	Pro SSA	2092c	192	1806	2221	1677a	446	1248	2123

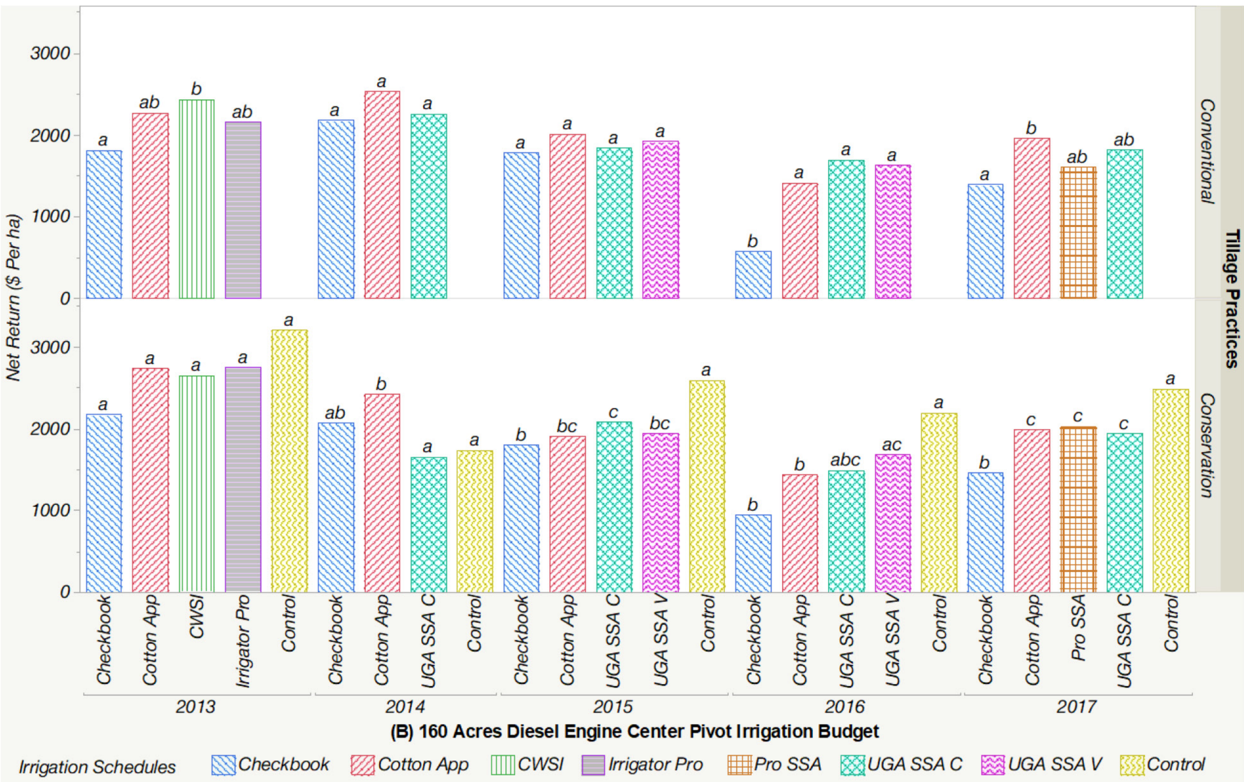
Means not sharing a common letter within a given year and a given tillage practice are significantly different ($p < 0.05$).

pacting yield and reducing net returns. This supports the finding that extra irrigation can be detrimental to yield and profitability when sufficient precipitation is available. Second, in some years, although irrigation increased yield above the Control, the associated costs, especially the fixed costs, could outweigh the revenue increase from higher yields. It is important to note that these results do not imply that irrigation is unnecessary in humid regions with higher rainfall. Even in such areas, drought can occur, leading to severe yield losses. For example, Chastain et al. (2014) reported a 35% yield reduction due to drought in 2012 in southern Georgia, whereas Chastain et al. (2016) found that the yield loss was 59 to 75% in 2014 due to drought. In contrast, over-irrigation only reduced yield by 14.3% in 2016 (Ermanis et al., 2021). Therefore, maintaining irrigation is crucial to ensure consistent yields and protect against unpredictable drought conditions, even in humid regions.

Results indicated that the extra costs associated with installing new irrigation systems could not be offset by the increase in productivity over the long term. However, for farmers who already have irrigation systems installed, the fixed costs of these systems do not influence their irrigation decisions. This is because daily operational decisions, such as when to irrigate, are short-term decisions, and in the short term, the fixed costs are treated as sunk costs. These sunk costs are incurred regardless of whether the farmer decides to irrigate or not. For farmers with existing irrigation infrastructure, the key decision is not whether to irrigate, but when to do so. Our results demonstrated that the advanced irrigation scheduling methods outperformed the calendar-based

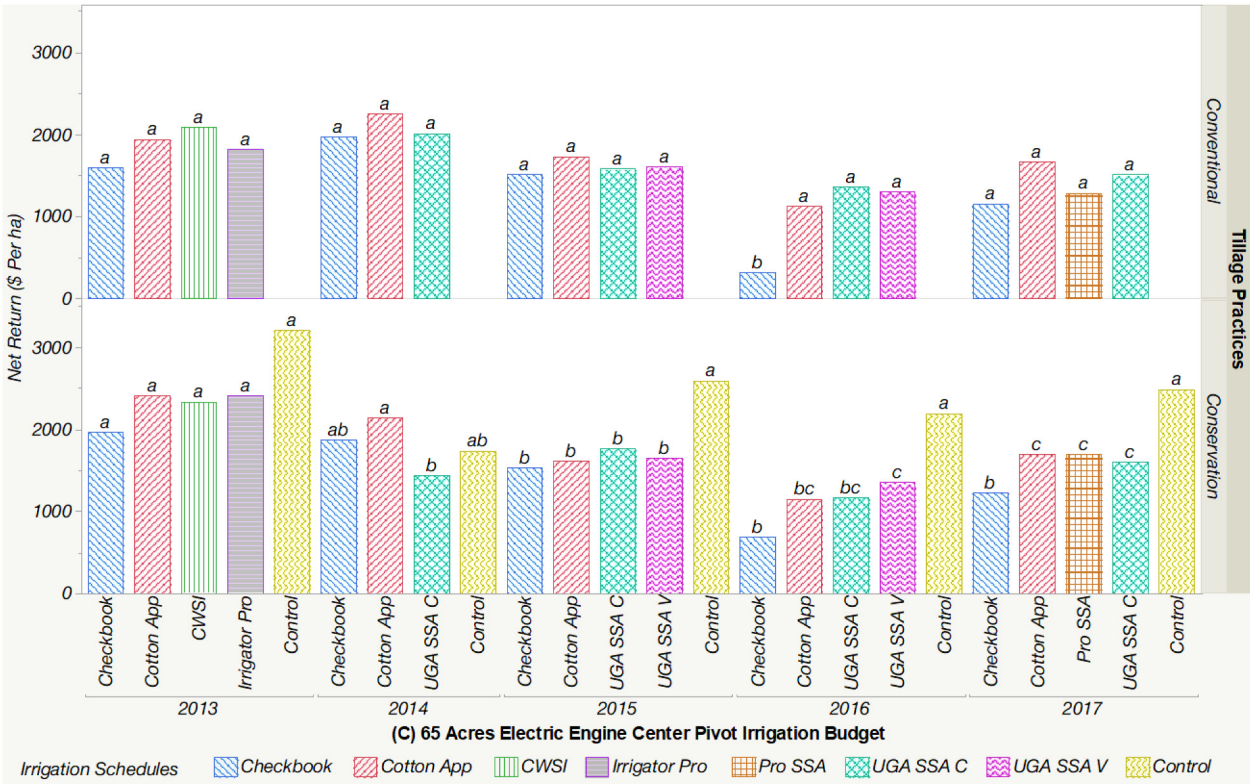
Figure 1.





Continued

Figure 1. Continued



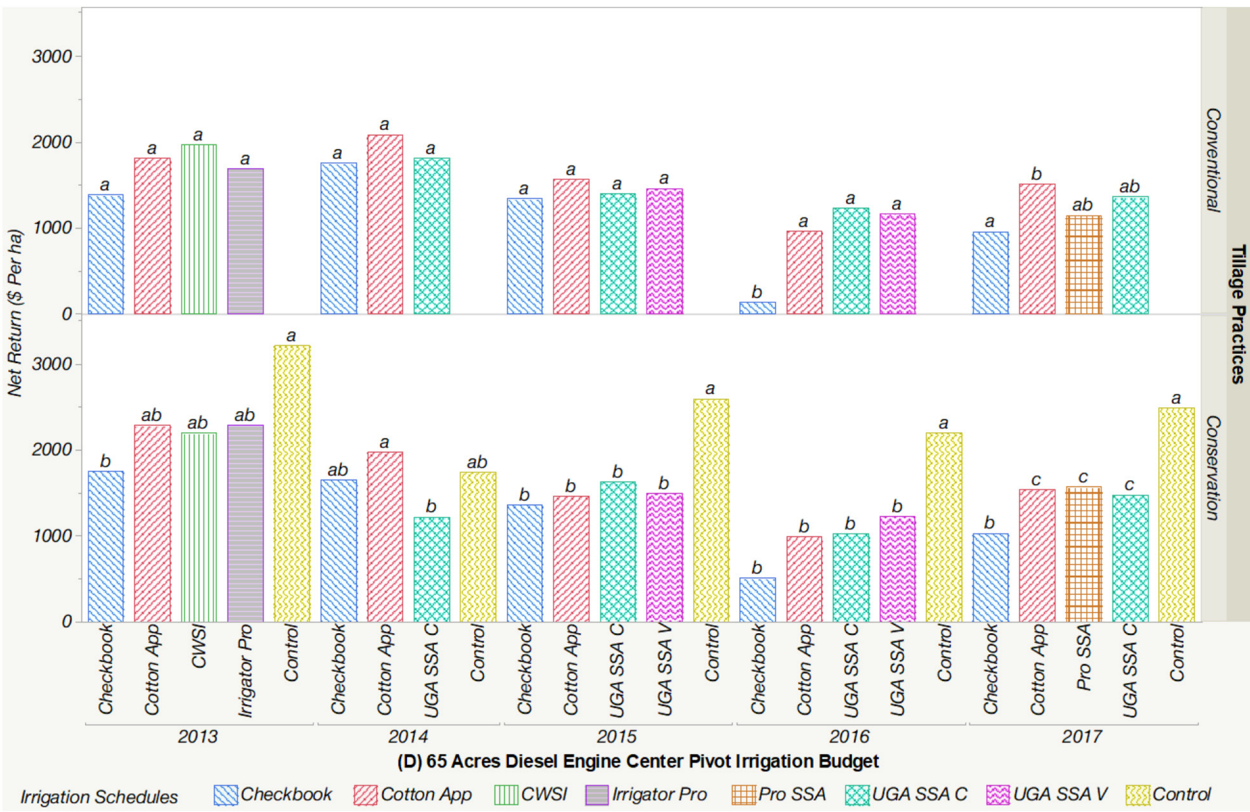


Figure 1. Cotton net returns for different irrigation scheduling treatments from 2013 to 2017 growing seasons under conservation and conventional tillage practices near Camilla, GA using a 160-acre, electricity-powered irrigation budget (A), 160-acre, diesel-powered (B), 65-acre electricity-powered (C), and 65-acre diesel-powered (D) center-pivot system. Within a given year, means for different irrigation treatments followed by the same letter are not significantly different from each other at $p < 0.05$.

Checkbook method, indicating that adopting these advanced irrigation scheduling methods can improve productivity and profitability more effectively than relying on the calendar-based Checkbook method. Incorporating advanced irrigation scheduling methods can lead to greater economic profitability and more efficient water use.

In 2013, there was no significant difference in net returns among different irrigation treatments for both conservation and conventional tillage practices. In 2014, however, the Cotton App had a significantly higher net return than both Control and UGA SSA C under conservation tillage. Because the Cotton App is free to download on a smartphone and does not require additional sensor-related costs, it can be more cost effective and beneficial than sensor-based methods such as UGA SSA C. For conventional tillage, no significant differences were observed among the scheduling systems in 2014. In 2015, Control resulted in a significantly higher net return than all other scheduling systems for conservation tillage. However, no significant differences were observed in net returns among irrigated treatments in conventional tillage practices. In 2016, under conservation tillage, Control and UGA SSA V significantly outperformed the Checkbook method. Under conventional tillage in the same year, all the advanced irrigation scheduling methods produced a significantly higher net return than the Checkbook method. In 2017, advanced irrigation schedules, including the Cotton App, UGA SSA C, and UGA SSA V yielded significantly higher net returns than the Checkbook method under conservation tillage. Control also outperformed the Checkbook method and all other scheduling systems. For conventional tillage in 2017, there were no significant differences in net returns among the treatments.

In summary, conventional tillage shows no statistically significant differences in four out of the five-year studies; only 2016 exhibited a significant difference. Similarly, for conservation tillage, two years showed no statistically significant difference between the Checkbook method and any of the scheduling methods, whereas the other three years showed mixed results. In humid regions, irrigation is not primarily used to boost yield but rather as a risk mitigation strategy to minimize downside risks during epidemic drought or dry years (Liu et al., 2022). Although there are no statistically significant yield differences, income variations between these different methods are another critical factor for producers. Further risk analysis research on modern irrigation scheduling methods could help identify the most risk-efficient approach. Moreover, cotton is typically rotated with peanuts and corn in Georgia, and although cotton might not require irrigation, peanuts and corn benefit from it. Therefore, investing in irrigation can be advantageous for crop rotation systems, but this requires confirmation with further study.

SENSITIVITY ANALYSIS

We conducted sensitivity analyses using different irrigation budgets developed by UGA Extension to assess how changes in irrigation cost impact the profitability of alternative irrigation scheduling methods (Bhattarai et al., 2021a, 2021b, 2021c, 2021d). In addition to the 160-acre electric-powered center -pivot irrigation budget (160 E), three other irrigation budgets were utilized: a 160-acre diesel-powered center-pivot irrigation budget (160 D), a 65-acre electric-powered center-pivot irrigation budget (65 E), and a 65-acre diesel-powered center-pivot Irrigation Budget (65 D).

Table 6 presents the irrigation costs based on three alternative irrigation budgets. Compared to the 160 E budget, irrigation costs have increased. The 65 D budget resulted in the highest ownership and operating costs, followed by 65 E and 160 D. This change in costs can be attributed to two major factors: pivot size and energy source used for operation. Larger pivots cover more area for irrigation and generally have a lower cost per hectare. Additionally, pivots powered by electricity are less expensive to operate than those using diesel, as diesel systems have lower energy transformation efficiency and higher fuel costs.

As shown in Fig. 1, net return values changed across different irrigation scheduling treatments when using different irrigation budgets. Higher irrigation costs led to lower net returns for irrigated treatments. The highest net returns were observed with 160 E budget, followed by 160 D, 65 E, and 65 D. The rankings of average net return among different irrigation treatments within each year remained consistent except in 2013, 2014, and 2016 under conservation tillage. In 2014, under conservation tillage, increased irrigation costs caused the Checkbook method to rank after the Control with 65 D budget, whereas with 160 E, 160 D, and 65 E, the Checkbook method ranked higher than the Control. Similarly, in the same year, the UGA SSA

Table 6. The change of irrigation cost for cotton grown near Camilla, GA, during the 2013 to 2017 growing season for conservation and conventional tillage practices based on three irrigation budgets developed by the University of Georgia Extension

Year	Treatment	Conservation Tillage 160 D[Z]	Conservation Tillage 65 E[Y]	Conservation Tillage 65 D[X]	Conventional Tillage 160 D	Conventional Tillage 65 E	Conventional Tillage 65 D
		$\$ ha^{-1}$					
2013	Checkbook	670	878	1098	659	873	1088
	Cotton App	456	782	913	456	782	913
	Irrigator Pro	448	791	915	448	791	915
	CWSI	498	814	959	448	791	915
2014	Checkbook	675	880	1102	675	880	1102
	Cotton App	540	819	985	540	819	985
	UGA SSA C	671	892	1108	621	869	1065
2015	Checkbook	555	826	999	555	826	999
	Cotton App	522	811	970	533	816	980
	UGA SSA C	493	811	954	592	856	1040
	UGA SSA V	531	829	988	504	816	964
2016	Checkbook	583	839	1023	583	839	1023
	Cotton App	522	811	970	522	811	970
	UGA SSA C	487	809	950	465	799	931
	UGA SSA V	476	804	940	471	801	935
2017	Checkbook	621	856	1056	621	856	1056
	Cotton App	511	806	961	511	806	961
	UGA SSA C	460	796	926	476	804	969
	Pro SSA	469	800	934	509	818	940

[Z]160-Acre Diesel Powered Center Pivot Irrigation Budget
[Y]65-Acre Electric Powered Center Pivot Irrigation Budget
[X]65-Acre Diesel Powered Center Pivot Irrigation Budget

C method rank fell below the Control with 160 D, 65 E, and 65 D. This suggests that when irrigation costs rise, yield improvement from using UGA SSA C compared to the Control is insufficient to offset the additional irrigation expenses. In 2013 and 2016, under conservation tillage, change in irrigation costs did not alter the ranking of net returns between the Control and the irrigation treatments, nor between the Checkbook and other irrigation treatments. The rank changes observed in both 2013 and 2016 occurred only within the advanced irrigation treatments.

CONCLUSIONS

This research evaluates the economic efficiency of four advanced irrigation scheduling methods compared to the Control and the traditional calendar-based Checkbook under both conservation and conventional tillage practices. The advanced irrigation scheduling methods include the Cotton App, UGA SSA, CWSI, and Irrigator Pro. We compared water usage, yield, and profitability for cotton production among alternative irrigation scheduling methods by using field trials conducted near Camilla, GA, from 2013 to 2017.

Results indicate that irrigation enhances cotton productivity and profitability during dry years but can negatively impact yield and profitability during wet years under conservation tillage. In dry years, irrigation boosts yield and productivity when there is less preexisting moisture in the soil. However, in years with high precipitation, additional irrigation can reduce both yield and profitability. During wet years, the Control under conservation tillage achieved a higher average net return than all irrigated scheduling methods, suggesting that there is room for improvement in irrigation water usage efficiency. Among all irrigated treatments, the calendar-based Checkbook method consumed the most water and produced the lowest yield during wet years, indicating over-irrigation. In contrast, advanced irrigation scheduling methods demonstrated the ability to reduce water usage while simultaneously increasing yield and profitability compared to the calendar-based Checkbook method. This suggests that modern irrigation scheduling methods can be particularly beneficial for cotton growers in drier regions with limited precipitation. Moreover, the percentage of water saved by using advanced irrigation scheduling methods ranges from 21 to 94%, with an average of 57% compared with the Checkbook method. By adopting modern irrigation methods, farmers can improve their productivity and profitability while conserving water, which is crucial for maintaining sustainability and addressing water scarcity for future generations.

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