Irrigation Water Management Technologies for Furrow-Irrigated Corn that Decrease Water Use and Improve Yield and On-Farm Profitability

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Abstract
Withdrawal from the Mississippi River Valley alluvial aquifer by row-crop irrigators in the Mid-Southern USA has caused a precipitous decline in groundwater levels. The objective of this research was to determine if irrigation water management (IWM) practices can reduce the amount of water applied without having an adverse effect on corn (Zea mays L.) grain yield and profitability when compared with the regional standard, that is, no IWM. The effect of computerized hole selection, surge irrigation, and irrigation scheduling based on soil moisture sensors on corn grain yield, total water applied, irrigation water use efficiency, and net returns above irrigation costs were determined from 2013 through 2017 on 18 paired fields with the same cultivar, soil texture, planting date, and management practices. One field was randomly assigned as the control (CONV) and was irrigated according to each producer’s standard procedure while the other field used the IWM practices. Flowmeters were installed at the inlets to both fields and monitored the total volume of water applied while the cooperating farmers provided yield data. Relative to CONV, IWM decreased total water applied by 39.5% (P = 0.002) while increasing corn grain yield by 6.5 bu/acre (P = 0.0137), irrigation water use efficiency by 51.3% (P = 0.0062), and net returns above irrigation costs from $25.03 to $39.18/acre for pumping depths ranging from 18 to 400 ft and diesel costs ranging from $1.60/gal to $3.70/gal (P = 0.0115). Our research indicates that integrating computerized hole selection, surge flow irrigation, and irrigation scheduling with soil moisture sensors reduces the demand on depleted groundwater resources while improving corn grain yield, irrigation water use efficiency, and net returns above irrigation costs.

The Mississippi River Valley alluvial aquifer (MRVAA) has the third highest rate of daily water withdrawal of any aquifer in the United States (Maupin and Barber, 2005). Ninety-eight percent of the water withdrawn from the MRVAA is for irrigation, and Arkansas and Mississippi are the first and second largest users, respectively, of the seven states overlying the aquifer (Barlow and Clark, 2011; Maupin and Barber, 2005). In Mississippi, more than 17,000 permitted
Across the Mid-Southern USA, furrow irrigators do not utilize computerized hole selection (CHS), a free computer program that improves irrigation application efficiency (Bryant et al., 2017). Traditionally, a single hole size is punctured in the poly-tubing at every furrow for the entire length of the irrigation set. When the same size hole is used for every hole throughout the length of the poly-tubing, the head pressure decreases with distance from the water source, resulting in irregular furrow discharge. Uneven furrow advancement reduces irrigation application efficiency, which is compounded on irregularly shaped fields. Computerized hole selection improves irrigation application efficiency by considering the shape of the field, length of poly-tubing, and elevation changes along the field crown (Bryant et al., 2017). Hole sizes are computed for each furrow to ensure partitioned furrow delivery based on head pressure, creating a more uniform advance pattern. Larger holes are selected for longer furrow lengths and further distances from the riser while smaller holes are chosen for shorter furrow lengths and closer distances to the water source. The result is a consistent volume of water applied to each furrow and similar furrow advance times for a given field (Henry and Krutz, 2016). By improving irrigation uniformity, CHS reduces tail-water runoff and decreases total water applied (Kebede et al., 2014).

The Delta region of Mississippi and Arkansas, which accounts for the majority of each state’s corn production, is predominantly furrow-irrigated (Massey et al., 2017). Irrigation events are currently scheduled using non-scientific cultural practices (USDA-NASS, 2012). A continuous-flow, furrow-irrigation delivery system, which utilizes lay-flat polyethylene tubing (poly-tubing) attached to the field inlet and laid perpendicular to the furrows along the field crown, is one of the most inefficient delivery methods (Kebede et al., 2014; Sammis, 1980; Smith et al., 2005). Holes are punctured in the poly-tubing wall to direct water flow down each furrow. Producers typically initiate irrigation at the first sign of perceived stress, irrespective of soil moisture content (Henry and Krutz, 2016). Subsequently, irrigations are scheduled by crop condition, the feel of the soil, or a personal calendar schedule (USDA-NASS, 2013) and terminated at the R5 growth stage, which is when nearly all of the kernels are denting near the crown. Improving irrigation uniformity, efficiency, and scheduling in furrow-irrigated environments must be a primary research objective to achieve sustainable irrigated corn production in the Mid-Southern USA.

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The two primary factors causing inefficiencies in furrow irrigation are deep percolation losses and tail-water runoff, both of which can be addressed with surge irrigation (SURGE). Deep percolation losses, i.e., water moving below the root zone, in conventional furrow irrigation typically occur at the portion of the field near the poly-tubing as more water is applied to this part of the field (Henry and Krutz, 2016; Musick et al., 1987). As described by Bryant et al. (2017), SURGE is an application technique that intermittently applies water to furrows in a series of short, on-and-off cycles. SURGE increases infiltration and furrow advance time, reduces deep percolation losses, and improves irrigation application efficiency (Gudissa and Edossa, 2014; Horst et al., 2007; Musick et al., 1987).

Currently, most irrigators in the Mid-Southern USA do not use scientific tools to schedule irrigations. Soil moisture sensors are a scientific scheduling tool that can improve irrigation timing by in situ measurements of soil moisture in the rooting zone. Sensor-based scheduling can reduce total water applied up to 50% (Hassanli et al., 2009). The adoption of soil moisture sensors in the Delta region of Mississippi and Arkansas is less than 11%, indicating tremendous potential for improvement in irrigation application (USDA-NASS, 2013).

As noted for soybean [Glycine max (L.) Merr.], CHS, SURGE, and sensor-based irrigation scheduling may decrease consumptive water use without negatively affecting corn grain yield and profitability in the Mid-Southern USA (Bryant et al., 2017). The objective of this research was to determine the effect of the IWM practices of CHS, SURGE, and sensor-based irrigation scheduling on corn grain yield, total water applied, irrigation water use efficiency (IWUE), and net returns above irrigation costs at a production scale.

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### Table A. Useful conversions.

| To convert Column 1 to Column 2, multiply by | Column 1 Suggested Unit | Column 2 SI Unit |
|---------------------------------------------|--------------------------|------------------|
| 0.405                                       | acre                      | hectare, ha      |
| 3.78                                        | gallon, gal               | liter, L         |
| 10.26                                       | acre-inch                 | hectare-millimeter, ha-mm |
| 62.71                                       | 56-lb bushel per acre, bu/acre | kilogram per hectare, kg/ha |
| 6.09                                        | bushel/acre-inch, bu/acre-inch | kilogram/hectare-millimeter, kg/ha-mm |
Table 1. Year, state, county, and soil texture for fields where irrigation water management tools including computerized hole selection, surge irrigation, and sensor-based scheduling (IWM) were compared with conventional (CONV) irrigation of corn in the Delta regions of Mississippi and Arkansas and the Prairie region of Arkansas during the 2013 through 2017 growing seasons.

| Year | Paired fields | State       | County       | Soil texture        | Field size (acres) | Irrigation method |
|------|---------------|-------------|--------------|---------------------|--------------------|-------------------|
| 2013 | 1             | Mississippi | Tallahatchie | very fine sandy loam | 51                 | CONV 55           |
|      | 2             | Mississippi | Yazoo        | silt loam           | 32                 | IWM               |
|      | 3             | Mississippi | Yazoo        | silt loam           | 35                 |                  |
|      | 4             | Mississippi | Coahoma      | silt loam           | 31                 |                  |
|      | 5             | Mississippi | Humphreys    | silt loam           | 22                 |                  |
|      | 6             | Mississippi | Washington  | very fine sandy loam| 46                 |                  |
| 2014 | 1             | Mississippi | Tallahatchie | very fine sandy loam| 51                 |                  |
|      | 2             | Mississippi | Washington  | silty clay          | 45                 |                  |
|      | 3             | Mississippi | Issaquena    | silty clay loam     | 23                 |                  |
|      | 4             | Mississippi | Quitman      | fine sandy loam     | 83                 |                  |
|      | 5             | Mississippi | Sharkey      | very fine sandy loam| 13                 |                  |
|      | 6             | Mississippi | Ashley       | clay                | 46                 |                  |
|      | 7             | Mississippi | Coahoma      | very fine sandy loam| 23                 |                  |
|      | 8             | Arkansas    | Ashley       | silt loam           | 34                 |                  |
|      | 9             | Arkansas    | Phillips     | silt loam           | 40                 |                  |
| 2017 | 1             | Arkansas    | Ashley       | silt loam           | 29.5               |                  |

Research Location and Design

The effects of IWM on corn grain yield and profitability were evaluated from 2013 through 2017 at 18 locations in the Prairie region of Arkansas and the Delta region of Mississippi and Arkansas. Each location contained two paired fields with the same hybrid, soil texture, planting date, and management practices (Table 1). The paired fields were randomly assigned as CONV and IWM. Producers irrigated the CONV fields according to their standard irrigation methodology while the other fields were instrumented with IWM tools, including CHS, SURGE, and soil moisture sensors. Total water applied was determined with a McCrometer FS100 flow straightener, with attached McPropeller bolt-on saddle flowmeter (McCrometer, Inc., Hemet, California). Producers harvested both CONV and IWM fields and reported corn grain yield using calibrated onboard yield monitors or scale tickets.

Computerized Hole Selection

Computerized hole selection was implemented into IWM fields as described by Bryant et al. (2017). Elevation along the run of poly-tubing, length of poly-tubing (ft), water output (gpm), furrow spacing (ft), length of irrigated furrows (ft), and diameter of poly-tubing (inch) are the input parameters for CHS (Kebede et al., 2014). Elevations were measured every 100 ft along the pad of the poly-tubing with a Topcon self-leveling slope-matching rotary laser level (Topcon positioning systems Inc., Livermore, CA) while poly-tubing and furrow length were measured using aerial imagery. Furrow spacing was the same as row spacing because irrigation was applied down each furrow. Pipe Hole and Universal Crown Evaluation Tool (PHAUCEC) version 8.2.20 (USDA-NRCS, Washington, DC) or Delta Plastics Pipe Planner (Delta Plastics, Little Rock, AR) was used to perform CHS.

Surge Flow Irrigation

Surge flow irrigation was implemented on IWM fields as described by Wood et al. (2017). Water was delivered through a P&R STAR surge valve (P&R Surge Systems, Inc., Lubbock, TX). Advance and soak cycles were optimized to minimize tail-water runoff (Henry and Krutz, 2017). Irrigation was terminated when approximately 2.5 acre-inches were applied.

Irrigation Scheduling

Irrigation water management fields utilized soil moisture sensors for irrigation scheduling. Four Watermark 200S5 soil moisture sensors (Irrometer Company Inc., Riverside, CA) were installed at depths of 6, 12, 24, and 36 inches in the lower third of the field as previously described by Bryant et al. (2017). Irrigation was applied when the weighted average of the soil water potential over the 36-inch depth was between –75 and -100 cbar. Irrigation was terminated if the average weighted soil moisture potential was –50 cbar or less at the 50% milk line growth stage. Irrigation water use efficiency was calculated as described by Vories et al. (2005):

\[ IWUE = \frac{Y}{IWA} \]
Table 2. Estimated purchase price, useful life, fuel use, cost for fuel and repair and maintenance (R&M), and direct, fixed, and total costs per year based on pumping nine acre-inches per year and 2017 input prices.

| Item name                          | Unit of measure | Purchase price | Useful life | Fuel use | Costs                      |
|------------------------------------|-----------------|----------------|-------------|----------|---------------------------|
|                                    |                 |                |             | gal/hr   | Fuel | R&M | Direct | Fixed | Total |
| Land forming (§390)                | acre            | $450           | 25          | 0        | 0.00 | 0.00 | 0.00   | 31.93 | 31.93 |
| Surge valve- 10”                   | each            | 3483           | 10          | 0        | 0.00 | 0.00 | 0.00   | 348.30 | 348.30 |
| Pipe elbows                        | each            | 127            | 20          | 0        | 0.00 | 0.00 | 0.00   | 6.35   | 6.35  |
| Soil moisture sensors              | each            | 39             | 3           | 0        | 0.00 | 0.00 | 0.00   | 13.00  | 13.00 |
| Irrrometer datalogger (package)    | each            | 450            | 10          | 0        | 0.00 | 0.00 | 0.00   | 45.00  | 45.00 |
| Relift tractor: 75 hp              | acre-inch       | 21,113         | 10          | 3.86     | 1924.09 | 1055.56 | 2979.74 | 1894.94 | 4874.68 |
| Engine: 100 hp, 140 ft             | acre-inch       | 20,000         | 20          | 3.6      | 2346.13 | 750.00  | 3096.13 | 1604.85 | 4700.98 |
| Engine: 100 hp, 200 ft             | acre-inch       | 20,000         | 20          | 3.6      | 2592.00 | 750.00  | 3342.00 | 1604.85 | 4946.85 |
| Engine: 100 hp, 400 ft             | acre-inch       | 20,000         | 20          | 3.6      | 3732.48 | 750.00  | 4482.48 | 1604.85 | 6087.33 |
| Relift pump                        | each            | 6670           | 25          | 0        | 0.00 | 160.08 | 160.08 | 473.25  | 633.33 |
| Well and pump: 140 ft              | each            | 20,250         | 25          | 0        | 0.00 | 486.00 | 486.00 | 1436.78 | 1922.78 |
| Well and pump: 200 ft              | each            | 25,150         | 25          | 0        | 0.00 | 603.60 | 603.60 | 1784.45 | 2388.05 |
| Well and pump: 400 ft              | each            | 43,150         | 25          | 0        | 0.00 | 1035.60 | 1035.60 | 3061.59 | 4097.19 |

where IWUE is irrigation water use efficiency (bu/acre-inch), Y is corn grain yield (bu/acre), and IWA is total irrigation water applied (acre-inch).

Economic Analysis

Irrigation enterprise budgets were developed for both CONV and IWM technologies using the Mississippi State University (MSU) budget generator models developed for four different source depths as described in Bryant et al. (2017). All variable input costs for the 2013, 2014, 2015, 2016, and 2017 crop years were adjusted on an annual basis with the exception of diesel, which was held constant at the 5-year average diesel price of $2.55, based on MSU planning budgets. A baseline corn price of $3.79/bu, the average corn price reported by the USDA at Greenville, MS for the August and September harvest periods, was used in all scenarios (USDA-ERS, 2018).

The highest and lowest diesel prices for the prior 10-year period were considered to evaluate profitability response under each irrigation technology. The USDA Prices Paid Survey for the Delta States region during 2008 to 2017 reported a maximum annual diesel price of $3.70/gal and a minimum annual diesel price of $1.60/gal. These two prices were used in the high and low diesel price scenarios, respectively. Assumptions used in each enterprise budget related to equipment use and purchase price, fuel consumption, and irrigation supply rate are as described by Bryant et al. (2017) and are presented in Table 2.

Statistical Analysis

Statistical analyses were performed similarly to Wood et al. (2017). Analysis of variance and mean separation were performed for corn grain yield, total water applied, IWUE, and net returns above irrigation costs using the MIXED procedure of SAS (Statistical Analytical System Release 9.4; SAS Institute Inc., Cary, North Carolina), with year and field (year) as random effects.

General Site Statistics

Research was conducted during the 2013 to 2017 growing seasons on 18 paired fields in the Delta region of Mississippi and Arkansas, an alluvial floodplain of the Mississippi River encompassing approximately 17,000 sq mi, and the Prairie region of Arkansas, a 1850 sq mi terrace region within the Mississippi alluvial floodplain (Table 1) (Brye and Pirani, 2005; USDA-NRCS, 2006; YMD, 2006). Paired fields ranged in size from 13 to 132 acres. The primary soil textures in the irrigation sets included fine sandy loam, very fine sandy loam, silt loam, silty clay loam, silty clay, and clay, which represented 11, 26, 45, 3, 6, and 9% of the soil textures, respectively.

Corn Grain Yield

A primary hypothesis of this study was that IWM would have no adverse effect on corn grain yield due to improved irrigation application efficiency and timing relative to CONV. Yield was 6.5 bu/acre greater in IWM than in CONV ($P = 0.0137; Table 3). Contrary to our premise, IWM practices did not merely maintain the status quo but improved corn yield 3% relative to CONV.

Irrigation water management tools likely interacted to improve yield. Yield is positively correlated with irrigation application uniformity and efficiency (Cavero et al., 2001; Li, 1998; Salmerón et al., 2012). Computerized hole selection increases irrigation application uniformity across the irrigation set while SURGE improves irrigation application uniformity up to 20% down the furrow (Gudissa and Edossa, 2014; Henry and Krutz, 2016; Musick et al., 1987; Podmore and Duke, 1982). Likewise, sensor-based irrigation scheduling increases corn grain yield by ensuring adequate soil
moisture throughout the growing season (Hassanli et al., 2009; Henry and Krutz, 2016; Steele et al., 1994).

Reduced corn grain yields in CONV relative to IWM may be due to over-irrigation and subsequent effects on rooting depth and N dynamics. Mid-Southern USA agricultural consultants advise producers to initiate irrigation at the first sign of wilting, regardless of soil moisture content, which can saturate the soil profile (Henry and Krutz, 2016). Since rooting depth is inversely correlated with soil moisture content, it is likely that the frequent, unnecessary irrigations in CONV negatively affected root growth (Carmi et al., 1992; Dwyer et al., 1988; Proffitt et al., 1985). Moreover, excessive irrigation promotes denitrification and the leaching of NO$_3^-$, which has adverse effects on N use efficiency and yield (Rolston et al., 1982; Sextone et al., 1985). Since 40% more water was applied to CONV than IWM, it is possible that reduced yields in the former were partially due to denitrification and/or NO$_3^-$ leaching and the subsequent effect on N use efficiency (Pang et al., 1997).

**Total Water Applied**

Another hypothesis of this research was that total water applied would be less in IWM than CONV due to better irrigation application efficiency and timing in the former. Total water applied was 39.5% less in IWM than CONV ($P \leq 0.002$). Others noted that IWM tools including CHS, SURGE, and soil moisture sensors generally reduce total water applied. For example, CHS reduced total water applied in soybean 17% relative to CONV (Krutz, 2016). In cotton (*Gossypium hirsutum* L.), corn, and soybean, SURGE reduced total water applied from 21 to 80% depending on crop and soil texture (Horst et al., 2007; Izuno et al., 1985; Musick et al., 1987; Schepers et al., 1995; Testezlaf et al., 1987; Wood et al., 2017). Scheduling with soil moisture sensors reduced the total number of irrigations and total water applied up to 50% (Hassanli et al., 2009; Krutz et al., 2014; Steele et al., 1994). When all three IWM practices—SURGE, CHS, and scheduling with sensors—were used in conjunction, total water applied was 21% less than that of CONV, and there was no adverse effect on soybean grain yield (Bryant et al., 2017). Therefore, SURGE, CHS, and scheduling irrigations with soil moisture sensors can reduce water use without sacrificing yield.

Conventionally managed fields met or exceeded the Mississippi Department of Environmental Quality’s (MDEQ) permitted withdrawal limit of 18 acre-inches in 14.3% of evaluated fields while IWM fields never utilized more than half of the permitted value. These data indicate IWM practices are capable of reducing the number of producers who withdraw more than the permitted value and will help maintain compliance if regulators reduce the permitted value in the future. Assuming the MRVAA overdraft is 300,000 acre-feet/year, the 10-year average corn acreage of 675,000 acres, and 60% of corn is furrow-irrigated, the data for corn and soybean indicate that if IWM practices are implemented, the overdraft could be reduced up to 88% (Bryant et al., 2017; Kebede et al., 2014; Massey et al., 2017; USDA-NASS, 2018).

### Table 3. Estimated least square means for corn grain yield, total water applied, and irrigation water use efficiency for conventionally irrigated fields (CONV) and irrigation water management (IWM)$^+$ fields in the Delta regions of Mississippi and Arkansas and the Prairie region of Arkansas from 2013 through 2017.

| Parameter                              | CONV  | IWM  | $P$ value |
|----------------------------------------|-------|------|-----------|
| Yield (bu/acre)                        | 216.4 | 222.9| 0.0137    |
| Total water applied (acre-inch)        | 8.6   | 5.2  | 0.0020    |
| Irrigation water use efficiency (bu/acre-inch) | 31.4  | 47.5 | 0.0062    |

$^+$ IWM fields utilized computerized hole selection, surge irrigation, and sensor-based irrigation scheduling.

$\ddagger$ Least square means of 18 replicates.

**Irrigation Water Use Efficiency**

We postulated that if IWM could reduce total water applied relative to CONV without having an adverse effect on yield, then IWUE would be greater in the former. Relative to CONV, IWM reduced total water applied by 3.4 acre-inches while improving yield by 6.5 bu/acre. Consequently, the IWUE was 51.3% greater in IWM relative to CONV ($P = 0.0062$, Table 3). Others have noted that IWUE increased under IWM practices in soybean in the Mid-Southern USA (Bryant et al., 2017; Wood et al., 2017).

The effect of CHS, SURGE, and soil moisture sensors on the IWUE of corn and other crops is inconsistent in the literature. Computerized hole selection improved the IWUE of soybean 23% relative to CONV (Jason Krutz, personal communication, 2018). Surge irrigation had no effect on the IWUE of corn despite a 31% decrease in total water applied because the practice reduced yield 6.5% (Musick et al., 1987). Conversely, SURGE increased the IWUE of cotton, corn, and soybean from 23 to 29%, primarily due to its effect on total water applied rather than yield (Horst et al., 2007; Schepers et al., 1995; Ünlü et al., 2007; Wood et al., 2017). Scheduling with soil moisture sensors improved the IWUE of corn up to 146% due to its positive effect on both corn grain yield and total water applied (Hassanli et al., 2009; Steele et al., 1994). The synergy of CHS, SURGE, and soil moisture sensors improved the IWUE of soybean in the Delta and Prairie regions of Arkansas and the Delta region of Mississippi up to 36% (Bryant et al., 2017). These data show that integrating SURGE, CHS, and soil moisture sensors will also improve the IWUE of corn in the Mid-Southern, USA by maintaining or improving yield and reducing total water applied.

**Economic Simulations**

The estimated irrigation costs per acre calculated at the average acre-inch of water pumped at the baseline diesel price of $2.55/gal for CONV (8.6 acre-inches) and IWM (5.2 acre-inches) technologies are reported in Table 4. Reduced water applied in IWM fields decreased diesel costs. Diesel costs are positively correlated with pumping depth due to increased energy requirements for lifting water from greater depths.
Despite additional costs for transfer pipe and surge valve batteries, other direct costs are reduced for IWM due to lower repair and maintenance costs. Total fixed costs are greater for IWM due to the capital recovery costs for the surge valves, elbows, soil moisture sensors, and data loggers. Despite greater total fixed costs, the reduction in diesel costs for IWM decreased the total specified costs for each pumping scenario.

Table 5 shows the estimated least squares means for net returns above total specified irrigation costs for CONV and IWM at the baseline corn price of $3.79/bu and three diesel price scenarios including a baseline diesel price of $2.55/gal, a high diesel price of $3.70/gal, and a low diesel price of $1.60/gal. Irrigation water management strategies resulted in significantly greater net returns above irrigation costs than CONV for each diesel price scenario and each pumping depth. As diesel price and pumping depth increase, the advantage of IWM over CONV expands.

These data demonstrate that Mid-Southern USA producers who implement IWM technologies will not only recover the costs of purchasing and using these tools, but also will improve farm profitability and conserve water resources. The costs of surge valves, additional pipe fittings, soil moisture sensors, data loggers, transfer pipe, and batteries for surge valves and data loggers is outweighed by the additional revenue from increased yield and diesel costs savings. In fact, the vast majority of Mid-Southern USA corn producers are limiting the economic potential of their operations and decreasing sustainability by not using these technologies.

**Conclusion**

The objective of this research was to evaluate the impact of incorporating CHS, SURGE, and soil moisture sensors at a production scale on corn grain yield, total water applied, IWUE, and net returns above irrigation costs. Attaining the highest IWUE without having an adverse effect on yield and net returns above irrigation costs will ensure the long-term sustainability of irrigated agriculture in the Mid-Southern USA. Implementing CHS, SURGE, and soil moisture sensors in corn production systems in the Delta region of Mississippi will reduce water use and improve corn grain yield, IWUE, and net returns above irrigation costs. Our data indicate that producers can adopt CHS, SURGE, and soil moisture sensors in irrigation sets to mitigate overdrafts from the MRVAA while improving corn grain yield and profitability in the Mid-Southern USA.

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