Received: 12 October 2021 | Accepted: 5 January 2022

DOI: 10.1002/cft2.20149

Crop, Forage & Turfgrass Management

RESEARCH

Crop Management

Maximizing soybean productivity and profitability by transitioning from flood to furrow irrigation on clay-textured soils

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Assigned to Associate Editor Mark Licht

Abstract

The type of irrigation delivery system used in the mid-southern United States can have an effect on crop–water relationships and withdrawal from the Mississippi River Valley Alluvial Aquifer. This study was conducted to determine whether converting from flood irrigation to an optimized furrow irrigation delivery system improves soybean [*Glycine max* (L.) Merr.] grain yield, net returns, and irrigation water use efficiency (IWUE). The effects of flood and optimized furrow irrigation on soybean grain yield, net returns above specified costs, irrigation water applied, and IWUE were investigated from 2016 to 2018 on 24 paired fields with the same soil type, cultivar, planting date, and management practices in the Delta region of Mississippi. Transitioning from flood irrigation to an optimized furrow irrigation system increased soybean grain yield by 7% and net returns above specified costs by 18% but had no effect on consumptive water use or IWUE. Our data indicate that mid-southern US soybean producers should convert from flood to optimized furrow irrigation systems to maximize soybean grain yield and net returns; however, switching between irrigation delivery systems will have no effect on aquifer decline

Withdrawal from the Mississippi River Valley Alluvial Aquifer for row-crop irrigation has caused aquifer decline and is unsustainable. Mississippi is a leader in the implementation of programs designed to prevent further overdraft of the Mississippi River Valley Alluvial Aquifer. To reduce aquifer decline, Mississippi implemented a well permitting program in 1985. In 2019, furrow irrigators were required to adopt three approved irrigation water management practices to receive a well permit (Yazoo Mississippi Delta Joint Water Management District, 2019). The change in well permitting caused producers who rotate soybean [*Glycine max* (L.) Merr.] with rice (*Oryza sativa* L) to reevaluate their approach to soybean irrigation.

In Mississippi, soybean is traditionally rotated with rice on clay-textured soils and is either flood- or furrow-irrigated. The soybean–rice rotation was adopted because both crops are suited for growth on clay-textured soils, and there is a synergistic effect of the rotation on soybean grain yield (Heatherly & Spurlock, 2000; Kurtz et al., 1993). Flood irrigation appeals to producers using a soybean–rice rotation, as all of the necessary equipment is in place, and flood irrigation is more efficient when filling cracks that form in the 2:1 clay-textured soils (Heatherly & Spurlock, 2000; Mitchell & van Genuchten, 1993). However, flood irrigation may have a negative effect on soybean grain yield as a result of injury from flooding. Depending on flood depth and duration, soybean grain yield can be reduced by up to 93% (Heatherly & Pringle, 1991; Sullivan et al., 2001). Furthermore, the majority of approved irrigation water management practices that irrigators must adopt do not fit into flood irrigation systems, and it has been assumed that less water is applied in furrow irrigation systems. Optimization of furrow irrigation systems

Abbreviations: CHS, computerized hole selection; IWUE, irrigation water use efficiency.

may maximize soybean grain yield while maintaining irrigation efficiency.

Current research has optimized furrow irrigation for clay-textured soils by integrating multiple water management tools such as computerized hole selection (CHS), surge flow irrigation, and scheduling based on soil moisture sensors. On clay-textured soils, the application of CHS to lay-flat polyethylene tubing decreased consumptive water use by up to 17% without having any adverse effect on soybean grain yield (Krutz, 2016). Relative to furrow irrigating with only CHS, combining surge flow irrigation with CHS reduced consumptive water use by 24% and had no effect on soybean grain yield (Wood et al., 2017). Moreover, at the production scale, scheduling with soil moisture sensors and optimizing delivery via CHS and surge irrigation had no effect on soybean grain yield but reduced consumptive water use by 21% relative to the producer standard, namely, having no irrigation water management practices in place (Bryant et al., 2017). Integrating irrigation water management tools into furrow-irrigated environments reduces consumptive water use, improves irrigation water use efficiency (IWUE), and has no adverse effect on productivity. However, there are no reports of consumptive water use and IWUE for flood irrigation or comparisons of flood and furrow irrigation strategies to determine the optimal soybean irrigation system in the mid-southern United States. This research was conducted to determine whether converting from flood irrigation to an optimized furrow irrigation delivery system improves soybean grain yield, net returns, and IWUE while decreasing consumptive water use.

Core Ideas

- Flood irrigation of soybean does not increase consumptive water use on clay-textured soils.
- Irrigation method influenced soybean productivity but not irrigation water use efficiency.
- Optimized furrow irrigation systems should be adopted to maximize soybean profitability.

1 | SITE DESCRIPTION AND EXPERIMENTAL DESIGN

Soybean's response to flood and optimized furrow irrigation delivery systems was evaluated from 2016 to 2018 in 24 paired fields in the Delta region of Mississippi. Cooperating producers provided paired fields with the same soil type, cultivar, planting date, and production practices at each site (Table 1). The paired fields were randomly assigned to either flood or optimized furrow irrigation. Flood irrigation fields were managed by the producer according to their standard practices, and furrow irrigation fields were managed by university extension personnel. Consumptive water use was determined by installing a McCrometer flow tube with an attached McPropeller bolt-on saddle flowmeter (McCrometer, Inc.) at the field inlet. Irrigation water use efficiency was calculated as described by Vories et al. (2005):

$$\mathrm{IWUE} = \frac{Y}{\mathrm{IWA}}, \tag{1}$$

where IWUE is irrigation water use efficiency (bu acre-inch^{-1}), Y is soybean grain yield (bu acre^{-1}), and IWA is irrigation water applied (inches). Soybean was mechanically harvested at physiological maturity by the producers, and yields were determined with calibrated onboard yield monitors or elevator scale tickets.

2 | FLOOD IRRIGATION

Fields assigned to flood irrigation were planted either flat or on a raised seed-bed and irrigated according to the producer's standard farm practices. Prior to irrigation, earthen levees spaced approximately 400 ft apart, with one levee for every 4.8 inches of field fall, were constructed perpendicular to the field grade. Irrigation was supplied through a riser located at the highest elevation of the field. Water inundated the uppermost bay to approximately seven-eighths of the levee height.

The levee was returned to field grade with a tractor-mounted levee plow, causing the water to inundate the next bay. The levee-breaching process was repeated until the entire field was irrigated. The irrigation event was completed when the final levee was returned to field grade and all impounded water cascaded across the last bay, recharging the field's soil profile. The entire process of levee construction, water application, and levee deconstruction was repeated for subsequent irrigations.

3 | OPTIMIZED FURROW IRRIGATION

Optimized furrow irrigation is a system that improves water delivery and timing by incorporating CHS, surge irrigation, and sensor technology (Bryant et al., 2017). Briefly, optimized furrow irrigation fields were planted on raised seed-beds and surge flow irrigation was delivered to the field via lay-flat polyethylene tubing (Delta Plastics) attached to a P&R STAR surge valve (P&R Surge Systems)(Wood et al., 2017). Irrigation uniformity and application efficiency were maximized by selecting the size of holes punctured in the lay-flat polyethylene tubing at every furrow as recommended by Pipe Planner CHS (Delta Plastics). Irrigations were scheduled when the

TABLE 1 Fields used in on-farm research comparing flood irrigation with furrow irrigation of soybean in the Delta region of Mississippi during the 2016 to 2018 growing seasons

Year	Paired fields	County	Soil texture	Soil series	Irrigation method	
					Flood	Furrow
					———acre———	
2016	1	Bolivar	Clay	Sharkey clay	62	69
	2	Bolivar	Clay, silt loam	Sharkey clay, Dubbs silt loam	79	77
	3	Washington	Clay	Sharkey clay	52	59
	4	Bolivar	Silt loam	Dubbs silt loam	40	40
	5	Tunica	Clay	Sharkey clay	52	62
	6	Bolivar	Clay	Forestdale silty clay	74	64
	7	Bolivar	Clay	Sharkey clay	49	49
	8	Bolivar	Clay, silt loam	Tunica clay, Dubbs silt loam	62	59
2017	1	Bolivar	Silt loam	Dubbs silt loam	40	40
	2	Sunflower	Clay loam	Forest silty clay loam	62	57
	3	Bolivar	Clay	Sharkey silty clay	40	37
	4	Bolivar	Silt loam, clay	Dubbs silt loam, Dundee silty clay	74	69
	5	Bolivar	Clay	Sharkey clay	57	59
	6	Bolivar	Clay	Sharkey clay	59	59
	7	Bolivar	Clay	Sharkey clay	47	49
	8	Bolivar	Clay, sandy loam	Dundee silty clay, Dubbs very fine sandy loam	40	40
	9	Bolivar	Clay	Sharkey clay	62	57
2018	1	Bolivar	Silt loam	Dubbs silt loam	49	52
	2	Sunflower	Clay	Sharkey silty clay	49	49
	3	Bolivar	Clay	Sharkey silty clay	67	52
	4	Washington	Clay	Dowling clay	47	54
	5	Bolivar	Clay	Sharkey clay	69	62
	6	Bolivar	Clay	Sharkey clay	57	52
	7	Bolivar	Clay	Tunica clay	72	67
	8	Bolivar	Clay	Sharkey clay	49	54
	9	Bolivar	Clay, sandy loam	Dundee silty clay, Dubbs very fine sandy loam	52	47

weighted average soil water potential across a 24-inch depth was between −85 and −100 centibars, as indicated by Watermark 200SS soil moisture sensors (Irrometer Company). Further details regarding the placement and depth of soil moisture sensors, and the weighting of average soil water potential are described in Bryant et al. (2017).

4 | ECONOMIC ANALYSIS

Economic analysis was conducted to determine the effects of irrigation systems on net returns, which are the returns above specified costs. Production costs were determined for flood and optimized furrow irrigation soybean production systems within straight levee rice fields. The direct and fixed expenses for each system are modified versions of the costs found in the Mississippi State University Department of Agricultural Economics Delta planning budgets, which were revised to represent the two irrigation systems and averaged across the 3 yr (Mississippi State University, 2016, 2017, 2018). A breakdown of these costs for the furrow- and flood-irrigated systems can be found in Table 2 and Table 3, respectively.

All cultural practices were assumed to be identical, with the exception of grain hauling, which was directly related to yield and irrigation activities between the two systems. The irrigation supply allowance of \$19.01 acre^{-1} for the furrow-irrigated system included a \$10.76 acre^{-1} charge for the water management tools and an \$8.25 acre^{-1} charge for the lay-flat polyethylene tubing. The irrigation water management allowance included a surge valve, a transfer pipe, soil moisture sensors, batteries, and a data logger package. For the flood-irrigated system, the costs included the machinery and labor costs of building the inside levees twice, two 4-inch irrigation

TABLE 2 Estimated costs per acre for a furrow-irrigated soybean production system in a furrow- versus flood-irrigated soybean study in the Delta region of Mississippi during the 2016 to 2018 growing seasons

Item	Unit	Price per unit	Quantity	Amount
		——$——		——$——
Direct expenses				
Custom spray	acre	28.17	1.0000	28.17
Harvest aids	acre	6.56	1.0000	6.56
Fertilizers	acre	43.47	1.0000	43.47
Fungicides	acre	26.53	1.0000	26.53
Herbicides	acre	95.27	1.0000	95.27
Insecticides	acre	8.68	1.0000	8.68
Irrigation supplies	acre	19.01	1.0000	19.01
Seed or plants	acre	68.50	1.0000	68.50
Adjuvants	acre	3.88	1.0000	3.88
Custom fertilizer	acre	7.33	1.0000	7.33
Hauling	acre	20.25	1.0000	20.25
Custom lime	acre	14.38	1.0000	14.38
Crop consultant	acre	6.50	1.0000	6.50
Inoculant	acre	2.52	1.0000	2.52
Soil test	acre	3.32	1.0000	3.32
Hand labor	h	9.06	0.1241	1.12
Irrigation labor	h	9.06	0.3625	3.28
Operator labor	h	13.63	0.4643	6.33
Unallocated labor	h	13.62	0.3472	4.73
Diesel fuel	gal	2.03	12.3269	25.02
Repair and maintenance	acre	18.09	1.0000	18.09
Interest on operating capital.	acre	11.33	1.0000	11.33
Total direct expenses	–	–	–	**424.28**
Total fixed expenses	–	–	–	**99.54**
Total specified costs	–	–	–	**523.82**

events, and the machinery and labor costs of tearing down the levees twice.

A soybean price of \$9.59 bu^{-1}, the average price taken from the Delta Planning Budgets for the 3 yr of this research, was used to calculate gross revenue (Mississippi State University, 2016, 2017, 2018). The sensitivity analysis on the effect of varying soybean price and input costs on net returns was also conducted.

5 | STATISTICAL ANALYSIS

ANOVA and mean separation were performed for soybean grain yield, net returns above specified costs, irrigation water applied, and IWUE with the GLIMMIX procedure in SAS 9.4 (SAS Institute Inc.). Year, farm(year), and irrigation system × farm(year) were considered random effects. Differences were considered significant at $\alpha = .05$.

6 | AGRONOMIC, ECONOMIC, AND WATER USE IMPLICATIONS

The principal hypothesis of this research was that an optimized furrow irrigation system would reduce total water applied while maintaining or improving soybean grain yield, net returns above specified costs, and IWUE. As hypothesized, optimized furrow irrigation increased soybean grain yield by 7% ($P = .0075$) and net returns above specified costs by 18% (Table 4). Conversely, total water applied and IWUE averaged 8 inches and 10.5 bu acre-inch^{-1}, respectively, and did not differ as a function of the irrigation delivery system ($P > .6151$; Table 4). These data indicate that shifting from flood to optimized furrow irrigation will improve soybean grain yield and net returns above specified costs while having no effect on total water applied and IWUE.

The effect of optimized furrow irrigation systems on soybean grain yield is attributed to proper irrigation timing.

TABLE 3 Estimated costs per acre for a flood-irrigated soybean production system in a furrow- versus flood-irrigated soybean study in the Delta region of Mississippi during the 2016 to 2018 growing seasons

Item	Unit	Price per unit	Quantity	Amount
		———$———		—$—
Direct expenses				
Custom spray	acre	28.17	1.0000	28.17
Harvest aids	acre	6.56	1.0000	6.56
Fertilizers	acre	43.47	1.0000	43.47
Fungicides	acre	26.53	1.0000	26.53
Herbicides	acre	95.27	1.0000	95.27
Insecticides	acre	8.68	1.0000	8.68
Seed or plants	acre	68.50	1.0000	68.50
Adjuvants	acre	3.88	1.0000	3.88
Custom fertilizer	acre	7.33	1.0000	7.33
Hauling	acre	18.90	1.0000	18.90
Custom lime	acre	14.38	1.0000	14.38
Crop consultant	acre	6.50	1.0000	6.50
Inoculant	acre	2.52	1.0000	2.52
Soil test	acre	3.32	1.0000	3.32
Hand labor	h	9.06	0.1241	1.12
Irrigation labor	h	9.06	0.4500	4.08
Operator labor	h	13.63	0.5000	6.82
Unallocated labor	h	13.62	0.3472	4.73
Diesel fuel	gal	2.03	12.5749	25.53
Repair and maintenance	acre	18.54	1.0000	18.54
Interest on Operating Capital	acre	11.08	1.0000	11.08
Total direct expenses	–	–	–	**405.90**
Total fixed expenses	–	–	–	**100.30**
Total specified costs	–	–	–	**506.20**

TABLE 4 Least square means for soybean grain yield, gross revenue, total specified expenses, returns above specified costs (net returns), consumptive water use (CWU), and irrigation water use efficiency (IWUE) for an on-farm optimized furrow irrigation versus flood irrigation soybean study conducted on clay-textured soils in the Delta region of Mississippi from 2016 to 2018

Irrigation system	Yield	Gross revenue[a]	Total specified expenses	Net returns	CWU	IWUE
	bu acre^{-1}	——————$ acre^{-1}——————			inches	bu acre-inch^{-1}
Furrow	75 A	722.72	523.92	199.29	8 A	10 A
Flood	70 B	674.31	506.28	168.52	8 A	11 A

Note. Values in a column followed by the same letter are not different at the $\alpha \leq .1$ level of significance.
[a]Given a soybean price of $9.59 bu^{-1}.

In the optimized system, irrigation was scheduled between −85 and −100 cbars. For soil textures ranging from a very fine sandy loam to a clay, maintaining the irrigation threshold for soybean between −85 and −100 cbars never resulted in yield loss relative to a well-watered system, i.e., −50 cbars (Bryant et al., 2017). Conversely, decreasing the irrigation threshold to −125 cbars reduced soybean grain yield by up to 22%, relative to the producer standard (Krutz et al., 2014; Wood et al., 2020). Although soil moisture potential was not measured in the flood irrigation system, producers routinely irrigated for up to 3 wk later than with the optimized system. We suggest that delaying irrigation in the flooded system decreased the soil moisture content to approximately −125 cbars, a level known to reduce soybean grain yield (Wood et al., 2020).

Given the average yields across all 3 yr and a soybean price of $9.59 bu^{-1}, gross revenue for the optimized furrow-irrigated system was $48.41 greater than that of the flood-irrigated system. The furrow-irrigated system had additional costs of \$19.01 acre^{-1}, which was primarily because of the cost of irrigation supplies. However, the furrow irrigated system had reduced labor, repair and maintenance, and fixed costs. At a soybean price of \$9.59 bu^{-1}, the yield advantage from furrow irrigation needed to cover these additional costs would be around 2 bu acre^{-1}, well below the 5 bu acre^{-1} increase found in this research. The full breakdown of costs for furrow-irrigated and flood-irrigated systems can be found in Table 2 and Table 3, respectively. Overall, the gains in yield in the furrow-irrigated system more than offset the additional costs, and net returns were increased by \$30.77 acre^{-1} on average. Furthermore, a sensitivity analysis of soybean prices ranging from \$7.00 bu^{-1} to \$12.50 bu^{-1} found that a furrow-irrigated system had higher net returns than a flood-irrigated system even at relatively low soybean prices. Higher soybean prices increased the value of switching to furrow irrigation. A sensitivity analysis on the variable costs did not show a significant effect on the results. These results indicate that, on average, the adoption of furrow-irrigation would increase the profitability of soybean farms in the Delta region of Mississippi.

Contrary to our hypothesis, optimizing the timing and delivery in the optimized system had no effect on total water applied or IWUE. We assumed that improving the irrigation timing and delivery with soil moisture sensors and surge irrigation via lay-flat polyethylene tubing with CHS would greatly reduce the total water applied and IWUE. We suggest that the lack of differences in total water applied was caused by a greater number of irrigation events with lower irrigation volumes at each event in the optimized furrow irrigation system, which still matched the greater irrigation volume applied during fewer irrigation events in the flood-irrigated system. The phenomenon of reduced yields with equivalent water use yet numerically greater IWUE in the flood-irrigated systems was caused by the spatial variability inherent at the field scale. Although the majority of flood-irrigated systems applied water volumes exceeding those of optimized furrow-irrigated systems, several growers were able to reduce irrigation volumes in the flood-irrigated system by capturing the full benefits of in-season rainfall while achieving equivalent yields. These data indicate that properly managed flood irrigation systems are no less efficient than optimized furrow irrigation with regards to consumptive water use and irrigation water use efficiency for clay-textured soils where producers are restricting themselves to no more than three irrigation events because of levee failure.

7 | CONCLUSIONS

The objective of this research was to evaluate the effect of an optimized furrow irrigation system on soybean grain yield, net returns above specified costs, consumptive water use, and IWUE compared with standard flood irrigation systems. This research indicates that compared with flood irrigation, optimized furrow irrigation systems increased soybean grain yield and net returns above specified costs by 7% and 18%, respectively. However, replacing flood irrigation with optimized furrow irrigation will have no effect on aquifer decline in the mid-southern United States. Our data indicate that soybean producers should adopt optimized furrow irrigation systems to maximize on-farm soybean productivity and profitability.

ACKNOWLEDGMENTS

Research was supported by the Mississippi Soybean Promotion Board.

AUTHOR CONTRIBUTIONS

Corey J. Bryant: Data curation, Formal analysis, Writing – original draft, Writing – review & editing. L. Jason Krutz: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Visualization, Writing – review & editing. G. Dave Spencer: Data curation, Formal analysis, Writing – review & editing. Brian E. Mills: Data curation, Formal analysis, Writing – original draft, Writing – review & editing.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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How to cite this article: Bryant, C. J., Krutz, L. J., Spencer, G. D., & Mills, B. E. (2022). Maximizing soybean productivity and profitability by transitioning from flood to furrow irrigation on clay-textured soils. *Crop, Forage & Turfgrass Management*, *8,* e220149. https://doi.org/10.1002/cft2.20149