MISSISSIPPI SOYBEAN PROMOTION BOARD
PROJECT NO. 40-2019
Final Report

Title: Irrigation Scheduling of Soybean – A Dual Threshold Method to Eliminate Yield Reducing Stresses and Maximize Water-Use Efficiency

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BACKGROUND AND OBJECTIVES

Over the past 30 years, water level surveys have proven that more water is being pumped out of the Mississippi River Alluvial Aquifer than is replenished by recharge in the Mississippi Delta. As new wells are permitted and more water is pumped from the aquifer each year, water levels will decline and the area of greatest concern will continue to expand in the mid-Delta, such that declining water levels in this area will severely affect pump operation to the point that they will eventually fail. Efficient use of water in crop production is a necessary part of the solution. Increased emphasis is being placed on proper irrigation scheduling for all crops in the Delta using soil moisture sensors so that producers can reach maximum economical yields with the least amount of water. Research is continuing to develop and confirm irrigation thresholds that will maintain yield using soil moisture sensors alone. In previous soybean irrigation initiation field studies, there have been observations that would suggest that a wetter threshold may be needed to maximize yields when experiencing an extended heat period. A hypothesis was developed suggesting that a dual irrigation threshold for soil water potential sensors may be needed to deal with extended heat periods and moisture induced stress versus simply a moisture induced stress. Literature agrees that soybean yield losses are greater when subjected to higher temperatures and limited moisture than either higher temperatures or limited moisture alone. Likewise, thresholds need to be identified for volumetric water content sensors under these same conditions. Good irrigation scheduling protocol should tell you “when not to irrigate” as well as “when to irrigate.”

Objective(s): The overall purpose of this proposal is to maximize yield with the least amount of water by identifying thresholds which will alleviate temperature and moisture related yield-reducing stresses economically. Specific objectives were to 1) determine a dual irrigation threshold (heat & moisture induced or moisture induced) for soybean using soil water potential sensors (Watermarks) in silt loam, silty clay loam and silty clay textured soils; 2) monitor and identify irrigation thresholds (heat & moisture induced or moisture induced) in soybean using volumetric soil moisture sensors in silt loam, silty clay loam and clay textured soils; and 3) economically evaluate the yields and production costs of each irrigation treatment.

REPORT OF PROGRESS/ACTIVITY

Procedures

Three irrigation x variety field studies were established each year in 2017-2019, with two sites being furrow irrigated and one site sprinkler irrigated. A Sharkey SiCL soil at Stoneville, MS was the location of one furrow irrigated field study (Site 1, 2017-2019) whereas a Dundee / Forrestdale SiCL soil at Tribbett, MS (Site 2a, 2017) and a Sharkey SiCL soil at Stoneville, MS

(Site 2b, 2018-2019) were the locations of a second furrow irrigated field study. A Bosket VFSL / Dubbs SiL soil (Site 3a, 2017) and a Bosket VFSL / Commerce SiCL soil (Site 3b, 2018-2019) at Stoneville, MS were the locations of a sprinkler irrigated field study.

Sites 1 and 2 were laid out in a randomized complete block design with a factorial arrangement of treatments in four replicates. These plots, consisting of six 40-inch rows, were 500-650 ft long. At the Sharkey Sites 1 and 2b, two rows were left unplanted between all six-row plots to provide a non-shrinking buffer zone between the irrigation treatments. Site 3 was arranged in a randomized complete block design with a split-plot arrangement with four replicates. Irrigation initiation treatments were randomized within replicates and varieties were randomized within initiation treatments. Plots, eighteen 40-inch rows, were 67 ft long.

The varieties planted, planting date, and irrigation system are shown in Table 1 for each field study. Two varieties (mid- and late- MG 4) were planted in each field study. Liberty Link varieties were utilized on Sites 1 and 2b whereas Round-up Ready varieties were utilized on Sites 2a, 3a, and 3b. In 2018 and 2019, Site 2b planting was delayed as compared to Site 1 since they were located on similar soils. Weeds were managed accordingly so that weed competition was not a factor limiting crop production for each study.

Watermark soil water potential (SWP) sensors, resistance type, were installed in each irrigation x variety treatment in 2 reps of each study. The sensors were installed at three depths in each study (8, 16, 24-inch, Site 1 and 2b; 9, 18, 27-inch, Site 2a; and 6, 15, 24-inch, Site 3a and 3b). Each site was instrumented with dataloggers and set to read and store the data at 1-hour intervals. Additionally, 6 Sentek volumetric water content (VWC), capacitance type, probes were installed in three treatments in 2 reps of each study. These 48-inch probes had sensors every 4 inches from 2-inch depth down to a depth of 46 inches.

Extended heat periods are defined as three or more days where air temperature (Ta) max is greater than or equal to 95°F. Irrigation protocols given below included two single thresholds (S1 and S2) and three dual thresholds (D1, D2, and D3).

Protocol

S1	Irrigate at SWP <= -50 kPa
S2	Irrigate at SWP <= -80 kPa
D1	If Ta<95°F Irrigate at SWP <= -80 kPa; If Ta>=95°F Irrigate at SWP <= -50 kPa
D2	If Ta<95°F Irrigate at SWP <= -100/120 kPa[a]; If Ta>=95°F Irrigate at SWP <= -50 kPa
D3	If Ta<95°F Irrigate at SWP <= -100/120 kPa[a]; If Ta>=95°F Irrigate at SWP <= -80 kPa
RF	Rain-fed (non-irrigated)

[a] -100 kPa Bosket/Commerce; -120 kPa Sharkey.

Air temperature was obtained from automated weather stations located in the vicinity (within a mile) of each site, while rainfall was collected and measured at each Site. Irrigation dates for each irrigation protocol, study, and year are given in Table 2. Irrigation water applied for each protocol, study, and year are given in Table 3.

The middle six-rows of each plot at Site 1 were harvested with a commercial combine and seed were augured into a weigh cart to determine yield for 2017 and 2018. At all other locations and years, the two middle rows of each plot were harvested with a plot combine. A sample was taken for harvest moisture, test weight, and seed weight. Yields were adjusted to 13% moisture content. Data were subjected to analysis of variance and the means were separated by the least significant difference (LSD) procedure at the 5% level of significance. A nominal water use efficiency (WUE) was calculated from change in yield among an irrigated protocol and the rain-fed treatment divided by the applied water from irrigation. Harvest dates are given in Table 1.

The economic analysis for all three field studies is based on partial budgeting of net returns above irrigation and hauling costs since all other factors of production were held constant and no difference in the seed cost by variety was assumed. Irrigation cost estimates are based on MSU budgets for sprinkler irrigation of a ¼ mile center pivot system or for furrow irrigation of a 160 acre tract using roll-out pipe (MSU Department of Agricultural Economics Budget Report 2017-05, Appendix 9 & 10; 2018-05, Appendix 9 & 10; and 2019-05, Appendix 9 & 10). Fixed irrigation costs were applied to non-irrigation treatment costs. The average reported soybean price for the week including the harvest date in the Delta area (USDA Market News- JK_GR110) was used to set the soybean price in the analysis for each study.

Results and Discussion

Weather

The lowest winter rainfall (from 1 Oct, prior year – through 31 Mar, present year) at Stoneville, MS occurred in 2017 and was a little below normal at 25.0, 20.4, and 24.4 inches for Sites 1, 2a, and 3a, respectively, as compared to the 105 year average of 28.4 inches (Table 4). Rainfall in 2018 and 2019 were higher than normal at 32 to 39inches, respectively, for Site 1 and Site 2 and 3. Likely the entire rooting profile was recharged to start each season at all Sites, with some concern at Site 2a in 2017.

Rainfall and maximum/minimum air temperatures are given on a monthly basis during the growing season (April – September) in Table 4. Months that rainfall or air temperature values were greater than or less than one standard deviation of average are noted. Over the growing season, rainfall was higher than normal in all three years, with 2018 having the lowest total rainfall. Sites 1 and 2b were flooded three times in 2019. Maximum air temperatures were near normal all three years, with 2017 being the coolest and 2019 being the warmest. Minimum air temperatures were higher than normal all three years, with 2019 being the warmest.

Daily maximum and minimum air temperature (Ta max and Ta min) and rainfall or given in Figures 1_{a-d}. Within a given year, Sites 1, 2b, 3a, and 3b had similar temperature and rainfall data and are shown in Figures $1_{a,c,d}$ but Site 2a in 2017 had some differences as compared to Sites 1 and 3a so it is shown in Figure 1_b. Viewing these daily data shows the presence of extended heat periods during each growing season and if it was associated with rainfall or not. The major extended heat periods that had little rain associated with them occurred at Site 2a in mid- to early-August and at the later planted soybean in 2019 at Site 2b in September.

Seed Yield, and Economic Analysis

Estimated irrigation and hauling costs and soybean prices (Table 5) along with yield and water applied were used to calculate expected net returns above irrigation and hauling costs for each treatment at each site. Yield results for each study and year are given in Table 6, net returns in Table 7, and nominal WUE in Table 8.

Yields were increased with irrigation above rainfed at Site 2a, 2017; Site 2b and 3b, 2018; and Site 1 (HBK4950) and Site 2b, 2019. In general, where yields were increased, net returns were increased. No differences in yields were found among irrigated treatments except for three instances. The first, in 2018 at Site 3b, D3 the least irrigated treatment had a lower yield and net return than S2 likely due to timing or insufficient amount of water applied. The second, in 2019 at Site 1 HBK4950, S2 had a lower yield than S1, D1, D2, and D3 and lower net return than S1 and D2. No real explanation is given since S2 applied more total water than D3 but less than S1, D1 and D2. The third, in 2019, Site 2b, S1 had a higher yield and net returns than S2, D1, D2, and D3 likely related to the stunting of growth of the later planted soybean due to flood stress.

In general, net returns were similar between S1 and S2 except where noted above plus S1 was lower than S2 at Site 1, 2017. Dual threshold D1 net returns were similar to S1 except where noted above plus D1 was higher than S1 at Site 2b, 2018. Net returns were increased with dual thresholds D2 and D3 over S1 and S2 at Site 2b, 2018 and over S1 at Site 1 and Site 2a, 2017 and Site 1, 2018. Net returns were increased with D2 over S2 at Site 1, 2017 and with D3 over S1, D1, and D2 at Site 1, CZ4748, 2019. These increases in net returns were due to the added expense of water when there was no increase in yield.

In general, nominal WUE in bushels per inch of water applied were more positive when irrigation increased yield as compared to rainfed and other irrigation protocols and as less water was applied at these higher yields.

Irrigation Protocols

Single irrigation threshold protocol S2 was triggered less often and applied an average of 29% less water than S1, as expected since it was triggered at a drier threshold value of -80 kPa versus -50 kPa in all varieties, Sites and years (Tables 2 & 3). Dual threshold protocol D1 was triggered as many times as S1, with similar total applied water but different timing since D1 was triggered 50% of the time due to Ta>=95ºF. D1 applied 18% less water than S1 in 2017 and 2018 and applied 40% more water during the warmest year of the study, 2019. Dual threshold protocols, D2 and D3, applied less water than S2 (58%) during 2017 and 2018 but D2 applied 26% more water than S2 in 2019. D3 with its drier threshold triggers applied less water than D2 in 2018 and 2019.

In general, excluding results from Site 2b, 2019, due to flood stress, the single threshold S2 applied less water than S1 while yielding the same. The dual threshold protocols D2 and D3 to a lesser extent tended to apply less water than S1, S2, and D1 in the cooler years of 2017 and 2018 while maintaining irrigated yields and having higher or similar net returns. In theory, the optimum dual threshold protocol should apply the same amount of water as a water conservative single threshold in a cool year absent of any extended heat periods. This suggests that the single threshold trigger of -80 kPa was over irrigating and that it should be set at a drier threshold.

In the warmest year of the study, 2019, D2 applied more water than S2, yet did not increase yield. Theoretically, if the dual threshold protocol is viable it will increase applied water in years with extended heat periods but also increase yield over a water conservative single threshold that was triggered immediately ahead of a soil moisture stress level that would decrease yield in a cooler year. Again, with this limited data, this suggests that the single threshold trigger utilized was over irrigating and could be set at a drier threshold than the -80 kPa.

The difference between D2 and D3 protocols is that under conditions of air temperatures greater than or equal to 95ºF, D2 triggered at -50 kPa or drier while D3 triggered at -80 kPa or drier. From this limited data, D3 yielded less than S2 and D1 at Site 3b, 2018, suggesting that a wetter threshold may have avoided a yield decrease in that situation.

The dual threshold protocol should be compared to a single threshold that is triggered nearer to or immediately ahead of a soil moisture stress level that would decrease yield in a cooler year.

Further studies are needed to more precisely define the water conservative thresholds in the single and dual irrigation protocols and compare these under more adverse weather conditions.

Volumetric Water Content (VWC)

Sentek sensor data were collected for approximately 3 months of each growing season starting around early- to mid-June at all three locations. Internally, a universal algorithm was applied to the capacitance readings of the Sentek probes to calculate VWC. No effort was made to calibrate these sensors to specific soils. The manufacturer recommends looking at the data trends to determine where the root activity occurs and indicators of when the soil is not providing the water needed by the plant. Diurnal variations in VWC indicate where and when root activity is occurring at different depths and the composite VWC curves. As VWC is decreasing, due to drying of the soil, from specific depths or the composite VWC, a change in slope from a steeper to a less steep slope indicates that either the soil is no longer providing all the water the plant needs (a key to irrigate) or the environmental demand (ET_o) has decreased and the soil is still providing all the water the plant needs. More abrupt increases in VWC are due to rainfall or irrigation.

Each set of graphs and charts in Figures $2_{a\text{-}c}$, $3_{a\text{-}c}$, and $4_{a\text{-}c}$ (2017, 2018, and 2019, respectively) include a graph of individual sensors at depths from 2 in. to 46 in., a composite graph or summary graph that sums all VWC from all the individual sensors, and a chart showing estimated reference evapotranspiration (ET_o, grass) using data from a nearby weather station. These graphs depict a sensor that was located in a rain-fed (non-irrigated) treatment. Also, on the summation graph there are arrows corresponding to the date irrigations were initiated for the specified irrigation protocols so comparisons could be made to the moisture conditions at the time of initiation.

Root activity, as denoted by the diurnal variation and reduced soil moisture contents over the growing season in the rain-fed treatment of the individual sensors graph (Figures $2_{a\text{-}c}$, $3_{a\text{-}c}$, and $4_{a\text{-}c}$), indicates water was removed down to a depth of 46, 46, and 42 inches, for the earlier planted soybean on Sharkey SiCL in 2017, 2018, and 2019, respectively, at Site 1. Water removal was indicated down to a depth of 46 inches for Dundee/Forrestdale SiCL at Site 2a and 34 inches for the later planted soybean on Sharkey SiCL in 2018 and 2019 at Site 2b. On the Bosket VFSL/Dubbs SiL, Site 3a and the Bosket VFSL/Commerce SiCL, Site 3b water removal was indicated to occur down to depths of 46, 46, and 38 inches in 2017, 2018, and 2019, respectively. At Sites where water removal was shown to extend to a depth of 46 inches, it is possible that water removal could be at even deeper depths than the probes were measuring. Also, water removal at irrigated locations was not always as deep as the rainfed (data not shown).

Although the VWC readings are not calibrated, it appears there is less water removed from the deeper rooting depths which would be expected since rooting is likely less prolific at the deeper depths. At Sites 2a, 3a, and 3b, the less clayey soils, it appears there is a layer or two in which less water is removed as compared to areas above and below these layers. This generally occurs somewhere in the 10- to 18-inch depths. This could be related to compaction issues resulting in less root proliferation in the area or simply, the root systems have already removed water from these levels by the time the probes were installed and these layers are difficult to replenish with irrigation or rainfall due to the infiltration characteristics of the soil. This was not the case at Sites 1 and 2b where the cracking clay soil (Sharkey) allows deeper water infiltration.

Where there was no difference in irrigated and rainfed yields, it is difficult to find a change in slope during the growing season in the summation graphs that would key an irrigation (Figures 2_a, 2_c, 3_a, and 4_c). At Site 2a in 2017 (Figure 2_b) where rainfed experienced a loss in yield there is a well-defined change in slope starting July 23 which also was near the time the first irrigations for D1, D2, and D3 were scheduled. The change in slope was not as well-defined but appeared to occur in early-August about the time D3 was scheduled at Site 3b, 2018 (Figure 3_b), and in late-July/early-August after all protocols were scheduled at Site 3b, 2018 (Figure 3_c). The slope of the summation graph changed starting July 30 for Site 1, 2019 shown in Figure 4a (HBK4950), which had a reduction in rainfed yields. At Site 2b, in 2019 (Figure 4_b) where the late planted soybeans were flood stressed, the change in slope potentially started around July 30 and initial irrigations for S2, D1, D2, and D3 which yielded less than S1 were scheduled after July 30.

The key to irrigate (when the slope of the moisture withdrawal significantly changes to a lower slope) with the VWC sensors, is apparent in post-analysis. Whether this change will be at the same reported water content readings across years or if it changes for a given field will need to be investigated. Does yield loss start immediately or does it take three or four days after this change in slope starts before there is a significant yield loss? Further studies will be needed to address these questions and in more adverse weather conditions to help guide the interpretation of this data for irrigation scheduling purposes.

Summary

A more water conservative dual threshold protocol reduced applied water as compared to the single threshold protocols tested while maintaining yield and net returns in cooler years indicating that the single threshold protocols were over irrigating. During the warmest year, the more water conservative dual threshold protocols total applied water was closer to the value applied by the drier single threshold protocol (-80 kPa) while maintaining yield and net returns, again, indicating that the single threshold protocol was over irrigating. Currently, there is insufficient data to support one way or the other the merit of using a dual threshold protocol for irrigation scheduling. The dual threshold protocol should be compared to a single threshold that is triggered nearer to or immediately ahead of a soil moisture stress level that would decrease yield in a cooler year. Further studies are needed to more precisely define the water conservative thresholds in the single and dual irrigation protocols and compare these under more adverse weather conditions.

Scheduling irrigations with a VWC moisture probe using the irrigation key (an abrupt change in the slope of the moisture withdrawal to a lower slope) shows promise in this study. In post analysis of rainfed treatments, in fields of this study where there was a response to irrigation, the irrigation key was observed and in fields of this study where there was no response to irrigation, the irrigation key was not observed. Further studies are needed to determine the responses in more adverse weather conditions.

Impacts and Benefits to Mississippi Soybean Producers

The overall effort of this study is to apply water more timely to maximize yields economically while using the least amount of water. Results from this project will help determine “trigger value” recommendations on Mississippi soils of when to initiate irrigations with maximum temperature observations/forecasts and soil water potential & volumetric water content sensors, potentially saving an irrigation (water and pumping costs) on all irrigated soybean acreage. One less furrow irrigation will save approximately 3 acre-inches and would reduce irrigation operation costs by approximately $9.50/acre.

End Products-Completed or Forthcoming

1. A publication will be forthcoming after the conclusion of the project.
2. **-CANCELLED-** Pringle, H.C., Krutz, L.J., Falconer, L.L, Quintana, N., Fisher, D.K., and Lo, T.H. (2020). Joint Consideration of Soil Moisture Tension and Maximum Air Temperature when Scheduling Irrigations. Mississippi Water Resources Conference, Jackson, MS, March 31 – April 1, 2020.
3. Pringle, III, H. C. (2020). Irrigation Scheduling: Soybean – Single and Dual Threshold. Delta States Irrigation Conference/23rd Annual National Conservation Systems Cotton and Rice Conference, Memphis, TN, January 30 – February 1, 2020.
4. Pringle, III, H. C., Falconer, L. L., Fisher, D. K., Krutz, L. J., & Krutz, L. J. (2019). Soybean Irrigation Initiation in Mississippi: Yield, Soil Moisture, and Economic Response. *Applied Engineering in Agriculture*, *35*(1), 39–50. https://doi.org/10.13031/aea.12883
5. Delta States Irrigation Conference/21st Annual National Conservation Systems Cotton & Rice Conference, Memphis, TN, Soil moisture sensors sold and supported in the mid-South, January 10-12, 2018.

Graphics/Tables

Table 1. Variety, plant date, irrigation system, and harvest date for study areas in 2017-2019.

Site[A]	Year	Variety	Plant Date	Irrigation System	Harvest Date
1	2017	CZ4748 / HBK4950	10 Apr	Furrow	11 Sep / 9 Oct
1	2018	CZ4748 / HBK4950	2 May	Furrow	21 Sep[a], 9 Oct
1	2019	CZ4748 / HBK4950	30 Apr	Furrow	25 Sep / 1 Oct
2a	2017	AG4632 / AG4835	26 Apr	Furrow	21-25 Sep
2b	2018	CZ4748 / HBK4950	18 May	Furrow	9 Oct
2b	2019	CZ4748 / HBK4950	24 May	Furrow	1 Oct
3a	2017	P47T89R / P49T97R	10 May	Sprinkler	9 Oct
3b	2018	P45A23 / P48A60	20 Apr	Sprinkler	9 Oct
3b	2019	P46A57BX / P48A60X	29 Apr	Sprinkler	18 Sep

[A] Site 1 –Sharkey SiCL, Stoneville, MS; Site 2a –Dundee / Forrestdale SiCL, Stoneville, MS; Site 2b –Sharkey SiCL, Stoneville, MS; Site 3a – Bosket VFSL/Dubbs SiL, Stoneville, MS; Site 3b – Bosket VFSL/Commerce SiCL, Stoneville, MS;

Table 2. Irrigation protocol and irrigation dates for furrow and sprinkler irrigation studies, Delta Research and Extension Center, Stoneville, MS, 2017-2019.

		S1	S2	D1	D2	D3	Rain-fed
Irrigation protocol		----------	-----------	--kPa--	-----------	-----------	
		-50	-80	---	---	---	---
if Ta<95°F SWP<=		---	---	-80	-100[A]/-120[B]	-100[A]/-120[B]	---
if Ta>=95°F SWP<=		---	---	-50	-50	-80	---
	Site[F]	Irrigation Dates					
2017	1	6/14	---	---	---	---	---
		7/15	7/17	7/17[D]	---	---	---
		8/1	8/1	8/1[D]	---	---	---
		8/25[C]	8/25[C]		---	---	---
	2a	6/14	6/14	---	---	---	---
		7/8	---	---	---	---	---
		7/19	---	7/20[D]	7/20[D]	---	---
		7/25	7/25	---	---	7/25[E]	---
		7/31	---	7/31[E]	---	8/4[E]	---
	3a	6/15	---	---	---	---	---
		7/15	---	---	---	---	---
		7/20	7/20	7/20[D]	7/20[D]	7/20[D]	---
		8/1	8/1	8/1[E]	---	---	---
		8/5	8/5	8/5[E]	---	---	---
2018	1	6/13	---	---	---	---	---
		7/1	7/5	---	---	---	---
		7/15	---	7/15[D]	7/15[D]	7/15[D]	---
		7/27	---	---	---	---	---
		8/6	8/3	8/3[E]	---	---	---
		8/16	---	8/16[E]	---	---	---
		9/1[C]	9/1[C]	---	---	---	---
	2b	7/4	7/5	---	---	---	---
		7/18	7/18	7/15[D]	7/15[D]	---	---
		7/27	7/27	---	---	---	---
		8/6	8/14	8/14[E]	8/14[E]	8/3[E]	---
		9/1[C]	9/1[C]	---	---	---	---
	3b	6/7	---	---	---	---	---
		6/12	---	---	---	---	---
		7/1	---	---	---	---	---
		7/12	7/14	7/14[D,E]	7/14[D]	7/14[D]	---
		7/18	7/18	7/18[E]	7/18[E]	7/18[E]	---
		7/26	7/26	7/26[E]	---	---	---
		8/6	8/6	8/6[E]	8/6[E]	---	---
2019	1	7/10	---	7/10[D]	7/10[D]	---	---
		7/27	8/1	8/2[E]	8/7[D]	8/7[D]	---
		8/13	---	---	---	---	---
		8/31	9/3	9/3[D,E]	9/4[D]	9/4[D]	---
		9/9[C]	---	9/11[C,D]	9/11[C,D]	----	---
	2b	7/26	8/2	8/2 E]	8/7[D,E]	8/7[D,E]	---
		8/13	---	---	---	---	---
		8/31	9/3	9/3[D,E]	9/4[D,E]	9/4[D,E]	---
		9/9[C]	---	9/10[C,D]	9/10[C,D]	---	---
	3b	7/10	---	7/10[D]	7/10[D]	---	---
		8/3	8/7	8/7[D]	8/7[D]	8/7[D]	---

[a] Threshold in kPa for Sites 3a and 3b when maximum air temperature is less than 95°F.
[b] Threshold in kPa for Sites 1, 2a, and 2b when maximum air temperature is less than 95°F.
[c] Irrigations were applied to the later maturing variety, HBK4950, only.
[D] Irrigation was triggered due to Ta>=95°F and SWP<= corresponding SWP threshold value.
[E] Irrigation was triggered due to Ta<95°F and SWP<= corresponding SWP threshold value.
[F] Site 1 –Sharkey SiCL, furrow, Stoneville, MS; Site 2a –Dundee / Forrestdale SiCL, furrow, Stoneville, MS, 2017; Site 2b –Sharkey SiCL, furrow, Stoneville, MS, 2018-2019; Site 3a – Bosket VFSL/Dubbs SiL, sprinkler, Stoneville, MS, 2017; Site 3b – Bosket VFSL/Commerce SiCL, sprinkler, Stoneville, MS, 2018-2019;

Table 3. Irrigation water applied for furrow and sprinkler irrigation studies, Delta Research and Extension Center, Stoneville, MS, 2017-2019.

			S1	S2	D1	D2	D3	Rain-fed
Irrigation protocol			----------	-----------	--kPa--	-----------	-----------	
			-50	-80	---	---	---	---
		if Ta<95°F SWP<=	---	---	-80	-100[A]/-120[B]	-100[A]/-120[B]	---
		if Ta>=95°F SWP<=	---	---	-50	-50	-80	---
	Site[C]		Irrigation Water Applied (inches/acre)					
2017	1	CZ4748	7.52	5.4	5.4	0.0	0.0	0
		HBK4950	11.0	8.8	5.4	0	0	0
	2a	AG4632/AG4832	12.2	5.2	5.6	2.6	4.7	0
	3a	P47T89/P49T97	4.1	2.5	2.5	0.8	0.8	0
2018	1	CZ4748	13.6	7.3	10.6	4.0	4.0	0
		HBK4950	17.2	10.9	10.6	4.0	4.0	0
	2b	CZ4748	11.4	13.7	8.3	8.3	7.3	0
		HBK4950	16.1	18.4	8.3	8.3	7.3	0
	3b	P45A23/P48A60	5.2	3.0	3.0	2.3	1.5	0
2019	1	CZ4748	8.7	6.2	9.0	7.9	5.5	0
		HBK4950	11.8	6.2	10.9	9.8	5.5	0
	2b	CZ4748	8.4	7.8	7.8	7.0	7.0	0
		HBK4950	12.7	7.8	10.4	9.6	7.0	0
	3b	P46A57/P48A60	1.8	0.9	1.8	1.8	0.9	0

[a] Threshold in kPa for Sites 3a and 3b when maximum air temperature is less than 95°F.
[b] Threshold in kPa for Sites 1, 2a, and 2b when maximum air temperature is less than 95°F.
[C] Site 1 –Sharkey SiCL, furrow, Stoneville, MS; Site 2a –Dundee / Forrestdale SiCL, furrow, Stoneville, MS, 2017; Site 2b – Sharkey SiCL, furrow, Stoneville, MS, 2018-2019; Site 3a – Bosket VFSL/Dubbs SiL, sprinkler, Stoneville, MS, 2017; Site 3b – Bosket VFSL/Commerce SiCL, sprinkler, Stoneville, MS, 2018-2019;

Table 4. Rainfall and Air Temperature for select periods of the crop year for study areas in 2017-2019.

	2017			2018		2019		
SITE[A]	1	2a	3a	1	2b, 3b	1	2b, 3b	Historical[B]
	Rainfall (inches)							
OCTOBER-MARCH	25.0	20.4	24.4	32.7	32.9	39.1	39.3	28.4
APRIL	5.5	4.8	5.3	4.9	5.0	9.4[C]	9.4[C]	5.3
MAY	5.5	3.2	5.2	1.7[C]	1.7[C]	12.1 [C]	12.7[C]	4.8
JUNE	5.2	3.9	5.3	2.9	3.0	8.3[C]	8.5 [C]	3.8
JULY	5.6	5.9	6.1	2.6	3.2	5.1	5.2	3.8
AUGUST	7.9[C]	8.0[C]	8.0[C]	7.8[C]	6.8[C]	3.4	4.0	2.8
SEPTEMBER	3.0	2.2	2.6	6.4[C]	4.9	0.4[C]	0.04[C]	3.1
	Average Max/Min Air Temperature (°F)							
APRIL	80[C]/58[C]	80/58[C]	80[C]/60[C]	70[C]/47[C]	70[C]/49[C]	72/55	74/54	75/53
MAY	82/61	83/61	81/62	89[C]/67[C]	90[C]/68[C]	84/66[C]	85/66[C]	83/62
JUNE	86[C]/68	88/69	86[C]/68	91/72[C]	91/71	89/69	89/69	90/69
JULY	91/72	94/72	92/73	92/73	91/73	91/72	91/72	92/72
AUGUST	89[C]/71	90/72	89[C]/71	91/70	91/70	93/72	94/73[C]	92/70
SEPTEMBER	88/64	88/64	87/63	89/69[C]	89/70[C]	96[C]/70[C]	97[C]/70[C]	87/64

[A] Site 1 –Sharkey SiCL, Stoneville, MS; Site 2a –Dundee / Forrestdale SiCL, Stoneville, MS; Site 2b –Sharkey SiCL, Stoneville, MS; Site 3a – Bosket VFSL/Dubbs SiL, Stoneville, MS; Site 3b – Bosket VFSL/Commerce SiCL, Stoneville, MS;
[B] Historical average for Stoneville, Mississippi (Rainfall, 105 years; Air temperature, 90 years, located within 2 miles of each site.
[C] Values are greater than or less than one standard deviation of average.

Table 5. Estimated irrigation and hauling cost and soybean price for furrow and sprinkler irrigation studies in 2017-2019.

	Furrow 2017	Furrow 2018	Furrow 2019	Sprinkler 2017	Sprinkler 2018	Sprinkler 2019
Irrigation Cost ($ acre^{-1}) [A]	$74.73	$83.84	$83.01	$ 93.63	$ 103.72	$ 101.96
Water Lifting Cost ($ acre^{-1} In.$^{-1}$)	$ 2.32	$ 3.12	$ 2.82	$ 3.36	$ 4.60	$ 4.13
Haul Soybean ($ bu^{-1})	$ 0.27	$ 0.27	$ 0.27	$ 0.27	$ 0.27	$ 0.27
Soybean Price ($ bu^{-1}) [B] Site[C] 1	$ 9.48	$ 7.87	$ 8.74			
2a,b	$ 9.64	$ 8.01	$ 8.74			
3a,b				$9.54	$8.01	$8.55

[A] Irrigation cost excluding water lifting cost - Mississippi State University Budget Report.

[B] Greenville Farmers Grain Terminal average quote USDA-AMS JK-GR-110 for week of harvest (Site 1 - 11 September – 6 October, 2017; Site 2 – 18-22 September - 2017; Site 3 – 19-13 September 2017; Site 1 – 8-12 October, 2018; Site 2 – 1-5 October - 2018; Site 3 – 8-12 October 2018; Site 1 – 16-20 September 2019; Site 2 & 3 – average 23-27 September & 30 September – 4 October 2019);

[C] Site 1 –Sharkey SiCL, Stoneville, MS; Site 2a –Dundee / Forrestdale SiCL, Stoneville, MS, 2017; Site 2b –Sharkey SiCL, Stoneville, MS, 2018-2019; Site 3a – Bosket VFSL/Dubbs SiL, Stoneville, MS, 2017; Site 3b – Bosket VFSL/Commerce SiCL, Stoneville, MS, 2018-2019;

Table 6. Yield by irrigation protocol for furrow and sprinkler irrigation studies, Delta Research and Extension Center, Stoneville, MS, 2017-2019.

Irrigation protocol			S1	S2	D1	D2	D3	Rain-fed
			----------	-----------	--kPa--	-----------	-----------	
			-50	-80	---	---	---	---
		if Ta<95°F SWP<=	---	---	-80	-100[A]/-120[B]	-100[A]/-120[B]	---
		if Ta>=95°F SWP<=	---	---	-50	-50	-80	---
	Site[C]				Yield (bu acre^{-1})			
2017	1	CZ4748/HBK4950[D]	76	78	77	78	77	77
	2a[E]	AG4632	57a	57a	57a	60a	61a	43bc
		AG4835	41bc	40bc	44b	43bc	43b	38c
	3a	P47T89/P49T97[D]	66	65	65	63	62	62
2018	1	CZ4748/HBK4950[D]	77	76	76	76	75	75
	2b	CZ4748/HBK4950[D]	72a	72a	73a	74a	74a	69b
	3b	P45A23/P48A60[D]	78ab	80a	79a	78ab	75b	69c
2019	1[E]	CZ4748	61b	62b	61b	61b	62b	61b
		HBK4950	66a	62b	65a	65a	64a	58c
	2b	CZ4748/HBK4950[D]	62a	56b	58b	57b	58b	52c
	3b	P46A57/P48A60[D]	77	79	78	77	76	77

[a] Threshold in kPa for Sites 3a and 3b when maximum air temperature is less than 95°F.
[b] Threshold in kPa for Sites 1, 2a, and 2b when maximum air temperature is less than 95°F.
[C] Site 1 –Sharkey SiCL, furrow, Stoneville, MS; Site 2a –Dundee / Forrestdale SiCL, furrow, Stoneville, MS, 2017; Site 2b – Sharkey SiCL, furrow, Stoneville, MS, 2018-2019; Site 3a – Bosket VFSL/Dubbs SiL, sprinkler, Stoneville, MS, 2017; Site 3b – Bosket VFSL/Commerce SiCL, sprinkler, Stoneville, MS, 2018-2019;
[D] Irrigation treatment yield means followed by a common letter range are not different (p<0.05).
[E] Irrigation x variety treatment yield means followed by a common letter range are not different (p<0.05).

Table 7. Net returns by irrigation protocol for furrow and sprinkler irrigation studies, Delta Research and Extension Center, Stoneville, MS, 2017-2019.

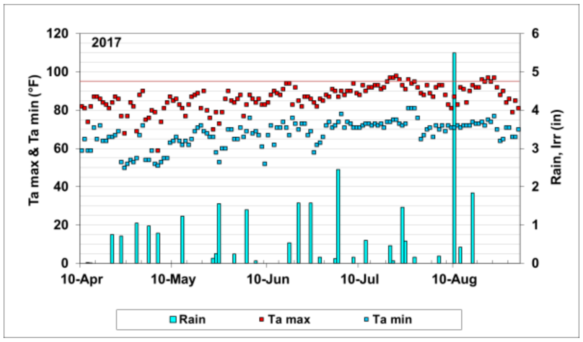
Irrigation protocol			S1	S2	D1	D2	D3	Rain-fed
			----------	-----------	--kPa--	-----------	-----------	
			-50	-80	---	---	---	---
		if Ta<95°F SWP<=	---	---	-80	-100[A]/-120[B]	-100[A]/-120[B]	---
		if Ta>=95°F SWP<=	---	---	-50	-50	-80	---
	Site[C]				Net Returns ($ acre^{-1})			
2017	1	CZ4748/HBK4950[D]	$608c	$626b	$625b	$641a	$638ab	$634ab
	2a[E]	AG4632	$432b	$446ab	$447ab	$479a	$485a	$325c
		AG4835	$278c	$285cd	$324c	$318cd	$319cd	$286c
	3a	P47T89/P49T97[D]	$501	$505	$503	$486	$477	$483
2018	1	CZ4748/HBK4950[D]	450c	468bc	462bc	478ab	479ab	489a
	2b	CZ4748/HBK4950[D]	433b	428b	459a	460a	465a	452a
	3b	P45A23/P48A60[D]	$479ab	$501a	$497ab	$488ab	$469b	$428c
2019	1[E]	CZ4748	414cde	424bcd	411de	412de	430abc	431ab
		HBK4950	443a	425bcd	435ab	443a	447a	406e
	2b	CZ4748/HBK4950[D]	415a	369bc	383b	373bc	369bc	356c
	3b	P46A57/P48A60[D]	$527	$545	$535	$526	$521	$536

[a] Threshold in kPa for Sites 3a and 3b when maximum air temperature is less than 95°F.
[b] Threshold in kPa for Sites 1, 2a, and 2b when maximum air temperature is less than 95°F.
[C] Site 1 –Sharkey SiCL, furrow, Stoneville, MS; Site 2a –Dundee / Forrestdale SiCL, furrow, Stoneville, MS, 2017; Site 2b – Sharkey SiCL, furrow, Stoneville, MS, 2018-2019; Site 3a – Bosket VFSL/Dubbs SiL, sprinkler, Stoneville, MS, 2017; Site 3b – Bosket VFSL/Commerce SiCL, sprinkler, Stoneville, MS, 2018-2019;
[D] Net return means followed by a common letter range are not different ($p<0.05$).
[E] Net return x variety treatment means followed by a common letter range are not different ($p<0.05$).

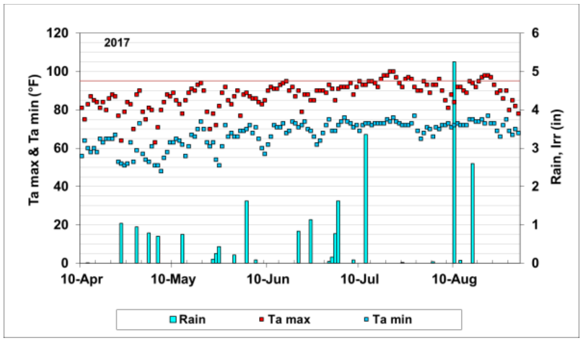
Table 8. Nominal Water Use Efficiency (WUE) by irrigation protocol for furrow and sprinkler irrigation studies, Delta Research and Extension Center, Stoneville, MS, 2017-2019.

Irrigation protocol			S1	S2	D1	D2	D3	Rain-fed
			----------	-----------	--kPa--	-----------	-----------	
			-50	-80	---	---	---	---
		if Ta<95°F SWP<=	---	---	-80	-100[A]/-120[B]	-100[A]/-120[B]	---
		if Ta>=95°F SWP<=	---	---	-50	-50	-80	---
	Site[C]				Nominal WUE (bu in^{-1})			
2017	1	CZ4748	-0.20	0.07	-0.01	---	---	---
		HBK4950	0.05	0.18	0.17	---	---	---
	2a	AG4632	1.19	2.75	2.56	6.63	3.89	---
		AG4835	0.18	0.24	0.98	1.60	1.00	---
	3a	P47T89	1.05	1.44	1.59	1.26	-0.05	---
		P49T97	0.62	1.27	0.92	0.29	-0.53	---
2018	1	CZ4748	-0.01	0.16	0.11	-0.04	-0.38	---
		HBK4950	0.14	0.06	0.05	0.15	0.19	---
	2b	CZ4748	0.19	0.10	0.23	0.37	0.65	---
		HBK4950	0.25	0.25	0.78	0.69	0.60	---
	3b	P45A23	1.38	2.63	3.06	3.62	2.72	---
		P48A60	2.33	4.86	4.07	4.46	5.53	---
2019	1	CZ4748	0.10	0.20	0.07	0.06	0.32	---
		HBK4950	0.70	0.69	0.64	0.78	1.21	---
	2b	CZ4748	1.07	0.50	0.61	0.33	0.47	---
		HBK4950	0.94	0.57	0.73	0.76	1.17	---
	3b	P46A57	-0.23	4.97	0.45	1.42	0.42	---
		P48A60	0.12	-1.46	0.53	-1.74	-3.45	---

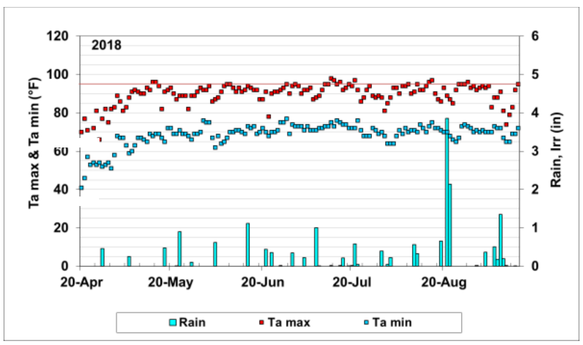
[a] Threshold in kPa for Sites 3a and 3b when maximum air temperature is less than 95°F.
[b] Threshold in kPa for Sites 1, 2a, and 2b when maximum air temperature is less than 95°F.
[C] Site 1 –Sharkey SiCL, furrow, Stoneville, MS; Site 2a –Dundee / Forrestdale SiCL, furrow, Stoneville, MS, 2017; Site 2b – Sharkey SiCL, furrow, Stoneville, MS, 2018-2019; Site 3a – Bosket VFSL/Dubbs SiL, sprinkler, Stoneville, MS, 2017; Site 3b – Bosket VFSL/Commerce SiCL, sprinkler, Stoneville, MS, 2018-2019;



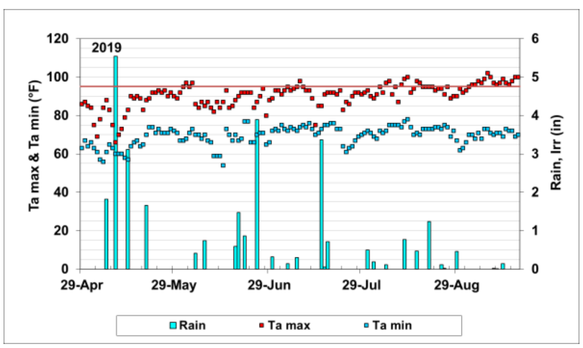
a) 2017, Site 3a.



b) 2017, Site 2a.

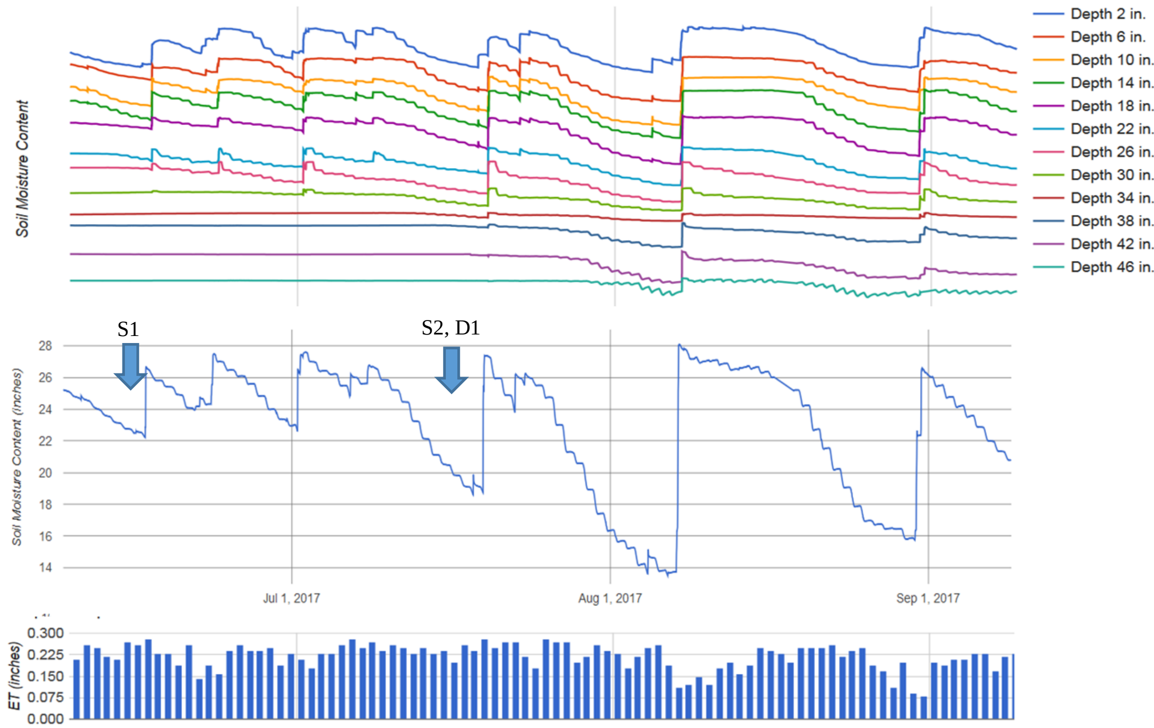


c) 2018, Site 3b.

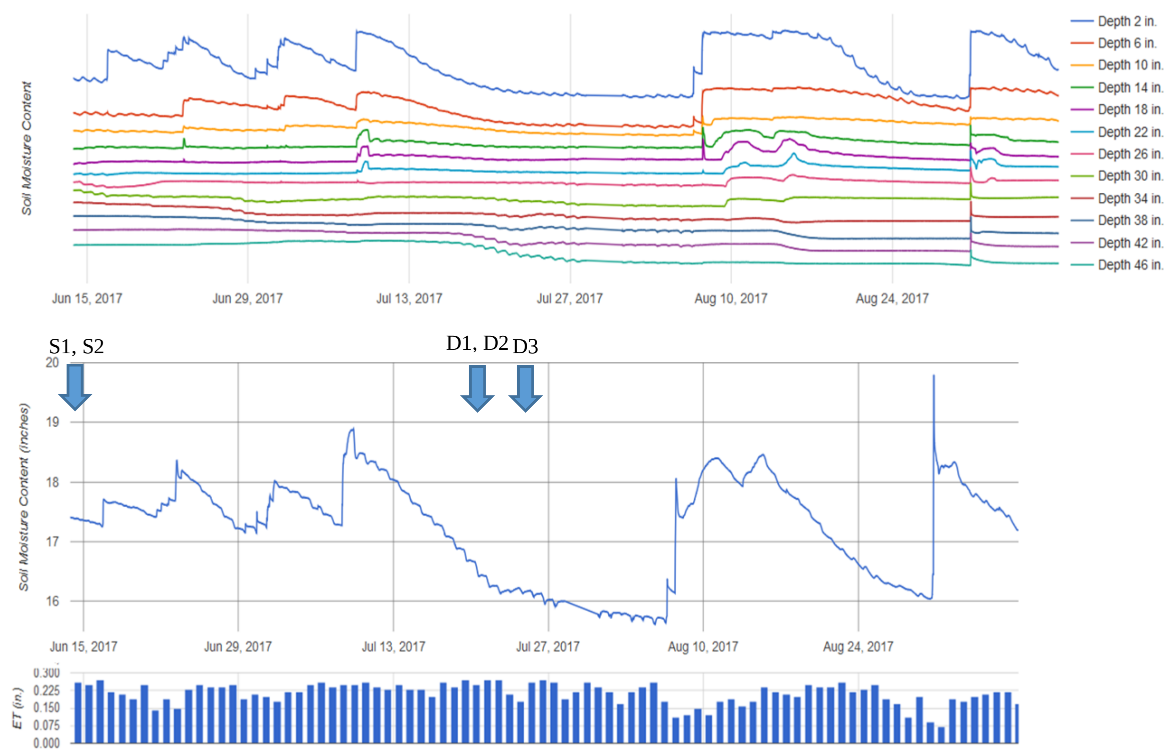


d) 2019, Site 3b.

Figure 1. Weather variables (air temperature and rainfall) during growing season at Delta Research and Extension Center, Stoneville, Mississippi, 2017-2019.

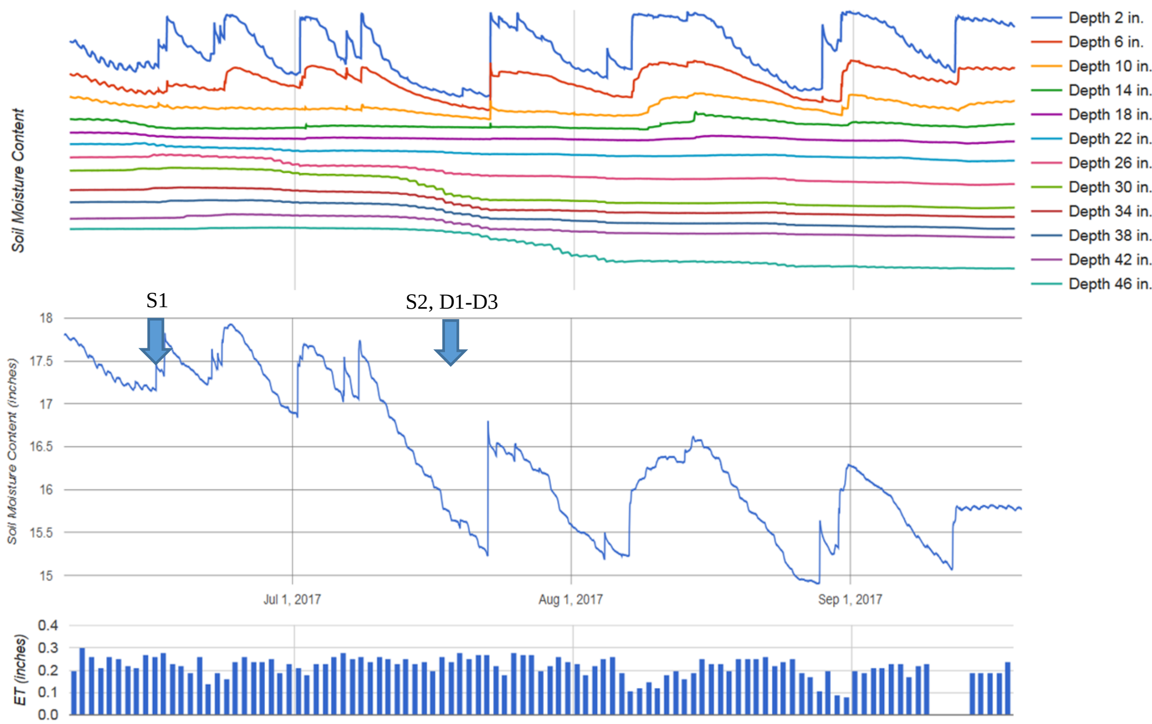


a) Sharkey SiCL (Site 1).



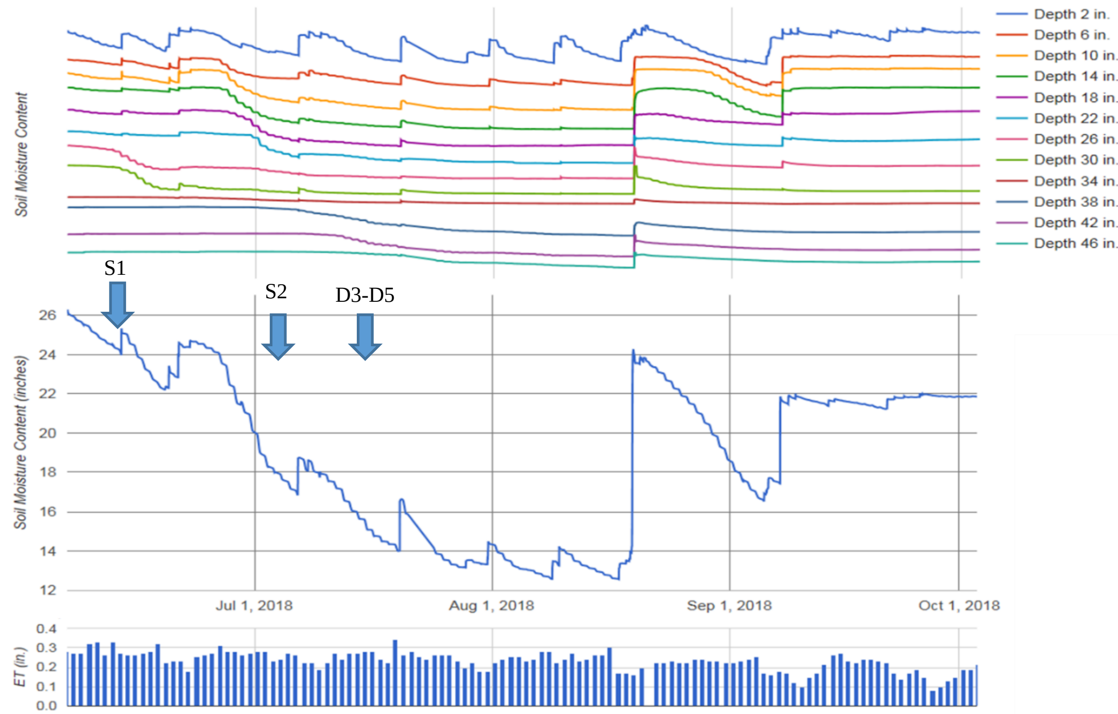
b) Dundee/Forrestdale SiCL (Site 2a).

Figure 2. Volumetric water content (VWC, Sentek) observations for rain-fed (non-irrigated) soybean during growing season at Delta Research and Extension Center, 2017.

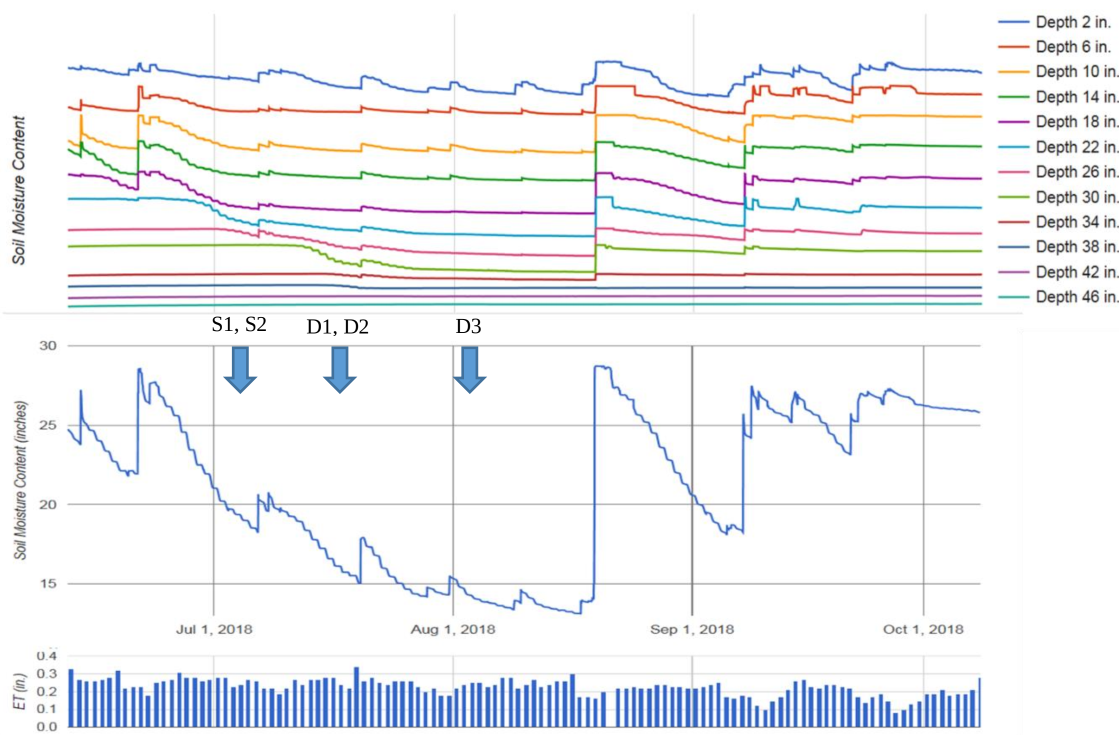


c) Bosket VFSL/Dubbs SiL (Site 3a).

Figure 2. – continued- Volumetric water content (VWC, Sentek) observations for rain-fed (non-irrigated) soybean during growing season at Delta Research and Extension Center, 2017.



a) Sharkey SiCL (Site 1).

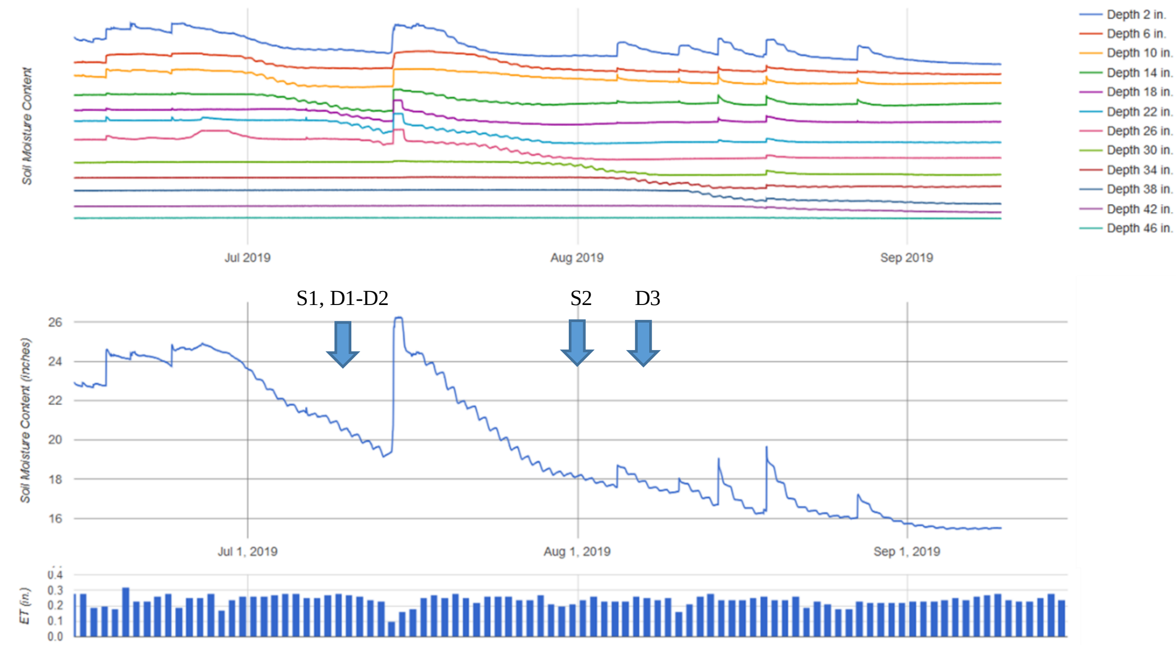


b) Sharkey SiCL (Site 2b).

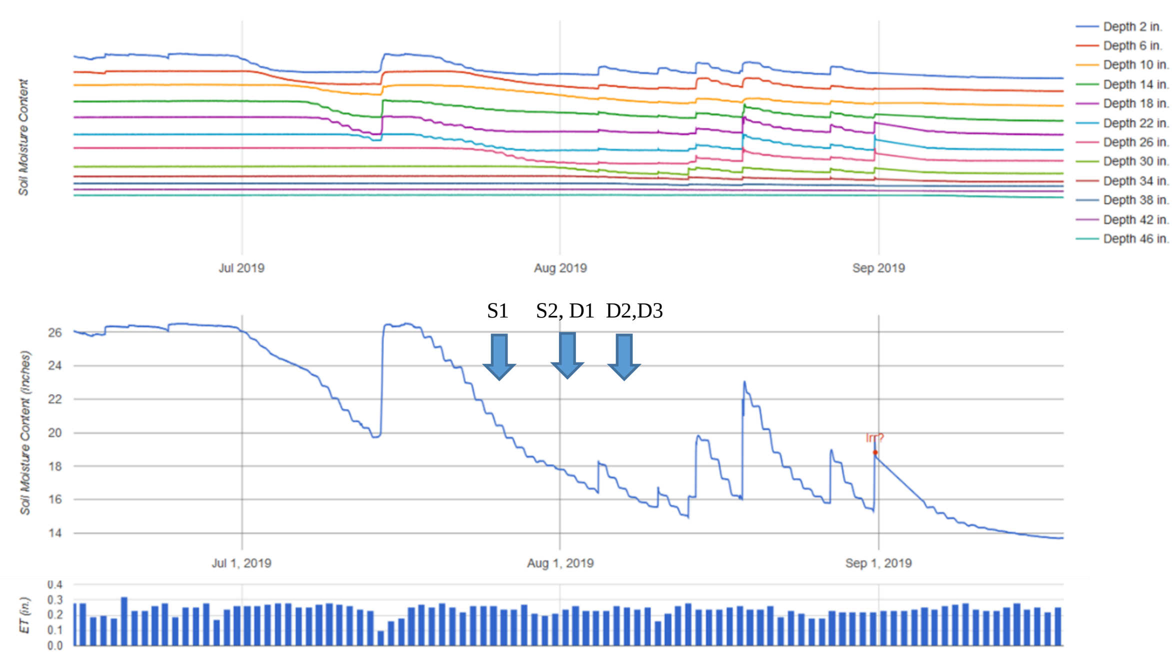
Figure 3. Volumetric water content (VWC, Sentek) observations for rain-fed (non-irrigated) soybean during growing season at Delta Research and Extension Center, 2018.

c) Bosket VFSL/Commerce SiCL (Site 3b).

Figure 3. – continued- Volumetric water content (VWC, Sentek) observations for rain-fed (non-irrigated) soybean during growing season at Delta Research and Extension Center, 2018.

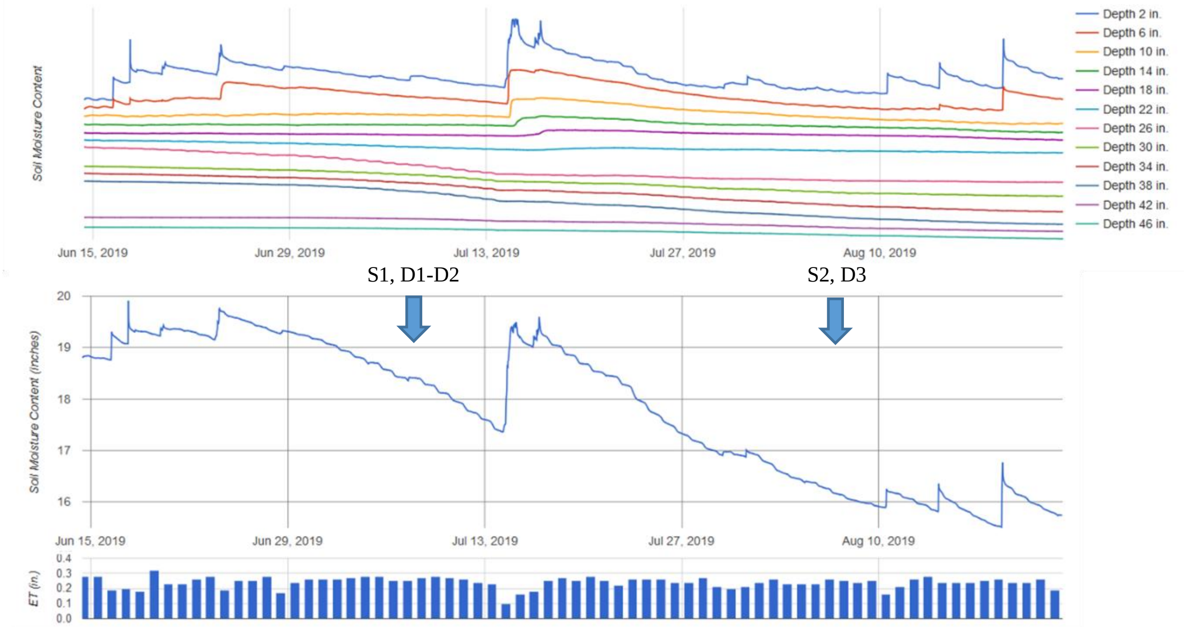


a) Sharkey SiCL (Site 1).



b) Sharkey SiCL (Site 2b).

Figure 4. Volumetric water content (VWC, Sentek) observations for rain-fed (non-irrigated) soybean during growing season at Delta Research and Extension Center, 2019.



c) Bosket VFSL/Commerce SiCL (Site 3b).

Figure 4. – continued- Volumetric water content (VWC, Sentek) observations for rain-fed (non-irrigated) soybean during growing season at Delta Research and Extension Center, 2019.