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Title: Yield and Economic Response of Soybean to Irrigation Initiation in Mississippi

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BACKGROUND AND OBJECTIVES

Recent concerns over the sustainability of the Mississippi Delta's shallow water aquifer, which serves as the water source for most agricultural irrigation in the Mississippi Delta, emphasizes the need for increasing agriculture's irrigation efficiency. Increased emphasis is being placed on proper irrigation scheduling for all crops in the Mississippi Delta so that producers can produce maximum economical yields with the least amount of water.

Proper irrigation scheduling begins with timely irrigation initiation. Three water conserving irrigation strategies available to irrigators were examined. One is critical growth stage irrigation which purports that soybean is more sensitive to moisture deficits at certain growth stages. A second is the utilization of granular matrix soil moisture sensors to indicate soil water potential levels of the crop to schedule irrigation. The third is using a checkbook method water balance that takes into account deposits (effective rainfall; effective irrigation), withdrawals (crop water use, or evapotranspiration) to determine the soil water deficit. Trigger values to schedule irrigations using moisture sensors and/or soil water deficits need to be determined for Mississippi Delta soils and crop growth stages in order to use only the water needed to maintain economic yields.

Three soybean field studies were established on different soils at the Mississippi State University, Delta Research and Extension Center. Growth stage, soil water potential data from Watermark granular matrix sensors, and soil water deficit calculations from a water balance model were strategies monitored under five irrigation initiation timings and compared with non-irrigated. Yields and economic returns were obtained for each.

The objective of this study is to utilize these irrigation initiation strategies to identify the relationship between irrigation initiation and soybean yield and economic returns of MG 4 varieties grown with irrigation on Mississippi Delta soils.

REPORT OF PROGRESS/ACTIVITY

Yield and Economic Response of Soybean to Irrigation Initiation in Mississippi

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Irrigation is a tool used to overcome the effects of moisture stress and increase soybean [*Glycine max (L.) Merr*] yields and profitability in the Mid-Southern USA (Heatherly and Ray, 2007). However, as irrigated acreage is expanding, ground water supplies are decreasing in the Mississippi Delta (YMD, 2006). Furrow irrigation is the most popular irrigation method in this region, yet generally one of the least efficient application methods for row crops (Negri and Hanchar, 1989). Anecdotally, some soybean producers in the Mississippi Delta focus on irrigation strategies that they believe will maximize yield, regardless of the amount of water used. Continuation of furrow irrigation in this area will depend on improving furrow irrigation strategies that focus more on irrigation practices that optimize yields and maximize economic returns while minimizing the amount of irrigation water applied.

One water conserving irrigation strategy that is available to producers and adopted to furrow irrigation is critical growth stage irrigation as opposed to the strategy of maximizing yield per unit area (Stegman et al., 1983). Hiler and Howell (1983) concluded that most row crops are more sensitive to moisture deficits at certain growth stages, and that the extent of yield reduction depends not only on the stage of growth but also the magnitude of the water deficit. For soybean, adequate water is important during R3 through seed-fill (R5-R6) periods since increases in yield result primarily from an increases in seed number (Heatherly and Ray, 2007). Like seed number, seed weight is also sensitive to water deficits late in the growing season (R5-R6) when soil water and rainfall are at seasonal lows. While adequate water is extremely important during soybean from R3-R6, there are subnormal rainfall conditions and shallow soils where irrigation is beneficial during vegetative and early reproductive growth (R1-R2) to ensure sufficient growth and development of the plant (Heatherly and Ray, 2007).

Another method to help soybean producers optimize soybean yield while reducing irrigation water applied involves the utilization of soil moisture sensors. A popular type of soil moisture sensor is a granular matrix sensor. Sensors are placed at several depths in the soil throughout the rooting zone, and are used to monitor moisture tension and root activity. These sensors indirectly measure the negative pressure (soil water potential, SWP) the plant has to exert to remove water from the soil. Field capacity (FC) is the moisture content of the soil after all free water has drained away due to gravity and occurs around 10 kPa for sandy soils and 30 kPa for clayey soils. The wilting point (WP) refers to the situation when there is no more available moisture in the soil, and generally occurs around 1500 kPa for most crops. The difference between FC and WP is the available water holding capacity (AWHC). Granular matrix sensors have a limited range of 0 to 200 kPa, but most of the readily available soil moisture is removed within this range (Evett, 2007; Irmak et al., 2006; McCann et al., 1992). Trigger values to schedule irrigations using moisture sensors need to be determined for Mississippi Delta soils and crop growth stages in order to use only the water needed to maintain economic yields.

Another tool that can be used to schedule irrigation is the checkbook method. The checkbook method is a water balance model that takes into account deposits (effective rainfall, P_e; effective irrigation, I_e), withdrawals (crop water use, or evapotranspiration, ET_c) to determine the soil water deficit (SWD). With this method estimates are made of effective rainfall and irrigation knowing the total amounts of rainfall occurring and irrigation water applied, respectively. Weather parameters are used to estimate reference crop evapotranspiration, ET_r, which then can be adjusted to ET_c using crop coefficients, $K_{c.}$ Allowable SWD need to be determined for Mississippi Delta soils and crops/growth stages to conserve water while maintaining or maximizing yields and net returns.

The objective of this study is to utilize these irrigation initiation strategies to identify the relationship between irrigation initiation and soybean yield and economic returns of MG 4 varieties grown with irrigation on Mississippi Delta soils.

Materials and Methods

Three soybean field studies were established on different soils at the Mississippi State University, Delta Research and Extension Center. Sites 1 and 3 were located at Stoneville, Mississippi (127 ft elev., 33° 26' N, 90°55' W). Site 2 was located at a satellite farm near Tribbett, Mississippi (118 ft elev., 33° 21' N, 90° 48' W). At Site 1, soybean was monocropped, while at sites 2 and 3, soybean was in a biennial rotation (1:1) with corn on two fields at each site.

Sites 1 and 2 were conducted in a randomized complete block design with a 6 x 2 factorial arrangement of treatments in four replicates. The first factor was irrigation strategy, which included five irrigation initiation timings and a non-irrigated (NI) treatment. The second factor was variety which included two varieties. Site 3 was conducted in a randomized complete block design with a split-plot arrangement of treatments in four replicates. Irrigation initiation treatments (whole-unit) were randomized within replicates and varieties (sub-unit) were randomized within initiation treatments. The irrigation whole-unit contained six irrigation practices, which included five irrigation initiation timings and NI. The variety sub-unit contained two varieties.

Site 1 was a Sharkey series (very-fine, smectitic, thermic Chromic Epiaquerts), which consists of very deep, poorly and very poorly drained, very slowly permeable soils that formed in clayey alluvium (USDA NRCS OSD) with a maximum rooting depth of 4 ft (USDA/SCS, 1974).

Site 2 was composed of a Dundee/Forestdale Sioty clay loam complex. The Dundee (Fine-silty, mixed, active, thermic Typic Endoaqualfs) sitly clay loam consists of very deep, somewhat poorly drained soils that formed in loamy alluvium (USDA NRCS OSD). The Forestdale series (Fine, smectitic, thermic Typic Endoaqualfs) consists of very deep, poorly drained, very slowly permeable soils that formed in clayey and silty alluvium (USDA NRCS OSD). The Dundee and Forestdale series belong to a 0.3 and 0.2 intake family, respectively, and tend to seal over following a rain or irrigation event, with both soils having a maximum rooting depth of 4 ft (USDA/SCS, 1974).

Site 3a was composed of a Bosket/Dubbs complex in 2013 and 2015 and site 3b was composed of a Bosket/Commerce complex in 2014. The Bosket (fine-loamy, mixed, active, thermic Mollic Hapludalfs) very-fine sandy loam consists of very deep, well drained, moderately permeable soils that formed in loamy alluvium (USDA NRCS OSD). The Dubbs (fine-silty, mixed, active, thermic Typic Hapludalfs) silt loam consists of very deep, well drained, moderately permeable soils formed in loamy alluvium (USDA NRCS OSD). The Commerce (fine-silty, mixed, superactive, nonacid, thermic Fluvaquentic Endoaquepts) loam consists of deep, somewhat poorly drained, moderately slowly permeable soils that formed in loamy alluvial sediments (USDA NRCS OSD). The Bosket belongs to a 0.5 intake family, while the Dubbs and Commerce belong to a 0.3 intake family and tends to seal after a rain or irrigation event (USDA/SCS, 1974). The Bosket, Dubbs, and Commerce have a maximum rooting depth of 5 ft (USDA/SCS, 1974).

No primary tillage was performed ahead of the soybean crop. Deep tillage was performed at sites 2 and 3 after soybean harvest and before planting corn to a depth of 14 in. with a 4-shank, low-till parabolic subsoiler designed and built by Mississippi State University (Tupper, 1995). This primary tillage occurred either in the fall after harvest or in late winter depending on weather conditions. Disking was performed prior to deep tillage if weeds became a problem such that it would interfere with deep tillage operations. The fields were bedded utilizing a John Deere F986 Bedder ™. At sites 1 and 2, plots consisted of 6 rows spaced 40 in. apart and 600 and 650 ft long, respectively. Two rows were left unplanted between all plots at site 1 to provide a non-shrinking buffer zone between the irrigation treatments. At site 3, plots consisted of eighteen rows spaced 40 in. apart and 67 ft long. All studies were maintained weed-free throughout the growing season using combinations of pre- and post-emergence herbicides.

Immediately after rows were conditioned in mid-April to late-May, soybean seed was planted at a depth of 1.25 in. at a rate of 140,000 seed acre^{-1}. Site 1 was planted with Halo or HBK Liberty Link varieties (Bayer Crop Science), both maturity group (MG) 4 (4.6 and a 4.9, respectively) each year. Site 2 and site 3 were planted with AsGrow (Monsanto Company), Pioneer (Pioneer Hi-Bred International, Inc., a Dupont Co.), and/or NK (Syngenta) Round-up Ready varieties each year, all MG 4.6. A water furrow was cultivated in between rows ahead of irrigation to help control weeds and to facilitate water flow down the intended middles at site 1 and 2.

Watermark™ Model 200SS soil water potential sensors (Irrometer Co., Riverside, CA) were prepared and installed in accordance with the manufacturer's recommendations. A length of PVC was attached to the sensor and used to push the sensor down to the desired depth, and then soil was backfilled around the access hole. They were installed in two replicates of each irrigation initiation x variety treatment of each study. They were installed at three depths within the profile and spaced evenly so a simple average of the readings could be performed. Slightly different depths were used for each site due to soil type and irrigation system (Site 1 - 8, 16, and 24 in. – furrow-irrigated; site 2 – 9, 18, and 27 in. – furrow-irrigated; and site 3 - 6, 15, 24 in. – sprinkler-irrigated). Each site was instrumented with non-commercial dataloggers (Fisher, 2012) and set to read and store data every hour.

Soil samples taken in previous years in the vicinity of the placement of Watermark sensors in each of the field sites were used to create soil water retention curves using Saxton's model (Saxton et al., 1986). Sites were sampled at 0-6, 6-12, 12-18, 18-24, and 24-30 in. depths and averaged over all depths and sample sites. The soil at site 1, a Sharkey silty clay, averaged 2% Sand, 47% Silt, 51% Clay, and 0.7% organic matter (OM). Site 2, a Dundee/Forestdale, was predominantly a silty clay loam with 17% Sand, 52% Silt, 31% Clay, and 0.8% OM. Site 3a, in 2013 and 2015, was a Bosket/Dubbs silt loam with 21% Sand, 59% Silt, 20% Clay, and 0.9% OM. In 2014 site 3b was a Bosket/Commerce silt loam to loam soil with 44% Sand, 49% Silt, 7% Clay, and 1.2% OM. These values were entered into Saxton's model for each site, leaving the salinity and gravel parameters at the default values of 0 and soil compaction factor at normal. The resulting estimated soil water retention curves are shown in figure 1. From these curves, SWP values of 196, 159, 153, and 117 kPa would indicate when 50% of the available water holding capacity (AWHC) had been reached at sites 1, 2, 3a, and 3b, respectively.

Subtracting the soil water content (SWC) value at 50% AWHC from the SWC at FC and multiplying by the depth of the root zone equates to soil water deficit (SWD) of 2.0, 2.4, 2.6, and 2.1 in. for a soil depth of 30 in. for sites 1, 2, 3a, and 3b, respectively. Irrigating soybean at a depletion of 50% of the AWHC on deep medium- and fine-textured soils is a common irrigation scheduling strategy (Kranz and Specht, 2012). A range of Watermark readings of 100 to 120 kPa have been recommended to trigger irrigation on a silt loam soil (Irmak et al., 2006). This range would shift a little higher for silty clay loam and silty clay soils and a little lower for loam soils. The lower value of this trigger range is lower than the 50% depletion of the AWHC to allow for the time it takes to irrigate the entire field.

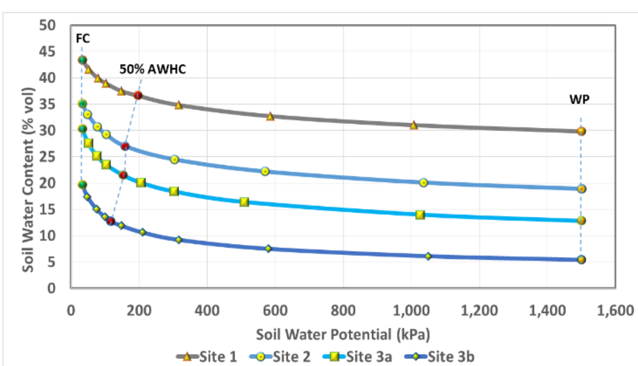

Figure 1. Estimated soil water retention curves using Saxton's model for site 1 (Sharkey), site 2 (Dundee/Forestdale), site 3a (Bosket/Dubbs) and site 3b (Bosket Commerce) soil, Stoneville and Tribbett, Mississippi including estimates of field capacity (FC), 50% available water holding capacity (AWHC), and wilting point (WP).

A roll-out pipe system (Delta Plastics, Little Rock, Arkansas) was used to furrow-irrigate the irrigated plots by providing water to the five middles of the 6-row plots. The first irrigation initiation treatment of the study commenced when soil water potential (SWP) readings averaged over all three depths was in the range from -30 to -60 kPa. Once the first irrigation initiation treatment began, subsequent initiation treatments were initiated 5 d apart for furrow-irrigated and 4 to 8 d apart for sprinkler-irrigated treatments except when rain occurred. Subsequent irrigations for each initiation treatment were applied on a 10-d interval for furrow-irrigated and a 4-d interval for sprinkler-irrigated treatments except when rain occurred during that time interval. Irrigations were terminated generally within 4 to 10 d prior to the occurrence of full seed (R6.5).

The volume of water applied was determined from a propeller type flow meter (McCrometer, Hemet, California; JM Geyser, Reykjavik, Iceland). The volume of water applied along with the area of the plots being irrigated was used to calculate the total irrigation water applied on an area basis for each irrigation. Total water applied for each treatment was summed over each irrigation. The seasonal irrigation water use efficiency (SIWUE), which was defined as the yield increase of an irrigation initiation treatment above the NI treatment divided by the total water pumped, was determined for each irrigation initiation treatment.

Growth stage as described by Kroger et al., (2010) was recorded once a week, and growth stage at irrigation initiation was estimated from these weekly records.

Soil water deficit during the growing season was calculated using the checkbook method. ET_c was calculated based on the FAO-56 Penman-Monteith method using a single crop coefficient (Allen et al., 1998). Weather data from the National Weather Service Cooperative Observing Station at Stoneville, Mississippi or from automated weather stations (Campbell Scientific, Logan, Utah) at sites 1 and 2 were used to calculate (ET_r). The crop coefficient (K_c) curve for soybean was derived using local observations for lengths of growth periods (initial, 19 d; development, 38 d; mid, 38 d; late, 32 d) and using local weather conditions to make adjustments to the magnitude of each K_c value (K_c initial 0.39; K_c mid, 1.1, K_c end, 0.48) for each growth period based on FAO-56 methodology (Allen et al., 1998). Measurements of rainfall collected on-site were input to the Curve Number Method (HSG Group B & D, Ag row crop, straight rows + crop residue cover-good condition, adjust for antecedent moisture condition) to predict runoff (USDA, 1986) and from that, estimate P_e.

Whole plant samples from one square meter were taken approximately midway of each plot the week before harvest of each study. Average seed m^{-2} was obtained from each sample. The two middle rows of each plot were harvested with a plot combine at Sites 2 and 3. For the large plots in Site 1, the upper and lower ends of the field were trimmed before plots were harvested. 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. A sample was taken to measure harvest moisture content, test weight, and seed weight, and yields were then adjusted to 13% moisture content.

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 yearly Mississippi State University 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). Fixed irrigation costs were applied to NI treatment costs. The average reported soybean price for the week including the harvest date in the Delta area (USDA-AMS) is used to set the soybean price in the analysis for each study for each year.

Data were analyzed using SAS (Statistical Analysis System). Yearly yield and net returns for sites 1 and 2 were subjected to Proc ANOVA analysis and the means were separated by the least significant difference (LSD) procedure at the 5% level of significance. Data from site 3 that was subjected to a Proc Mixed analysis in SAS and means were separated by the LSD procedure at the 5% level of significance.

Irrigation initiation timings were influenced by planting date, soil moisture, and weather conditions for a given year, resulting in a significant year x initiation x variety interaction; thus, data were analyzed for each year separately.

Results and Discussion

Weather

Winter rainfall (October 1– March 31) at Stoneville, MS was near normal all 4 years with the lowest total being 26.4 inches as compared to the 101 year average of 28 in. indicating that likely the entire rooting profile was recharged to start each season even on low infiltration rate soils. Too little rainfall in 2012 and too much rainfall in 2013 and 2014 (April – May) delayed planting especially at site 1 (Table 1). During most of the reproductive growing season (June – August) 2013 and 2015 received slightly less than normal rainfall while 2012 and 2014 received slightly higher to higher than normal rainfall. Maximum air temperatures ($T_{a\ max}$) were cooler than normal in 2013 and 2014 while normal or slightly higher than normal in 2012 and 2015. Minimum air temperatures ($T_{a\ min}$) were near normal in 2012 – 2014 and higher than normal in 2015. Higher than normal rainfall in September of 2012 interfered with timely harvest of early maturing soybean. Near normal or lower than normal rainfall in September of 2013 – 2015 enhanced harvest conditions.

Table 1. Rainfall and Air Temperature for select periods of the crop year for study areas.

	2012			**2013**			**2014**			**2015**			
SITE[A]	1	2	3	1	2	3	1	2	3	1	2	3	Historical[b]
	Rainfall (in.)												
APRIL	3.4	4.1	4.4	5.9	7.8	7.1	9.0[C]	8.7[C]	8.7[C]	5.0	4.0	6.1	5.2
MAY	1.2[C]	1.8[C]	1.5[C]	5.6	6.0	5.5	4.9	4.0	4.4	5.9	7.0	6.4	4.7
JUNE	5.0	5.1	5.5	2.4	1.2[C]	2.4	5.5	5.4	5.8	2.4	2.3	2.7	3.7
JULY	2.5	4.0	3.0	2.3	3.4	1.9	3.8	4.9	4.8	2.3	3.1	2.3	3.7
AUGUST	5.5[C]	3.6	5.0[C]	0.5[C]	0.7[C]	1.6	4.8[C]	3.3	3.9	0.7[C]	2.6	0.8[C]	2.6
SEPTEMBER	7.2[C]	7.4[C]	6.7[C]	4.2	4.4	3.9	1.3	0.7[C]	0.8	1.0	0.4[C]	0.5[C]	3.2

	Stoneville Average Max/Min Air Temperature (°F)				
	2012	2013	2014	2015	
APRIL	78/57	72/51	73/52	76/57	75/53
MAY	88[C]/66[C]	79[C]/60[C]	81/62	83/64	83/62
JUNE	89/69	87[C]/70	88/71	91/71	90/71
JULY	93/74[C]	89[C]/69[C]	88[C]/68[C]	93/74[C]	92/72
AUGUST	93/70	93/70	91/70	92/70	92/70
SEPTEMBER	87/64	90[C]/66	88/66	91[C]/65	87/64

[A] Site 1 – Sharkey SiCL, Stoneville, Mississippi; Site 2 – Dundee/Forestdale SiCL, Tribbett, Mississippi; Site 3 – Bosket/Dubbs SiL, Stoneville, Mississippi

[B] Historical average at Stoneville, Mississippi (Rainfall, 101 years; Air temperature, 86 years) located eight miles NNE of Tribbett, Mississippi.

[C] Values are greater than or less than one standard deviation of historical average.

Yield and Economic Analysis

Irrigation initiation had a significant effect ($p<0.05$) on treatment yield, seed number, seed weight, and returns at site 1 in 2012 and 2013. The MG 4.6 variety did not respond to irrigation in 2014, whereas initiation had an effect on yield, seed weight, and returns of the MG 4.9 variety. In 2015, both varieties responded differently to initiation, but initiation had an effect on yield, seed weight, and returns of both varieties. A varietal effect occurred on yield and returns in 2012 and also in 2014 and 2015 due to high F values even though there was an initiation x variety interaction. A varietal effect occurred with seed number in 2014 and seed weight in 2015.

At site 2 and 3, initiation had a significant effect on treatment yield, seed weight, and returns in 2013 and 2015, but only had an effect on returns at site 2 in 2014. Variety had an effect on seed weight in 2013 at site 2, and it had an effect on seed number and seed weight in 2014 at site 3. At site 2 in 2014, and at site 2 and 3 in 2015, variety had an effect on yield, seed number, seed weight, and returns.

Table 2. Analysis of variance ($p<0.05$) of initiation and tillage effects on soybean yield, yield components, and returns during each year in field studies on sites 1-3 at Stoneville and Tribbett, Mississippi.

		Site 1				Site 2			Site 3		
	Effect	2012	2013	2014	2015	2013	2014	2015	2013	2014	2015
Yield	Initiation	<.0001	<.0001	0.0085	<.0001	<.0001	0.2576	<.0001	0.0002	0.8664	0.0001
	Variety	<.0001	0.9145	<.0001	<.0001	0.8959	<.0001	<.0001	0.2464	0.2124	<.0001
	Init x Var	0.0890	0.2908	0.0069	<.0001	0.8779	0.2804	0.7485	0.4095	0.9516	0.6517
Seed no.	Initiation	0.0003	0.0002	0.0775	0.0706	0.1061	0.2946	0.0637	0.8999	0.1576	0.2182
	Variety	0.8264	0.1763	0.0016	0.2847	0.3129	0.0053	0.0101	0.7095	0.0650	0.0060
	Init x Var	0.9064	0.1277	0.3510	0.4133	0.4932	0.1076	0.1395	0.3846	0.8292	0.9205
Seed wt.	Initiation	<.0001	<.0001	0.0204	0.0012	<.0001	0.5625	<.0001	0.0002	0.1782	0.0005
	Variety	0.0005	<.0001	<.0001	<.0001	<.0001	0.0006	<.0001	0.5788	<.0001	<.0001
	Init x Var	<.0001	0.0007	0.0020	0.4272	0.3794	0.2456	0.1059	0.1650	0.7486	0.8385
Returns	Initiation	<.0001	<.0001	0.0574	<.0001	<.0001	0.0013	<.0001	0.0016	0.7397	0.0013
	Variety	<.0001	0.9944	<.0001	<.0001	0.9379	<.0001	<.0001	0.2507	0.1666	0.0001
	Init x Var	0.0354	0.2815	0.0235	0.0002	0.9038	0.2685	0.6148	0.4143	0.9388	0.6503

Irrigation costs were generally a little higher for sprinkler irrigation than furrow irrigation. The estimated variable and fixed irrigation set up cost averaged \$77.54 acre^{-1} for sprinkler and \$69.55 acre^{-1} for furrow, while the water lifting costs averaged \$4.89 acre^{-1} in.$^{-1}$ for sprinkler and \$3.43 acre^{-1} in.$^{-1}$ for furrow irrigation (Table 3). Estimated hauling costs did not change much over the years of the study with a range of \$0.27 to \$0.28 bu^{-1}. Soybean prices were the highest in 2012 at \$15.18 bu^{-1} and the lowest in 2015 at an average of \$9.12 bu^{-1}. These cost values for each year along with yield and water applied were used to calculate expected net returns above irrigation and hauling costs for each treatment at each site.

Table 3. Estimated irrigation and hauling cost and soybean price for furrow and sprinkler irrigation initiation studies for each year.

		Furrow				Sprinkler		
		2012	2013	2014	2015	2013	2014	2015
Irrigation Cost (\$ acre^{-1}) [a]		\$68.48	\$66.27	\$70.67	\$72.79	\$ 76.12	\$ 76.72	\$79.79
Water Lifting Cost (\$ acre^{-1} In.$^{-1}$)		\$ 5.56	\$ 2.99	\$ 3.07	\$ 2.08	\$ 5.56	\$ 5.45	\$ 3.66
Haul Soybean (\$ bu^{-1})		\$ 0.28	\$ 0.27	\$ 0.27	\$ 0.27	\$ 0.27	\$ 0.27	\$ 0.27
Soybean Price (\$ bu^{-1}) [b] **Site**[c]	**1**	\$ 15.18	\$13.42	\$ 9.25	\$ 9.13			
	2		\$13.63	\$10.07	\$ 9.05			
	3					\$14.12	\$10.07	\$ 9.18

[a] Irrigation cost excluding water lifting cost - Mississippi State University Budget Report.
[b] Greenville FGT average quote USDA-AMS JK-GR-110 for week of harvest (Site 1 - 25 October 2012, 23 October 2013, 29 September 2014, and 28 October & 22 September 2015; Site 2 – 18 September 2013, 15 September 2014, 22 September 2015; Site 3 – 10 September 2013, 16 September 2014, 14 & 23 September 2015).
[c] Site 1 – Sharkey SiCL, Stoneville, Mississippi; Site 2 – Dundee/Forestdale SiCL, Tribbett, Mississippi; Site 3 – Bosket/Dubbs SiL, Stoneville, Mississippi.

2012

Halo 4:94, MG 4.9, yielded 8.8 bu acre^{-1} and returned \$133 acre^{-1} more than Halo 4:65, MG 4.6 (table 4). All irrigated treatments had 14.3 to 26.6 bu acre^{-1} higher yields and \$175 to \$349 acre^{-1} higher returns compared to the NI treatment. Yields and mean returns declined to 48.3 bu acre^{-1} and \$613 acre^{-1} with the 7 July initiation likely due to a total of 2.5 in. that fell over the next 8 days that kept the ground saturated. The 7 July rain event along with the additional rainfall resulted in the actual date of initiation for the 25 July initiation treatment being 7 July. Yields and returns were maximized at averages of 60.4 and 60.7 bu acre^{-1} and \$771 – \$787 acre^{-1}, respectively, for both the 4.6 and 4.9 MG varieties with the 27 June and 2 July initiations at site 1. These two initiations increased seed number and seed weight as compared to NI. The 2 July initiation treatment applied one less irrigation (3.2 in.) than the 27 June initiation treatment, resulting in the maximum yield with the least amount of water applied for both varieties.

Table 4. Initiation date, water applied, irrigation costs, yields, yield components, returns, and water use by initiation treatment for furrow irrigated soybean irrigation initiation study at site 1, Sharkey soil, Stoneville, Mississippi, in 2012.

Init Date	27 June	2 July	7 July	25 July	30 July	Non-Irr	Average[a,c,f]
Irr (in acre^{-1})							
Halo 4:65	14.7	11.5	9.1	8.0	6.6		
Halo 4:94	16.8	13.6	11.2	10	8.6		
Irr Cost (\$ acre^{-1})							
Halo 4:65	\$124	\$112	\$103	\$99	\$94	\$68	
Halo 4:94	\$132	\$120	\$111	\$107	\$101	\$68	
Yield (bu acre^{-1})							
Halo 4:65	55.7	56.7	44.1	51.6	48.5	27.8	47.4 a
Halo 4:94	65.0	64.6	52.6	59.4	55.8	40.2	56.2 b
Average[b]	60.4 a	60.7 a	48.3 d	55.5 b	52.1 c	34.0 e	
Seed No. (seed m^{-2})							
Halo 4:65	2357	2204	1916	2117	2002	1268	1977 a
Halo 4:94	2277	2143	1789	2120	2186	1492	2001 a
Average[d]	2317 a	2173 ab	1853 b	2119 ab	2094 ab	1380 c	
Seed wt. [e] (g 100^{-1})							
Halo 4:65	15.8 a	15.5 ab	14.6 cde	15.1 bc	15.0 cd	13.0 g	
Halo 4:94	14.9 cd	14.6 cde	14.4 ef	14.5 def	14.2 ef	14.1 f	
Mean Return (\$ acre^{-1})							
Halo 4:65	\$706	\$733	\$554	\$670	\$629	\$345	\$606 b
Halo 4:94	\$837	\$842	\$672	\$778	\$730	\$531	\$739 a
Average[g]	\$771 a	\$787 a	\$613 d	\$724 b	\$680 c	\$438 e	
SIWUE (bu in.$^{-1}$)							
Halo 4:65	1.90	2.52	1.8	2.98	3.14		
Halo 4:94	1.48	1.79	1.11	1.92	1.82		

[a] Variety treatment yield means followed by a common letter range are not different ($p<0.05$; LSD = 1.1 bu acre^{-1}).
[b] Irrigation initiation treatment yield means followed by a common letter range are not different ($p<0.05$; LSD = 1.9 bu acre^{-1}).
[c] Variety treatment seed no. means followed by a common letter range are not different ($p<0.05$; LSD = ns; seed m^{-2})
[d] Irrigation initiation treatment seed no. means followed by a common letter range are not different ($p<0.05$; LSD = 380 seed m^{-2}).
[e] Irrigation initiation x variety treatment seed wt. means followed by a common letter range are not different ($p<0.05$; LSD = 0.2 g 100^{-1})
[f] Variety treatment return means followed by a common letter range are not different ($p<0.05$; LSD = \$16 acre^{-1}).
[g] Irrigation initiation treatment return means followed by a common letter range are not different ($p<0.05$; LSD = \$27 acre^{-1}).

2013

At site 1 no difference was found between average yields of 51.2 bu acre^{-1} or returns of \$580 acre^{-1} for MG 4.6 and MG 4.9 (table 5). The average 30.8 bu acre^{-1} NI yield and \$339 mean return was lower than all irrigated treatments, which averaged 53.1 to 60.3 bu acre^{-1} and \$607 acre^{-1} to \$680 acre^{-1}, due to lower seed number. Seed weight was increased with irrigation with the Halo 4:65 but not the Halo 4:94 variety. Analysis shows a difference between the 6 July and 11 July initiation treatments, while there was no difference with these two initiation treatments and the 22 July initiation treatment.

Yields and returns were lower with the 6 August initiation treatment than the earlier initiation treatments. Rainfall occurring on 11, 14, and 19 July (0.35, 0.79, and 0.26 in.) likely had some negative affect on the 11 July initiation yields due to the soil staying saturated longer, plus the rainfall delayed the next initiation to 22 July. With this rainfall, initiations could be delayed to as late as 22 July for the MG 4.6 and MG 4.9 varieties, respectively, and not be different than earlier initiations. So, the 11 July rainfall rain event then becomes the actual date of initiation for the 22 July initiation treatment.

Table 5. Initiation date, water applied, irrigation costs, yields, yield components, returns, and water use by initiation treatment for furrow irrigated soybean irrigation initiation study at site 1, Sharkey soil, Stoneville, Mississippi, in 2013.

Init Date	6 July	11 July	22 July	6 August	Non-Irr	Average[a,c,,f]
Irr (in acre^{-1})	15.5	10.9	11.0	8.5		
Irr Cost (($ acre^{-1})	$113	$99	$99	$92	$66	
Yield (bu acre^{-1})						
Halo 4:65	60.4	56.2	57.8	54.1	27.7	51.2 a
Halo 4:94	60.1	55.2	54.9	52.1	34.0	51.2 a
Average[b]	60.3 a	55.7 b	56.3 ab	53.1 b	30.8 c	
Seed No. (seed m^{-2})						
Halo 4:65	2202	2242	1960	2397	1398	2040 a
Halo 4:94	1942	2715	2613	2270	1518	2211 a
Average[d]	2072 b	2479 a	2286 ab	2333 ab	1458 c	
Seed wt. (g 100^{-1}) [e]						
Halo 4:65	16.8 a	15.7 bc	16.4 a	16.1 ab	14.3 e	
Halo 4:94	15.1 cd	14.3 e	14.4 e	14.5 de	14.5 de	
Mean Return ($ acre^{-1})						
Halo 4:65	$682	$640	$660	$620	$298	$580 a
Halo 4:94	$678	$627	$622	$593	$380	$580 a
Average[g]	$680 a	$641 ab	$633 ab	$607 b	$339 c	
SIWUE (bu in.$^{-1}$)						
Halo 4:65	2.11	2.61	2.73	3.11		
Halo 4:94	1.69	1.95	1.90	2.14		

[a] Variety treatment yield means followed by a common letter range are not different ($p<0.05$; LSD = ns; bu acre^{-1}).
[b] Irrigation initiation treatment yield means followed by a common letter range are not different ($p<0.05$; LSD = 4.5 bu acre^{-1}).
[c] Variety treatment seed no. means followed by a common letter range are not different ($p<0.05$; LSD = ns; seed m^{-2})
[d] Irrigation initiation treatment seed no. means followed by a common letter range are not different ($p<0.05$; LSD = 401 seed m^{-2}).
[e] Irrigation initiation x variety treatment seed wt. means followed by a common letter range are not different ($p<0.05$; LSD = 0.7 g 100^{-1})
[f] Variety treatment return means followed by a common letter range are not different ($p<0.05$; LSD = ns; acre^{-1}).
[g] Irrigation initiation treatment return means followed by a common letter range are not different ($p<0.05$; LSD = $60 acre^{-1}).

No differences were found between average yields of 74.8 and 74.7 bu acre^{-1} and for AG4632 and RY4620 varieties (MG 4.6) and returns of $894 acre^{-1} at site 2 (Table 6). Irrigated treatments increased yields by 25 to 31 bu acre^{-1} and returns by $300 to $361 acre^{-1} over NI, which had yield and net returns of 50.8 bu acre^{-1} and $613 acre^{-1}, respectively, due to an increase in seed weight. The irrigation treatments initiated at or before 24 June were not different in yield or returns. The 24 June initiation treatment applied one less irrigation (3.0 in.) than the 14 June initiation treatment.

Table 6. Initiation date, water applied, irrigation costs, yields, yield components, returns, and water use by initiation treatment for furrow irrigated soybean irrigation initiation study at site 2, Dundee/Forestdale soil, Tribbett, Mississippi, in 2013.

Init Date	14 June	19 June	24 June	29 June	3 July	Non-Irr	Average[a,c,e,g]
Irr (in acre^{-1})	19.6	17.5	15.6	12.9	11.3		
Irr Cost (($ acre^{-1})	$125	$119	$113	$105	$100	$66	
Yield (bu acre^{-1})							
AG4632	81.5	81.6	80.7	78.9	75.4	50.5	74.8 a
RY4620	82.6	82.0	79.6	77.7	76.3	51.2	74.7 a
Average[b]	81.5 a	81.8 a	80.1 ab	78.3 b	75.8 c	50.8 d	
Seed No. (seed m^{-2})							
AG4632	2834	2888	2965	2743	3534	2524	2915 a
RY4620	3063	2903	2897	2657	2762	2309	2765 a
Average[d]	2948 a	2895 a	2931 a	2700 a	3148 a	2417 a	
Seed wt. (g 100^{-1})							
AG4632	14.5	14.8	14.7	14.5	15.0	11.6	14.2 b
RY4620	16.0	15.9	15.5	15.6	15.6	12.8	15.2 a
Average[f]	15.3 a	15.4 a	15.1 a	15.1 a	15.3 a	12.2 b	
Mean Return ($ acre^{-1})							
AG4632	$964	$971	$965	$949	$907	$608	$894 a
RY4620	$965	$976	$951	$934	$919	$617	$894 a
Average[h]	$964 ab	$974 a	$958 ab	$941 bc	$913 c	$613 d	
SIWUE (bu in.$^{-1}$)							
AG4632	1.58	1.78	1.94	2.19	2.19		
RY4620	1.55	1.76	1.83	2.05	2.21		

[a] Variety treatment yield means followed by a common letter range are not different ($p<0.05$; LSD = ns; bu acre^{-1}).
[b] Irrigation initiation treatment yield means followed by a common letter range are not different ($p<0.05$; LSD = 2.2 bu acre^{-1}).
[c] Variety treatment seed number means followed by a common letter range are not different ($p<0.05$; LSD = ns; seed m^{-2}).
[d] Irrigation initiation treatment seed number means followed by a common letter range are not different ($p<0.05$; LSD = ns; seed m^{-2}).
[e] Variety treatment seed weight means followed by a common letter range are not different ($p<0.05$; LSD = 0.2 g 100^{-1}).
[f] Irrigation initiation treatment seed weight means followed by a common letter range are not different ($p<0.05$; LSD = 0.4 g 100^{-1}).
[g] Variety treatment return means followed by a common letter range are not different ($p<0.05$; LSD = ns; acre^{-1}).
[h] Irrigation initiation treatment return means followed by a common letter range are not different ($p<0.05$; LSD = $29 acre^{-1}).

Average soybean yields of 89.3 and 87.9 bu acre^{-1} for P94Y82 and RY4620 (MG 4.6) and returns of \$1106 to \$1125 acre^{-1}, respectively, were not different at site 3 (table 7). All irrigated treatments had a higher average yield of 87.5 to 93.2 bu acre^{-1} and returns of \$1103 to \$1163 acre^{-1} than the 78.0 bu acre^{-1} and \$1005 acre^{-1} NI treatment due to an increase in seed weight. No difference in yields of 88.9 to 93.2 bu acre^{-1} or returns of \$1113 to \$1163 acre^{-1} were found among irrigation treatments initiated at or before 25 June, but yields dropped to 87.5 bu acre^{-1} with the 29 June initiation treatment. The 25 June initiation treatment applied 2.5 in. less water than the 13 June initiation treatment.

Table 7. Initiation date, water applied, irrigation costs, yields, yield components, returns, and water use by initiation treatment for sprinkler irrigated soybean irrigation initiation study at site 3, Bosket/Dubbs soil, Stoneville, Mississippi, in 2013.

Init Date	13 June	17 June	21 June	25 June	29 June	Non-Irr	Average[a,c,e,g]
Irr (in acre^{-1})	9.3	8.7	7.7	6.8	6.0		
Irr Cost (\$ acre^{-1})	\$128	\$124	\$119	\$114	\$109	\$76	
Yield (bu acre^{-1})							
RY4620	93.6	94.3	91.4	92.7	87.2	76.5	89.3 a
P94Y82	92.7	91.1	86.5	90.1	87.8	79.6	87.9 a
Average[b]	93.2 a	92.7 a	88.9 ab	91.4 ab	87.5 b	78.0 c	
Seed No. (seed m^{-2})							
RY4620	3224	3101	3355	3096	3159	3234	3195 a
P94Y82	3175	3447	3254	3330	3326	3144	3279 a
Average[d]	3199 a	3274 a	3305 a	3213 a	3242 a	3189 a	
Seed wt. (g 100^{-1})							
RY4620	16.7	16.4	16.2	15.9	16.4	15.7	16.2 a
P94Y82	17.1	16.9	16.8	16.3	15.8	15.3	16.4 a
Average[f]	16.9 a	16.6 ab	16.5 b	16.1 b	16.1 b	15.5 c	
Mean Return (\$ acre^{-1})							
RY4620	\$1157	\$1137	\$1079	\$1133	\$1107	\$1025	\$1106 a
P94Y82	\$1169	\$1182	\$1146	\$1170	\$1099	\$984	\$1125 a
Average[h]	\$1163 a	\$1159 a	\$1113 a	\$1152 a	\$1103 a	\$1005 b	
SIWUE (bu in.$^{-1}$)							
RY4620	1.84	2.04	1.94	2.38	1.79		
P94Y82	1.42	1.32	0.90	1.54	1.37		

[a] Variety treatment yield means followed by a common letter range are not different ($p<0.05$; LSD = 2.4 bu acre^{-1}; ns).
[b] Irrigation initiation treatment yield means followed by a common letter range are not different ($p<0.05$; LSD = 4.5 bu acre^{-1}).
[c] Variety treatment seed number means followed by a common letter range are not different ($p<0.05$; LSD = ns; seed m^{-2}).
[d] Irrigation initiation treatment seed number means followed by a common letter range are not different ($p<0.05$; LSD = ns; seed m^{-2}).
[e] Variety treatment seed weight means followed by a common letter range are not different ($p<0.05$; LSD = ns; g 100^{-1}).
[f] Irrigation initiation treatment seed weight means followed by a common letter range are not different ($p<0.05$; LSD = 0.7 g 100^{-1}).
[g] Variety treatment return means followed by a common letter range are not different ($p<0.05$; LSD = ns; acre^{-1}).
[h] Irrigation initiation treatment return means followed by a common letter range are not different ($p<0.05$; LSD = \$62 acre^{-1}).

The later maturing variety Halo 4:94, MG 4.9, had higher yields and returns than the early maturing variety Halo 4:65, MG 4.6, under all initiation dates and NI treatments (table 8) due to higher seed number. Yields and returns were not increased above the 69.9 bu acre^{-1}, \$556 acre^{-1} NI treatment with irrigation for Halo 4:65. Irrigation of Halo 4:94 increased yields by 3.7 to 5.8 bu acre^{-1} by increasing seed weight over the 80.2 bu acre^{-1} NI treatment. Although the returns of the 8 July, 13 July, and 1 August were not different, only the 8 July initiation was higher than the NI treatment for the Halo 4:94 variety. The return of the 8 July initiation was also higher than the 21 June and 3 July initiations. The SIWUE of the Halo 4:94 variety was low at less than 0.8 bu in^{-1} when getting a response to irrigation.

Table 8. Initiation date, water applied, irrigation costs, yields, yield components, returns, and water use by initiation treatment for furrow irrigated soybean irrigation initiation study at site 1, Sharkey soil, Stoneville, Mississippi, in 2014.

Init Date	21 June	3 July	8 July	13 July	1 August	Non-Irr	Average[a,c,f]
Irr (in acre^{-1})							
Halo 4:65	8.4	6.4	5.4	5.4	2.4		
Halo 4:94	11.1	9.1	8	8	5.1		
Irr Cost (\$ acre^{-1})							
Halo 4:65	\$96	\$90	\$87	\$87	\$78	\$71	
Halo 4:94	\$105	\$99	\$95	\$95	\$86	\$71	
Yield [b] (bu acre^{-1})							
Halo 4:65	69.4 de	71.2 d	69.9 d	67.3 e	69.0 de	69.9 d	69.5 b
Halo 4:94	84.9 ab	83.9 b	86.0 a	84.1 ab	84.2 ab	80.2 c	83.9 a
Seed No. (seed m^{-2})							
Halo 4:65	2647	2373	2616	2382	2655	2558	2538 b
Halo 4:94	2586	2612	3054	2710	2830	3100	2815 a
Average[d]	2617 a	2493 a	2835 a	2546 a	2743 a	2829 a	
Seed wt. [e] (g 100^{-1})							
Halo 4:65	15.7 bc	15.7 bc	15.4 cd	16.2 ab	16.3 a	16.1 ab	
Halo 4:94	15.5 cd	15.2 cd	15.0 d	15.2 cd	15.2 cd	14.3 e	
Mean Return [g] (\$ acre^{-1})							
Halo 4:65	\$528 de	\$547 c	\$541 cd	\$517 e	\$542 cd	\$556 c	\$538 b
Halo 4:94	\$656 b	\$653 b	\$679 a	\$659 ab	\$668 ab	\$650 b	\$661 a
SIWUE (bu in.$^{-1}$)							
Halo 4:65	-0.05	0.20	0.01	-0.48	-0.35		
Halo 4:94	0.42	0.41	0.73	0.49	0.78		

[a] Variety treatment yield means followed by a common letter range are not different ($p<0.05$; LSD = 1 bu acre^{-1}).
[b] Irrigation initiation x variety treatment yield means followed by a common letter range are not different ($p<0.05$; LSD = 2.4 bu acre^{-1}
[c] Variety treatment seed number means followed by a common letter range are not different ($p<0.05$; LSD = 164 seed m^{-2}).
[d] Irrigation initiation treatment seed number means followed by a common letter range are not different ($p<0.05$; LSD = ns; seed m^{-2}).
[e] Irrigation initiation x variety treatment seed weight means followed by a common letter range are not different ($p<0.05$; LSD = 0.5 g 100^{-1}).
[f] Variety treatment return means followed by a common letter range are not different ($p<0.05$; LSD = \$9 acre^{-1}).
[g] Irrigation initiation x variety treatment return means followed by a common letter range are not different ($p<0.05$; LSD = \$22 acre^{-1}).

RY4620 had higher yield, 69.5 bu acre^{-1}, and higher return, \$596 acre^{-1}, than NKS46L2 with 63.0 bu acre^{-1} and \$532 acre^{-1}, at site 2 (table 9). Irrigation did not increase yield or returns over the 66.6 bu acre^{-1} and \$582 acre^{-1} NI treatment in 2014.

Table 9. Initiation date, water applied, irrigation costs, yields, yield components, returns, and water use by initiation treatment for furrow irrigated soybean irrigation initiation study at site 2, Dundee/Forestdale soil, Tribbett, Mississippi, in 2014.

	Init Date	19 June	3 July	8 July	31 July	7 August	Non-Irr	Average[a,c,e,g]
Irr (in acre^{-1})		10.2	6.0	6.2	2.7	3.3		
Irr Cost (($ acre^{-1})		$102	$89	$90	$79	$81	$71	
Yield (bu acre^{-1})								
	NKS46L2	59.5	63.3	63.1	64.5	63.7	63.9	63.0 b
	RY4620	68.9	71.7	69.0	68.5	69.5	69.4	69.5 a
	Average[b]	64.2 b	67.5 a	66.0 ab	66.5 ab	66.6 ab	66.6 ab	
Seed No. (seed m^{-2})								
	NKS46L2	2727	2802	2827	2143	2882	2361	2624 b
	RY4620	2931	3157	3015	2973	2630	3023	2955 a
	Average[d]	2829 a	2979 a	2921 a	2558 a	2756 a	2692 a	
Seed wt. (g 100^{-1})								
	NKS46L2	16.3	16.3	17.5	17.0	17.0	16.7	16.8 a
	RY4620	16.0	16.1	15.9	16.2	15.9	16.3	16.1 b
	Average[f]	16.2 a	16.2 a	16.7 a	16.6 a	16.5 a	16.5 a	
Mean Return ($ acre^{-1})								
	NKS46L2	$481	$531	$529	$554	$544	$555	$532 b
	RY4620	$573	$614	$587	$592	$600	$609	$596 a
	Average[h]	$527 b	$572 a	$558 a	$573 a	$572 a	$582 a	
SIWUE (bu in.$^{-1}$)								
	NKS46L2	-0.43	-0.10	-0.13	0.25	-0.05		
	RY4620	-0.04	0.40	-0.06	-0.33	0.04		

[a] Variety treatment yield means followed by a common letter range are not different ($p<0.05$; LSD = 1.5 bu acre^{-1}).
[b] Irrigation initiation treatment yield means followed by a common letter range are not different ($p<0.05$; LSD = 2.6 bu acre^{-1}).
[c] Variety treatment seed number means followed by a common letter range are not different ($p<0.05$; LSD = 226 seed m^{-2}).
[d] Irrigation initiation treatment seed number means followed by a common letter range are not different ($p<0.05$; LSD = ns; seed m^{-2}).
[e] Variety treatment seed weight means followed by a common letter range are not different ($p<0.05$; LSD = 0.4 g 100^{-1}).
[f] Irrigation initiation treatment seed weight means followed by a common letter range are not different ($p<0.05$; LSD = ns; g 100^{-1}).
[g] Variety treatment return means followed by a common letter range are not different ($p<0.05$; LSD = \$14 acre^{-1}).
[h] Irrigation initiation treatment return means followed by a common letter range are not different ($p<0.05$; LSD = \$25 acre^{-1}).

Average soybean yields of 73.7 and 74.7 bu acre^{-1} for NKS46L2 and P94Y82, respectively, were not different (table 10) at site 3. Yields or returns were not increased above the NI yield of 73.5 bu acre^{-1} and return of \$644 acre^{-1} in 2014.

Table 10. Initiation date, water applied, irrigation costs, yields, yield components, returns, and water use by initiation treatment for sprinkler irrigated soybean irrigation initiation study at site 3, Bosket/Commerce/Dowling soil, Stoneville, Mississippi, in 2014.

Init Date	21 June	3 July	7 July	29 July	6 August	Non-Irr	Average[a,c,e,g]
Irr (in acre^{-1})	4.6	4.0	2.7	1.8	0.9		
Irr Cost (($ acre^{-1})	$102	$99	$91	$87	$82	$77	
Yield (bu acre^{-1})							
NKS46L2	74.1	74.1	74.4	73.6	73.5	72.6	73.7 a
P94Y82	74.4	75.9	74.3	75.5	73.8	74.3	74.7 a
Average[b]	74.3 a	75.0 a	74.4 a	74.6 a	73.7 a	73.5 a	
Seed No. (seed m^{-2})							
NKS46L2	2853	2831	3112	2498	2574	2545	2735 a
P94Y82	3052	2843	3121	2754	3019	2875	2944 a
Average[d]	2952 a	2837 a	3116 a	2626 a	2797 a	2710 a	
Seed wt. (g 100^{-1})							
NKS46L2	16.4	16.8	16.7	16.6	16.9	16.9	16.7 a
P94Y82	15.6	16.5	16.0	16.2	15.9	16.3	16.1 b
Average[f]	16.0 a	16.7 a	16.3 a	16.4 a	16.4 a	16.6 a	
Mean Return ($ acre^{-1})							
NKS46L2	$623	$627	$639	$636	$638	$634	$633 a
P94Y82	$628	$646	$639	$653	$641	$653	$643 a
Average[h]	$626 a	$636 a	$639 a	$645 a	$640 a	$644 a	
SIWUE (bu in.$^{-1}$)							
NKS46L2	0.32	0.36	0.66	0.55	0.93		
P94Y82	0.04	0.41	0.03	0.67	-0.47		

[a] Variety treatment yield means followed by a common letter range are not different ($p<0.05$; LSD = ns; bu acre^{-1}).
[b] Irrigation initiation treatment yield means followed by a common letter range are not different ($p<0.05$; LSD = ns; bu acre^{-1}).
[c] Variety treatment seed number means followed by a common letter range are not different ($p<0.05$; LSD = ns; seed m^{-2}).
[d] Irrigation initiation treatment seed number means followed by a common letter range are not different ($p<0.05$; LSD = ns; seed m^{-2}).
[e] Variety treatment seed weight means followed by a common letter range are not different ($p<0.05$; LSD = 0.3 g 100^{-1}).
[f] Irrigation initiation treatment seed weight means followed by a common letter range are not different ($p<0.05$; LSD = ns; g 100^{-1}).
[g] Variety treatment return means followed by a common letter range are not different ($p<0.05$; LSD = ns; acre^{-1}).
[h] Irrigation initiation treatment return means followed by a common letter range are not different ($p<0.05$; LSD = ns; acre^{-1}).

At site 1, HBK4950, MG 4.9, had average of 32.9 bu acre^{-1} higher yields and \$283 acre^{-1} returns than HBK 4650, MG 4.6, over all initiations and NI treatment (table 11). All initiations of the MG 4.6 variety increased yield, seed weight and returns over the NI treatment. The 17 June initiation treatment increased yield over all other initiations except the 22 June but increased returns over all initiation treatments including the 22 June initiation treatment. The 17 June initiation treatment applied 1.6 in. less than the 9 June initiation treatment. All initiations of the MG 4.9 variety increased yield, seed weight and returns over the NI treatment but there were no difference in yields or returns among the initiation treatments averaging 94.3 bu acre^{-1} and \$737 acre^{-1}. The 18 July initiation treatment applied 4.0 in. less water than the 9 June initiation treatment.

Table 11. Initiation date, water applied, irrigation costs, yields, yield components, returns, and water use by initiation treatment for furrow irrigated soybean irrigation initiation study at site 1, Sharkey soil, Stoneville, Mississippi, in 2015.

	Init Date	9 June	17 June	22 June	13 July	18 July	Non-Irr	Average[a,c,e,g]
Irr (in acre^{-1})								
	HBK4650	9.2	7.6	6.6	5.9	5.0		
	HBK4950	14.5	12.8	12.9	10.5	10.5		
Irr Cost ((\$ acre^{-1})								
	HBK4650	\$92	\$89	\$89	\$84	\$84	\$73	
	HBK4950	\$103	\$99	\$100	\$95	\$95	\$73	
Yield [b] (bu acre^{-1})								
	HBK4650	58.5 d	64.3 c	59.9 cd	56.3 d	57.1 d	47.4 e	57.3 b
	HBK4950	93.9 a	94.9 a	93.5 a	95.5 a	93.7 a	69.6 b	90.2 a
Seed No. [d] (seed m^{-2})								
	HBK4650	2651	3015	3194	2837	2367	2335	2733 a
	HBK4950	2887	2781	3026	3250	3040	2379	2894 a
		2769 a	2898 a	3110 a	3044 a	2703 a	2357 a	
Seed wt. [f] (g 100^{-1})								
	HBK4650	16.4	16.6	16.5	15.8	17.2	15.3	16.3 a
	HBK4950	14.9	14.5	14.2	14.0	14.1	12.3	14.0 b
		15.6 a	15.5 a	15.4 a	14.9 a	15.7 a	13.8 b	
Mean Return[h] (\$ acre^{-1})								
	HBK4650	\$426 d	\$481 c	\$442 d	\$415 d	\$422 d	\$347 e	\$422 b
	HBK4950	\$729 a	\$741 a	\$728 a	\$752 a	\$735 a	\$544 b	\$705 a
SIWUE (bu in.$^{-1}$)								
	HBK4650	1.20	2.21	1.63	1.68	1.82		
	HBK4950	1.68	1.97	1.86	2.48	2.30		

[a] Variety treatment yield means followed by a common letter range are not different ($p<0.05$; LSD = 1.8 bu acre^{-1}).
[b] Irrigation initiation x variety treatment yield means followed by a common letter range are not different ($p<0.05$; LSD = 4.4 bu ac
[c] Variety treatment seed number means followed by a common letter range are not different ($p<0.05$; LSD = ns; seed m^{-2}).
[d] Irrigation initiation treatment seed number means followed by a common letter range are not different ($p<0.05$; LSD = ns; seed m
[e] Variety treatment seed weight means followed by a common letter range are not different ($p<0.05$; LSD = 0.5 g 100^{-1}).
[f] Irrigation initiation x variety treatment seed weight means followed by a common letter range are not different ($p<0.05$; LSD = 0.9
[g] Variety treatment return means followed by a common letter range are not different ($p<0.05$; LSD = \$16 acre^{-1}).
[h] Irrigation initiation x variety treatment return means followed by a common letter range are not different ($p<0.05$; LSD = \$38 acre

AG4632, MG 4.6, on average yielded 9.1 bu acre^{-1} higher and returned \$80 acre^{-1} more than the RY4620, MG 4.6 at site 2 (table 12). Irrigation increased yield, and returns by an average of 19.7 bu acre^{-1} and \$140 acre^{-1}, respectively, due to increases in seed weight. No difference was found among initiation treatments. The 14 July initiation treatment applied 5.2 in. less water than the 10 June initiation treatment.

Table 12. Initiation date, water applied, irrigation costs, yields, yield components, returns, and water use by initiation treatment for furrow irrigated soybean irrigation initiation study at site 2, Dundee/Forestdale soil, Tribbett, Mississippi, in 2015.

Init Date	10 June	15 June	19 June	24 June	14 July	Non-Irr	Average[a,c,e,g]
Irr (in acre^{-1})	18.3	17.5	15.8	14.4	13.1		
Irr Cost (($ acre^{-1})	$111	$109	$106	$103	$100	$73	
Yield (bu acre^{-1})							
RY4620	51.7	52.3	51.7	51.9	52.0	32.3	48.7 b
AG4632	60.9	60.0	63.0	59.7	61.7	41.3	57.8 a
Average[b]	56.3 a	56.2 a	57.4 a	55.8 a	56.9 a	36.8 b	
Seed No. (seed m^{-2})							
RY4620	2716	2753	2752	2659	3087	2084	2675 b
AG4632	3272	3358	3051	3311	2590	2658	3040 a
Average[d]	2994 a	3055 a	2901 a	2985 a	2838 a	2371 a	
Seed wt. (g 100^{-1})							
RY4620	13.0	13.1	13.0	12.7	13.3	10.5	12.6 b
AG4632	14.1	13.9	14.1	13.7	13.8	10.4	13.3 a
Average[f]	13.6 a	13.5 a	13.6 a	13.2 a	13.6 a	10.5 b	
Mean Return ($ acre^{-1})							
RY4620	$343	$350	$349	$353	$357	$211	$327 b
AG4632	$424	$418	$448	$421	$442	$290	$407 a
Average[h]	$383 a	$384 a	$398 a	$387 a	$399 a	$250 b	
SIWUE (bu in.$^{-1}$)							
RY4620	1.06	1.14	1.23	1.36	1.50		
AG4632	1.07	1.07	1.38	1.28	1.56		

[a] Variety treatment yield means followed by a common letter range are not different ($p<0.05$; LSD = 1.3 bu acre^{-1}).
[b] Irrigation initiation treatment yield means followed by a common letter range are not different ($p<0.05$; LSD = 2.3 bu acre^{-1}).
[c] Variety treatment seed number means followed by a common letter range are not different ($p<0.05$; LSD = 272 seed m^{-2}).
[d] Irrigation initiation treatment seed number means followed by a common letter range are not different ($p<0.05$; LSD = ns; seed m^{-2}).
[e] Variety treatment seed weight means followed by a common letter range are not different ($p<0.05$; LSD = 0.3 g 100^{-1}).
[f] Irrigation initiation treatment seed weight means followed by a common letter range are not different ($p<0.05$; LSD = ns; g 100^{-1}).
[g] Variety treatment return means followed by a common letter range are not different ($p<0.05$; LSD = \$12 acre^{-1}).
[h] Irrigation initiation treatment return means followed by a common letter range are not different ($p<0.05$; LSD = \$20 acre^{-1}).

Yields and returns were increased by an average of 15.2 bu acre^{-1} and \$132 acre^{-1} with P49T97R as compared to RY4620, both MG 4.6, at site 3 (Table 13). Irrigated yields of 63.9 to 70.2 bu acre^{-1} and irrigated returns of \$465 to \$512 acre^{-1} were higher than the NI 53.9 bu acre^{-1} yield and \$401 acre^{-1} return due to increased seed weight. The 24 June initiation had lower yield than the 10 June initiation but the 10 June initiation yield was not different than the 20 June, 14 July, and 18 July initiations. No difference in returns was found among initiations treatments. The 18 July initiation treatment applied 4.2 inches less than the 10 June initiation treatment.

Table 13. Initiation date, water applied, irrigation costs, yields, yield components, returns, and water use by initiation treatment for furrow irrigated soybean irrigation initiation study at site 3, Bosket/Dubbs soil, Stoneville, Mississippi, in 2015.

Init Date	10 June	20 June	24 June	14 July	18 July	Non-Irr	Average[a,c,e,g]
Irr (in acre^{-1})	9.2	7.6	6.6	5.9	5.0	0.0	
Irr Cost ((\$ acre^{-1})	\$99	\$96	\$94	\$92	\$90	\$80	
Yield (bu acre^{-1})							
RY4620	61.9	61.6	54.8	59.2	59.8	47.9	57.5 b
P49T97R	78.5	76.5	73.0	74.4	73.5	60.0	72.7 a
Average[b]	70.2 a	69.0 ab	63.9 b	66.8 ab	66.7 ab	53.9 c	
Seed No. (seed m^{-2})							
RY4620	2960	3061	3015	2866	2902	2449	2875 b
P49T97R	3323	3237	3287	3312	3088	2989	3206 a
Average[d]	3141 a	3149 a	3151 a	3089 a	2995 a	2719 a	
Seed wt. (g 100^{-1})							
RY4620	14.9	14.2	13.2	13.8	14.0	11.8	13.6 b
P49T97R	15.9	15.3	14.6	15.0	14.6	12.9	14.7 a
Average[f]	15.4 a	14.7 ab	13.9 b	14.4 ab	14.3 b	12.4 c	
Mean Return (\$ acre^{-1})							
RY4620	\$438	\$441	\$384	\$426	\$435	\$347	\$412 b
P49T97R	\$586	\$574	\$547	\$562	\$557	\$455	\$547 a
Average [h]	\$512 a	\$508 a	\$465 a	\$494 a	\$496 a	\$401 b	
SIWUE (bu in.$^{-1}$)							
RY4620	1.53	1.80	1.03	1.92	2.38		
P49T97R	2.03	2.18	1.97	2.46	2.71		

[a] Variety treatment yield means followed by a common letter range are not different ($p<0.05$; LSD = 2.3 bu acre^{-1}).
[b] Irrigation initiation treatment yield means followed by a common letter range are not different ($p<0.05$; LSD = 5.3 bu acre^{-1}).
[c] Variety treatment seed number means followed by a common letter range are not different ($p<0.05$; LSD = 229 seed m^{-2}).
[d] Irrigation initiation treatment seed number means followed by a common letter range are not different ($p<0.05$; LSD = ns; seed m^{-2}).
[e] Variety treatment seed weight means followed by a common letter range are not different ($p<0.05$; LSD = 0.4 g 100^{-1}).
[f] Irrigation initiation treatment seed weight means followed by a common letter range are not different ($p<0.05$; LSD = 1.0 g 100^{-1}).
[g] Variety treatment return means followed by a common letter range are not different ($p<0.05$; LSD = \$20 acre^{-1}).
[h] Irrigation initiation treatment return means followed by a common letter range are not different ($p<0.05$; LSD = \$47 acre^{-1}).

Initiation Parameters

A window, denoted the Window of Opportunity (WOP), is drawn and highlighted around the two to five initiation treatments where yields and were maximized yet no statistical difference in yield and net return for each year were observed (fig. 2-4). The only exception is in 2015, site 1, the HBK4650, MG 4.6 variety where the 17 June initiation had higher returns than all other initiations (fig. 2d). Attention should be focused on the drier side or last initiation timing within the WOP to maximize yield with least amount of water. The longer irrigation initiation can be delayed without reducing yield, the more opportunity to capture rainfall which will reduce pumping requirements. In several cases a rainfall event occurred ahead of an initiation treatment giving relief to higher SWP values than occurred at the initiation date. This rainfall event could be considered as the actual initiation date for that treatment. Table 14 lists the initiation parameter values monitored in this study (growth stage, SWP, and SWD) that occurred on the drier side of this window or at the occurrence of a rainfall event that occurred ahead of that initiation treatment on the drier side of the window.

Table 14. Growth stage and soil moisture data for the last initiation date of each year that did not statistically reduce yield in irrigation initiation studies at the Delta Research and Extension Center, Stoneville, Mississippi.

Planting Date	Year	Variety	Initiation Date	Growth Stage	Average SWP [a] (kPa)	SWD [b] (in.)	ΔYield [c] (bu acre^{-1})	SIWUE [d] (bu in.$^{-1}$)
a) Site 1, furrow irrigated, Sharkey SiCL soil, Stoneville, Mississippi.								
21 May	2012	Halo 4:65 Halo 4:94	2 July	R2 V8	48	2.6	26.7	2.2
30 May	2013	Halo 4:65 Halo 4:94	14 July	R2 R1	48	3.2	25.5	2.3
7 May	2014	Halo 4:65 Halo 4:94	NA 14 July	NA R3	NA 121	NA 5.1	NS 4.0	NA 0.8
9 April	2015	HBK4650 HBK4950	17 June 24 June	R3 R2	51 117	1.9 3.4	16.9 24.1	2.2 2.3
b) Site 2, furrow irrigated, Dundee/Forrestdale soil, Tribbett, Mississippi.								
30 April	**2013**	**RY4620** AG4632	**24 June**	**R2**	**78**	**3.6**	**29.3**	**1.9**
4 May	2014	NKS46L2 AG4632	NA	NA	NA	NA	NS	NA
2 May	2015	RY4620 AG4632	24 June	R4	97	3.4	20.1	1.5
c) Site 3, sprinkler irrigated on a Bosket/Dubbs and Bosket/Commerce soil, Stoneville, Mississippi.								
23 April	**2013**	**RY4620** P94Y82	**25 June**	**R2**	**62**	**4.2**	**13.4**	**2.0**
5 May	2014	NKS46L2 P94Y82	NA	NA	NA	NA	NS	NA
1 May	2015	RY4620 P49T97R	25 June	R2	99	3.8	12.8	2.5

[a] Average soil water potential, averaged over three depths and all sensor sites that were non-irrigated at initiation date shown.
[b] Calculated soil water deficit at initiation date shown.
[c] Average change in yield between yield of initiation treatment shown and the non-irrigated treatment.
[d] Seasonal irrigation water-use efficiency, yield increase as compared to non-irrigated divided by irrigation water applied.

Growth Stage

In practice irrigations are initiated during early reproductive development, R1-R2, and irrigation is continued through seedfill, R6-R6.5, to ensure maximum yield. This methodology is excellent in some years but in others is not efficient use of water. Research has indicated that soybean are more sensitive to drought stress during podset and podfill, R3-R5, affecting seed number, than during vegetative stages through flowering R2, affecting mainly growth and development of the plant (Heatherly and Ray, 2007). Yet, irrigation can be beneficial prior to R3 on shallow soils and in years of subnormal rainfall during early growth stages. In these irrigation initiation studies yields were increased when initiations or rainfall were received at or before V8-R4 at site 1, R2-R4 at site 2, and R2 at site 3 in the years when soybean responded to irrigation (table 14). At all sites in 2014, the MG 4.6 varieties did not respond to irrigation, although the MG 4.9 variety did show a response to irrigation. This data suggest that drought stress conditions that reduce yield can occur at any time from late vegetative stages to full seed and the occurrence of this stress varies likely due to differences in environmental conditions and planting dates. The task is to define the conditions that cause these yield reducing stresses.

Soil Water Potential

Changes in SWP readings indicated root activity at all three sensor depths each year at each site at the time of initiation. SWP readings were averaged over non-irrigated sensor sites, varieties, and sensor installation depths for each initiation timing, site and year when there were no Initiation x Variety interactions. If there was an interaction SWP readings were averaged over sensor sites and sensor depths for each initiation timing, variety, site and year. The SWP readings were highly variable as indicated by horizontal error bars representing the standard deviation of SWP readings from the treatment replicates (figure 2a-d, 3a-c, and 4a-c). Differences in soil texture, root density, and rooting depth by site likely attributed to this variation. Additionally, granular matrix sensors are reported to have a slow response to rapid drying of the soil or partial rewetting of the soil (McCann et. al., 1992), and need to be adjusted due to soil temperature (Clinton and Shock, 1998).

SWP values on the drier side of the WOP varied from 48 - 121 kPa for site 1, 78 – 97 kPa for site 2 and 62 – 99 kPa for site 3a (table 14) when there was a response to irrigation. When there was no response to irrigation in 2014, a cool year, SWP values climbed as high as 113, 114, and 70 kPa for sites 1, 2, and 3b, respectively, before rainfall relieved this potential stress. These values are all higher than the 196, 159, 153, and 117 kPa calculated from the soil water retention curve that indicates when 50% of the available water holding capacity (AWHC) has been removed from sites 1, 2, 3a, and 3b, respectively.

The greatest variation (48-121 kPa) in trigger values occurred at site 1. If using SWP alone to schedule irrigations, the safe recommendation is to initiate at the greater SWP value of 48 kPa that would ensure maximum yield every year but at the expense of over irrigating in some years on this Sharkey soil. Scheduling irrigation at 121 k Pa would minimize irrigation water applied but risk reducing yield in some years. The difference of 48 to 121 kPa would equate to 7 to 12 days difference in triggering initiation under dry conditions when using a range of average SWP rates of 6 to 10 kPa d^{-1} occurring in this study. The range in trigger values for sites 2 and 3 which had one less year of study were not as large as site 1. This lower variation in range of trigger values may be related to the water characteristics of the soils at these sites, but more years of study on these soils could result in a larger variation.

This variability of trigger values is a concern when trying to recommend a single SWP trigger value that will optimize initiations to maximize yield and minimize water applied for these soil types every year. The sensors give good information on moisture in the soil but other parameters may be needed in conjunction with to directly or indirectly quantify the environmental stresses on the plant to finely tune when a yield reducing drought stress is occurring.

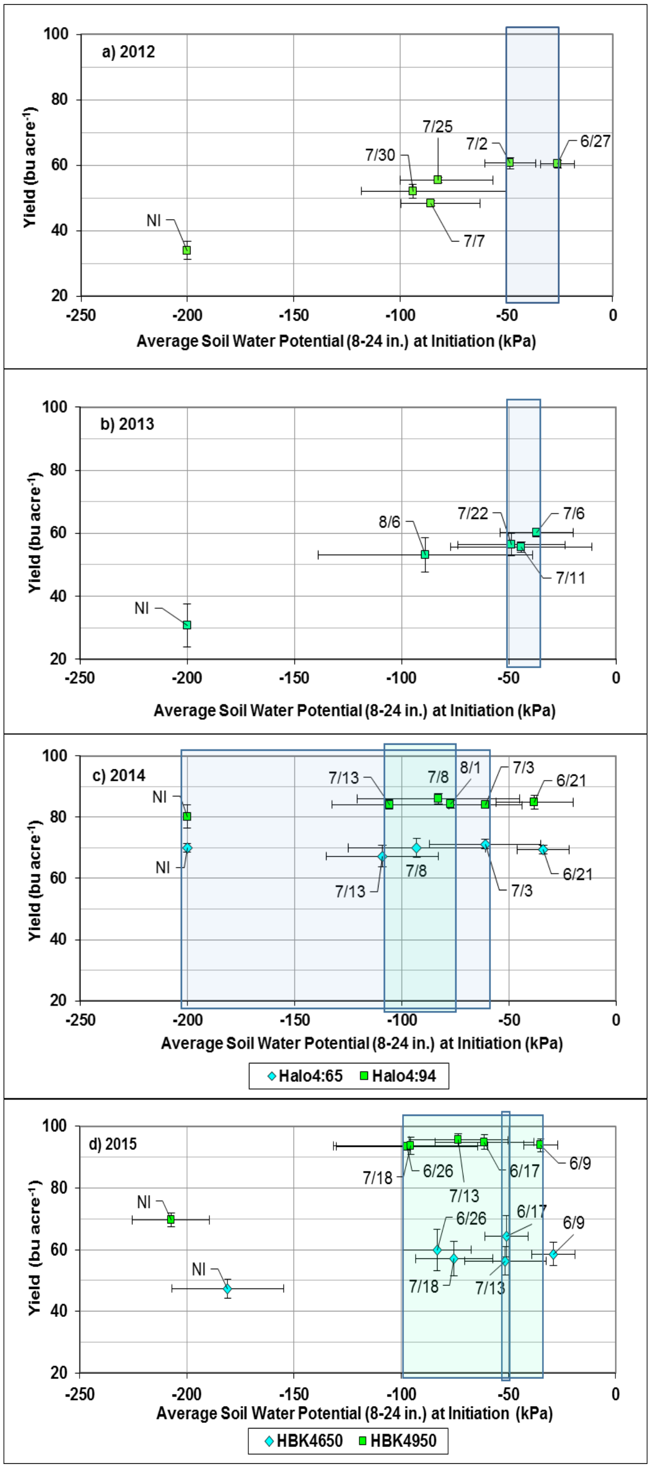

Figure 2. Average soybean yield and soil water potential at irrigation initiation (average of sensor readings from 8, 16, and 24 in. depths) for a furrow irrigated initiation study on a Sharkey soil, Delta Research and Extension Center, Stoneville, MS 2012-2015. Highlighted area represents the window of opportunity (WOP) which indicates times of initiation where no significant differences among yield and economic net returns were observed.

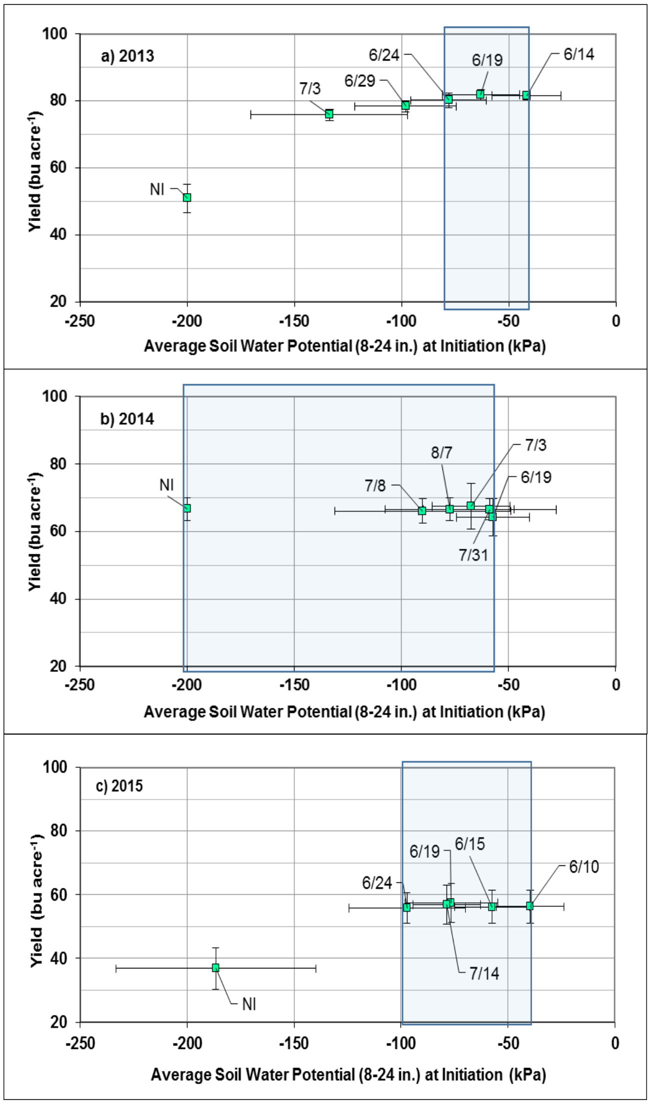

Figure 3. Average soybean yield and soil water potential at irrigation initiation (average of sensor readings from 9, 18, and 27 in. depths) for a furrow irrigated initiation study on a Dundee/Forestdale soil, Tribbett, MS 2013-2015. Highlighted area represents the window of opportunity (WOP) which indicates times of initiation where no significant differences among yield and economic net returns were observed.

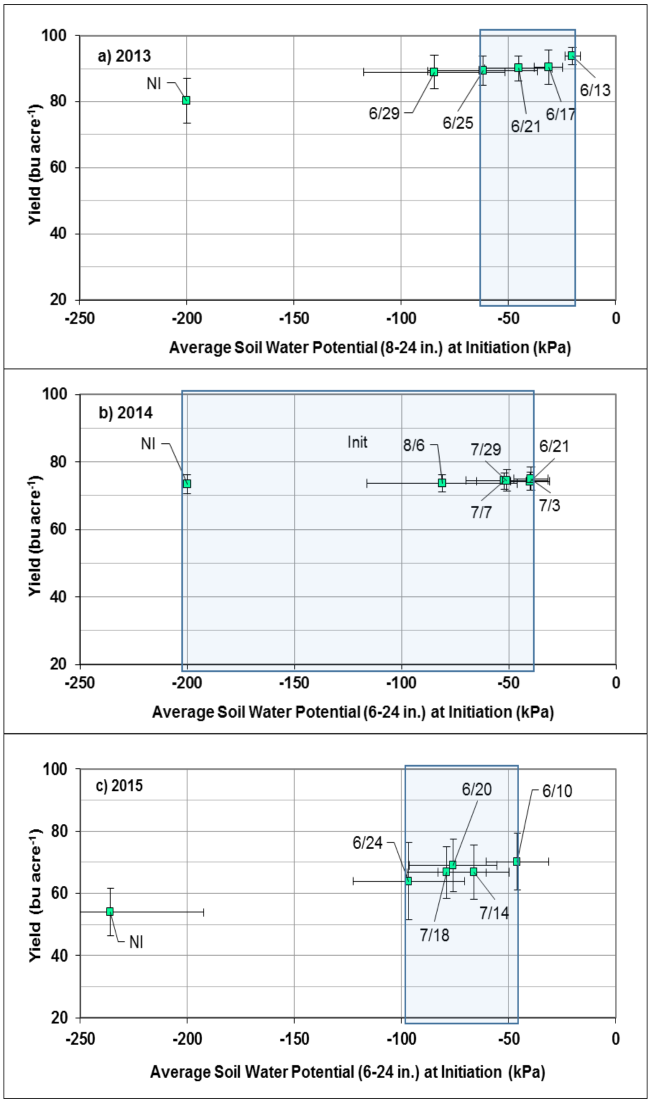

Figure 4. Average soybean yield and soil water potential at irrigation initiation (average of sensor readings from 6, 15, and 24 in. depths) for a furrow irrigated initiation study on a Bosket/Dubbs (a and c) and Bosket/Commerce (b) soil, Delta Research and Extension Center, Stoneville, MS 2013-2015. Highlighted area represents the window of opportunity (WOP) which indicates times of initiation where no significant differences among yield and economic net returns were observed.

Soil Water Deficit

The SWD estimates at time of initiation from the water-balance spreadsheet were calculated starting at each planting date for each site and year. These estimates are plotted for each site and each year in figures 5 - 7. SWD values on the drier side of the WOP varied from 2.6 – 5.1 in. for site 1, 3.4 to 3.6 in. for site 2, and 3.8 to 4.2 in. for site 3a in 2012, 2013, and 2015 (table 14) when responding to irrigation, while SWD values climbed to 5.1, 4.7, and 4.7 in., by the last initiation, when not responding to irrigation in 2014. These values are higher than the 2.0, 2.4, 2.6, and 2.1 in. estimated from the soil water retention curves, equal to 50% of the available water holding capacity (AWHC) for a 30 in. soil depth, from sites 1, 2, 3a, and 3b, respectively. The water-balance model relies on estimates of all of its components, so errors in the estimates would lead to errors in the final SWD values. Over-estimating ET_c, due to high values of ET_r or K_c, as well as lengths of the maximum water use period and/or magnitude, and over-estimating ET_c when the soil was not well-watered, could lead to overly large estimates of SWD. Under-estimating I_e and P_e would also result in larger SWD values.

There are several methods of calculating $ET_{c,} = ET_r K_c$ such as FAO-56, Hargreaves, and Turc methods (Fisher and Pringle, 2013), and P_e, such that SWD trigger values can be different for each and need to be determined for each. For the method of calculating SWD described in this text, the trigger values varied from 2.6 – 5.1 in. for site 1, 3.4 to 4.7 in. for site 2, and 3.8 to 4.2 in. for site 3a, a difference in the maximum allowable SWD of 2.5, 1.3, and 0.4 in., respectively. The difference of 2.5 in. for site 1 would equate to eight to ten days difference in triggering initiation when using an average ET_c of 0.24 in. d^{-1} and 0.3 in. d^{-1}, respectively, during this time period. The differences of 1.3 and 0.4 in. for sites 2 and 3a would equate to four to five days and one to two days difference, respectively.

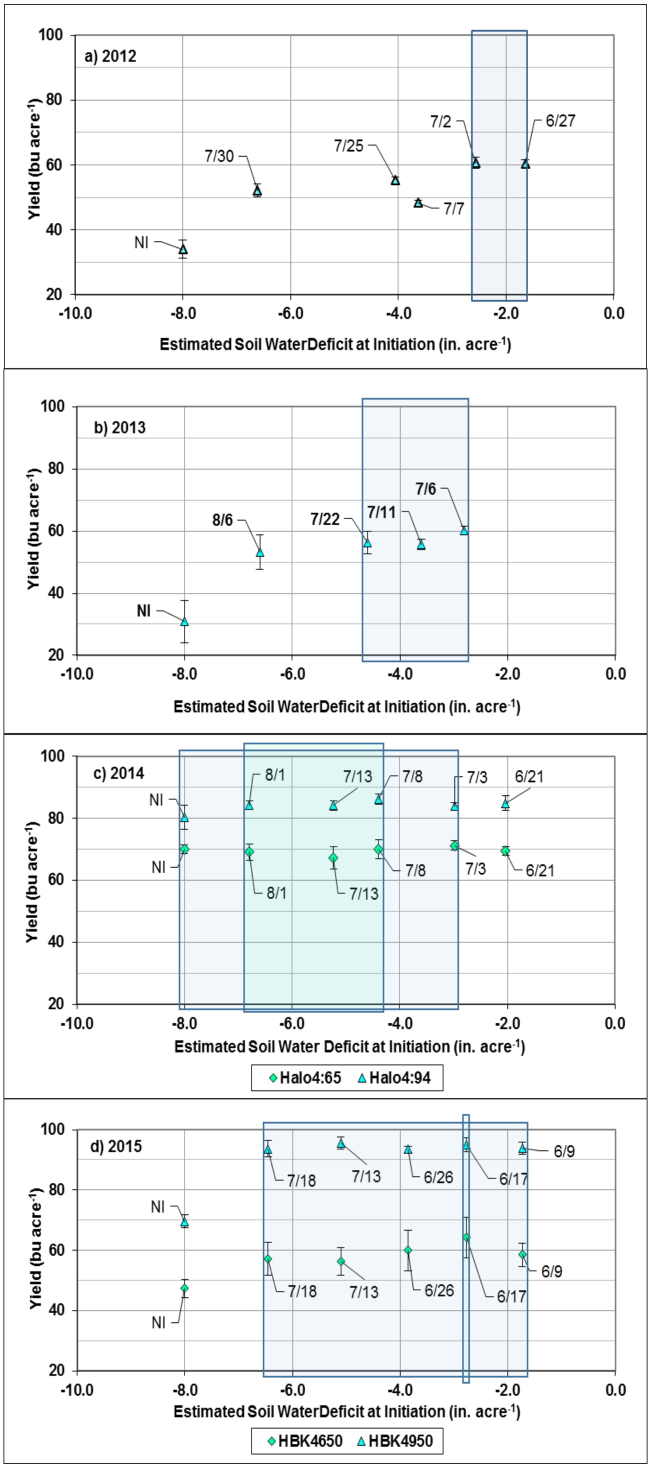

Figure 5. Average soybean yield and soil water deficit at irrigation initiation (average of sensor readings from 8, 16, and 24 in. depths) for a furrow irrigated initiation study on a Sharkey soil, Delta Research and Extension Center, Stoneville, MS 2012-2015. Highlighted area represents the window of opportunity (WOP) which indicates times of initiation where no significant differences among yield and economic net returns were observed.

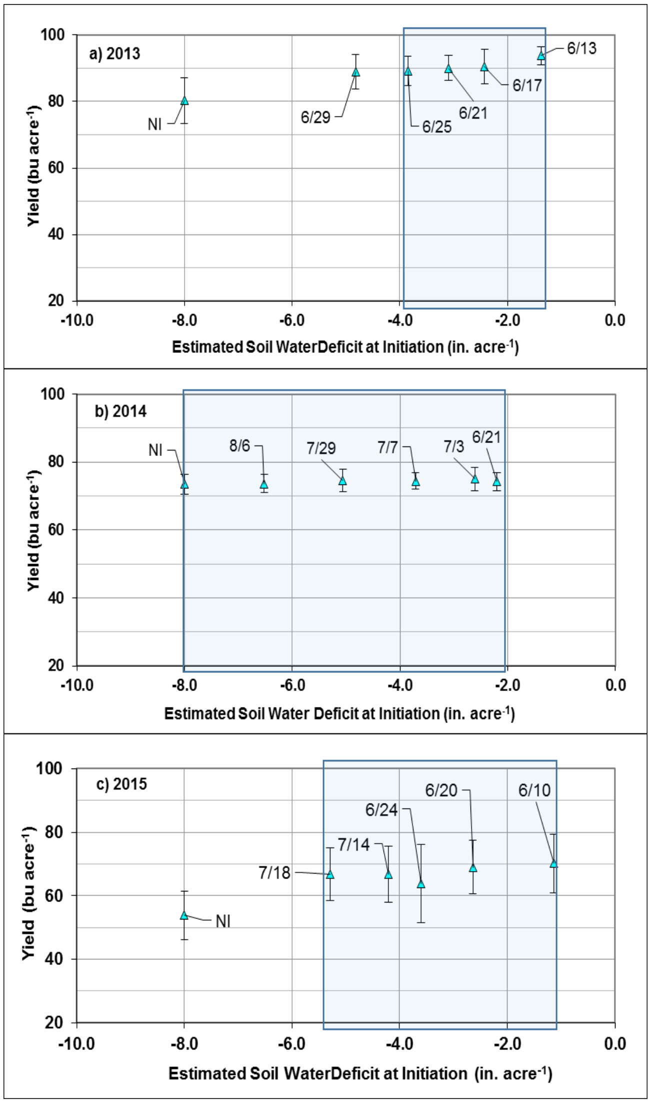

Figure 3. Average soybean yield and soil water deficit at irrigation initiation (average of sensor readings from 9, 18, and 27 in. depths) for a furrow irrigated initiation study on a Dundee/Forestdale soil, Tribbett, MS 2013-2015. Highlighted area represents the window of opportunity (WOP) which indicates times of initiation where no significant differences among yield and economic net returns were observed.

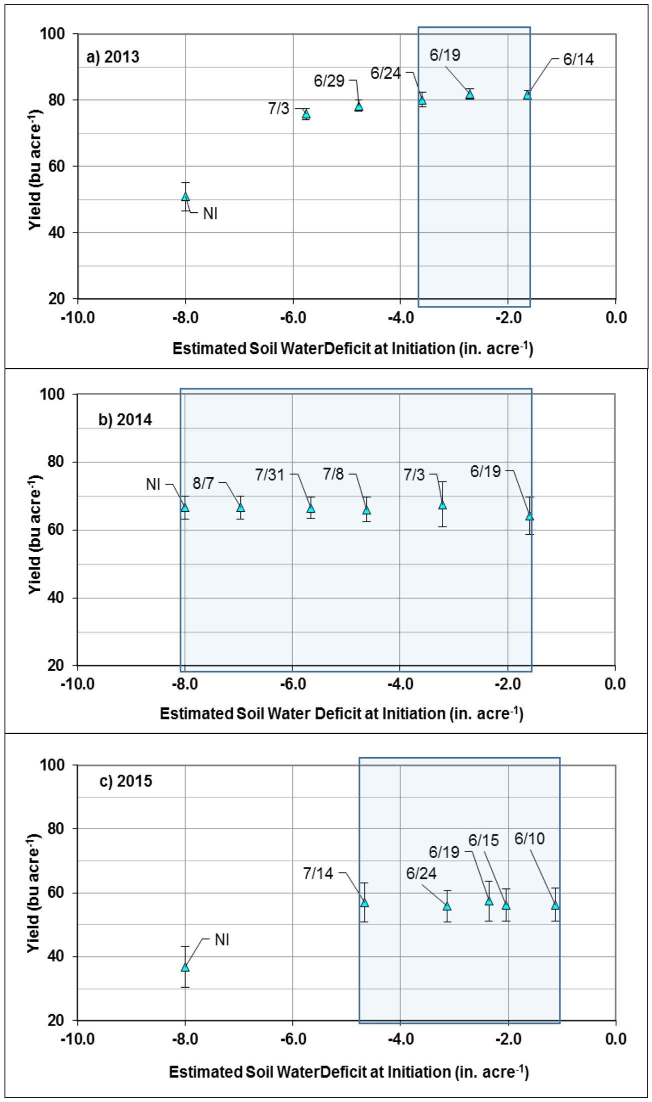

Figure 4. Average soybean yield and soil water potential at irrigation initiation (average of sensor readings from 6, 15, and 24 in. depths) for a furrow irrigated initiation study on a Bosket/Dubbs (a and c) and Bosket/Commerce (b) soil, Delta Research and Extension Center, Stoneville, MS 2013-2015. Highlighted area represents the window of opportunity (WOP) which indicates times of initiation where no significant differences among yield and economic net returns were observed.

Temperature Interactions

Research concerned about global warming has shown nonlinear relationships between air temperature and yields for major row crops (Schlenker and Roberts, 2009). Soybean yields increased with air temperatures up to an average growing season temperature of 86°F but above these thresholds yield declined rapidly.

Heat stress can occur in soybean when daily $T_{a\ max}$ rise above some threshold, causing yield loss, especially if soil moisture is limiting. Extended periods of high $T_{a\ max}$ of 95°F can reduce soybean yield during reproductive growth (Gibson and Mullen, 1996; Puteh et al., 2013; Thuzar et al., 2010) where some research suggests that the maximum optimum temperature is 95°F (Board and Kahlon, 1997). High nighttime temperatures ($T_{a\ min}$) of 86°F has been shown to decrease soybean yield slightly (<10%) (Peters et al., 1971; Huxley et al., 1976) or not at all (Gibson and Mullen, 1996). From an irrigation standpoint, irrigating to minimize the negative effect of daily high $T_{a\ max}$ and $T_{a\ min}$ might have when one or both get above certain thresholds is of interest.

A 3D plot (fig. 8) was drawn to show the relationship that the average $T_{a\ max}$ and cumulative rainfall (May-August growing season) have with NI soybean yield for site 1, Sharkey soil, for 2012–2013. Site 1 was used since it had the most years of data. A 3D, plane, nonlinear regression of this data resulted in the following equation:

$$\text{NI yield} = 484.6 + 7.0 * (\text{average } T_{a\ max}) -6.3 * (\text{Cumulative rainfall})$$

Adjusted R-square = 0.81

The higher average $T_{a\ max}$ and the lower the cumulative rainfall, the lower the NI yield, while the lower average $T_{a\ max}$ and the higher the cumulative rainfall, the higher the NI yield. A similar relationship was found with average $T_{a\ min}$. These relationships warrant a closer look at temperature and its effect on irrigation initiation. For the purpose of this investigation an extended heat period (EHP) will be defined as a period of time lasting three days or more with $T_{a\ max}$ >= 95°F and/or $T_{a\ min}$ >=75°F.

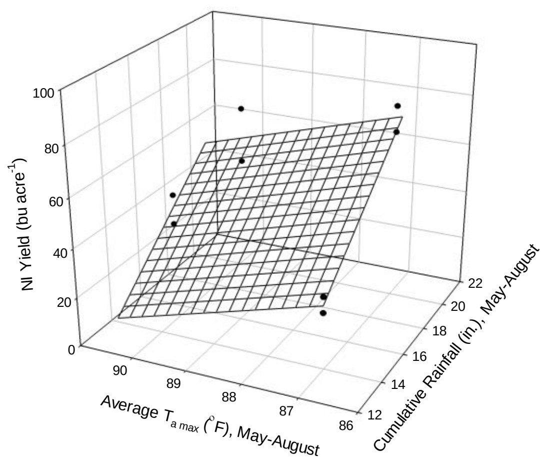

Figure 8. Non-irrigated yield as related to Average $T_{a\ max}$ and Cumulative Rainfall for the May-August period of the growing season, for a soybean irrigation initiation study, furrow irrigated, on a Sharkey soil, Stoneville, Mississippi, for 2012-2015. 3D, Plane equation; NI yield = 484.6 + 7(Rainfall) + -6.3($T_{a\ max}$); Adjusted Rsquare = 0.81

An EHP with $T_{a\ max}$ averaging 96.5°F lasting 11 d started 28 June for late planted soybean at site 1 in 2012 (fig. 9a). The 2 July initiation, SWP 48 kPa, SWD 2.6 in. (fig. 2a, 5a), which occurred in the middle of this EHP increased yield over later initiations.

At site 1, in 2013, an EHP, average $T_{a\ max}$ 96.5°F, lasting 11 d (fig. 9b) started 3 d before the 6 August initiation, SWP 89 kPa; SWD 5.4 in. (fig. 2b, 5b), which yielded less than the 22 July initiation, SWP 49 kPa; SWD 4.6 in. On earlier planted soybean at site 2 and 3, the initiations on the drier side of the WOP, 24 June, SWP 78 kPa; SWD 3.6 in. (fig. 3a, 6a), and 25 June, SWP 62 kPa; SWD 4.2 in. (fig. 4a, 7a), respectively, yielded higher than the 29 June initiation for site 2, SWP 98 kPa; SWD 4.6 in., and site 3, SWP 85 kPa; SWD 5.2 in., in the absence of an EHP.

In 2014 with cool temperatures and normal rainfall, there was no response to irrigation with the MG 4.6 varieties at any field site. The MG 4.6 varieties which reached R6.5 on 17 August, sites 2 and 3, and 20 August, site 1, did not experience an EHP (fig. 9c, 10b, 11b). In the absence of an EHP, SWP values climbed as high as 113-121, 114, and 70 kPa, and SWD values climbed as high as 5.1, 4.7, and 4.7 in. for sites 1(MG 4.6 - 4.9), 2, and 3, respectively, before rainfall rewet the soil on 17 July, site 1, and 11 July, sites 2 and 3. The later maturing MG 4.9 variety that reached R6.5 on 27 August, at site 1, did respond positively, 4-6 bu $acre^{-1}$, to irrigation. An EHP, average $T_{a\ max}$ 95°F, started on 21 August, lasted 10 days (fig. 9c, 10b, and 11b) and occurred after the MG 4.6 but before the MG 4.9 matured. The last initiation date occurred 1 August with a subsequent irrigation on 21 August for the MG 4.9 resulting in an SIWUE of 0.8 bu in^{-1}, lower than the 2.2-2.3 bu in^{-1} calculated for site 1 in 2012, 2013, and 2015 (table 14). The 1 August irrigation, SWP 80 kPa; SWD 6.0 in. (fig. 2c, 5c), did not prove effective for the MG 4.6 and likely was not necessary for the MG 4.9. If only the 21 August irrigation, which occurred at the beginning of the extended heat period, had been applied and it had yielded the same, the resulting SIWUE would increase to 1.5 bu in^{-1}. This would still be lower than the other years for this site but is plausible since the increase in yield was due only to an increase in seed weight.

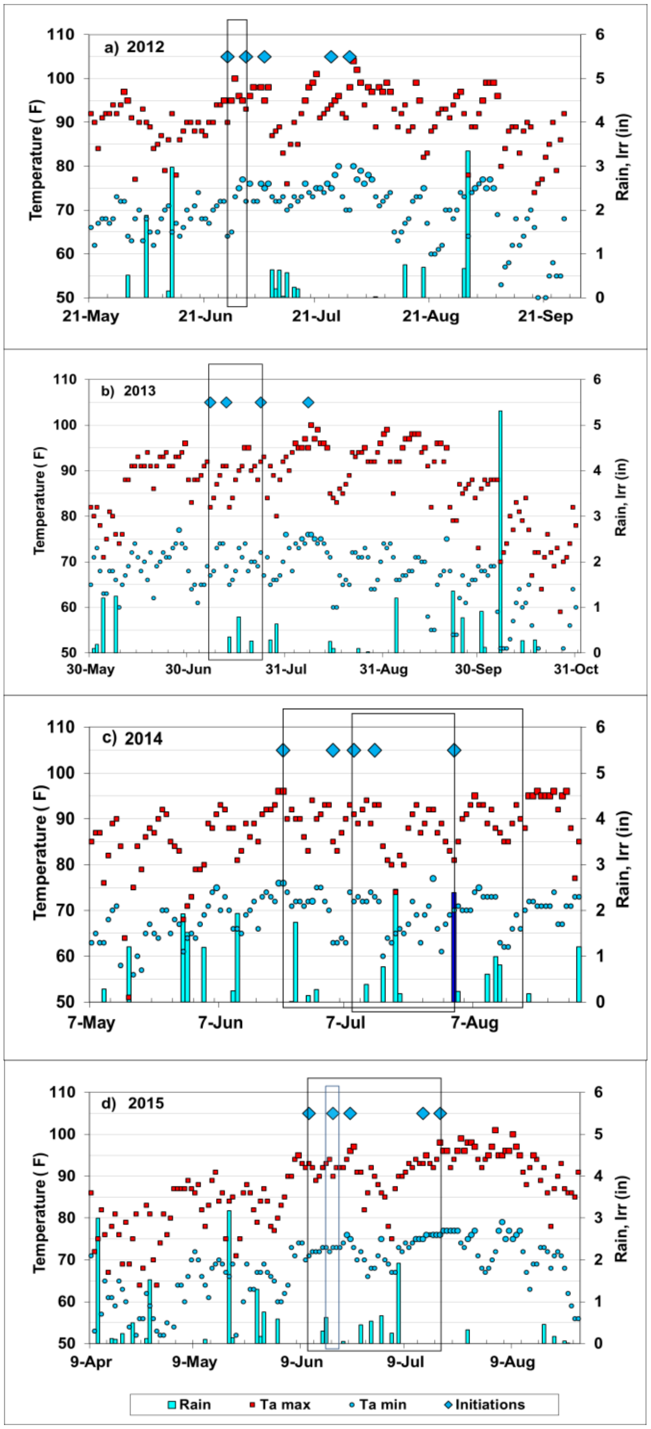

Figure 9. Daily maximum and minimum air temperature, rainfall and irrigation initiation date for a soybean irrigation initiation study, furrow irrigated, on a Sharkey soil, Stoneville, Mississippi, for 2012-2015. Highlighted area represents the window of opportunity (WOP) which indicates times of initiation where no significant differences among yield and economic net returns were observed.

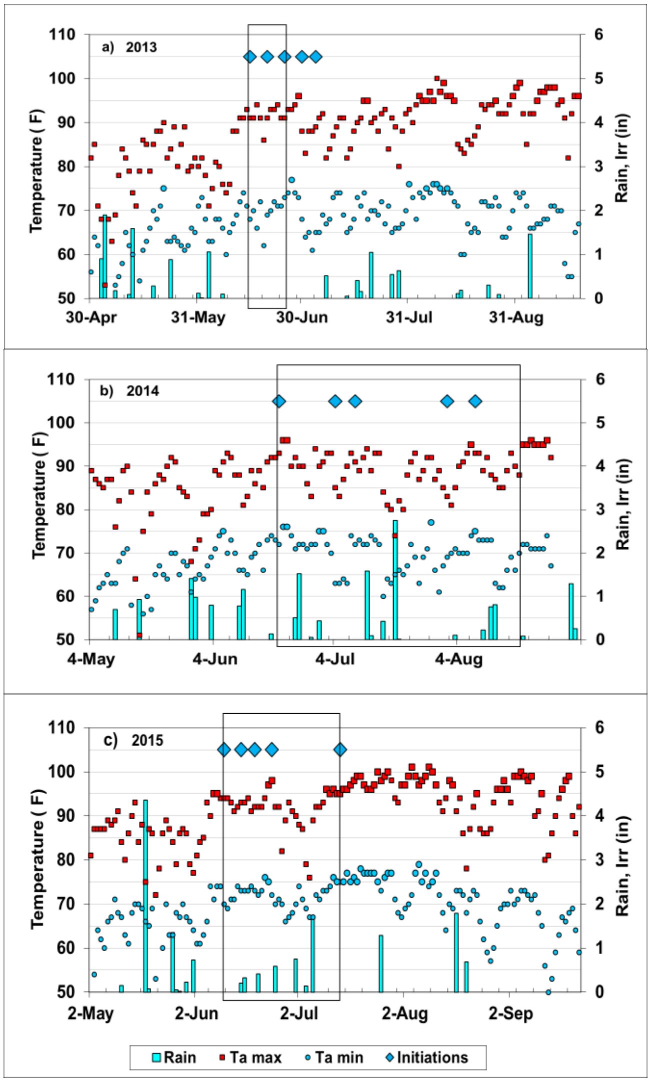

Figure 10. Daily maximum and minimum air temperature, rainfall and irrigation initiation date for a soybean irrigation initiation study, furrow irrigated, on a Dundee/Forestdale soil, Tribbett, Mississippi, for 2013-2015. Highlighted area represents the window of opportunity (WOP) which indicates times of initiation where no significant differences among yield and economic net returns were observed.

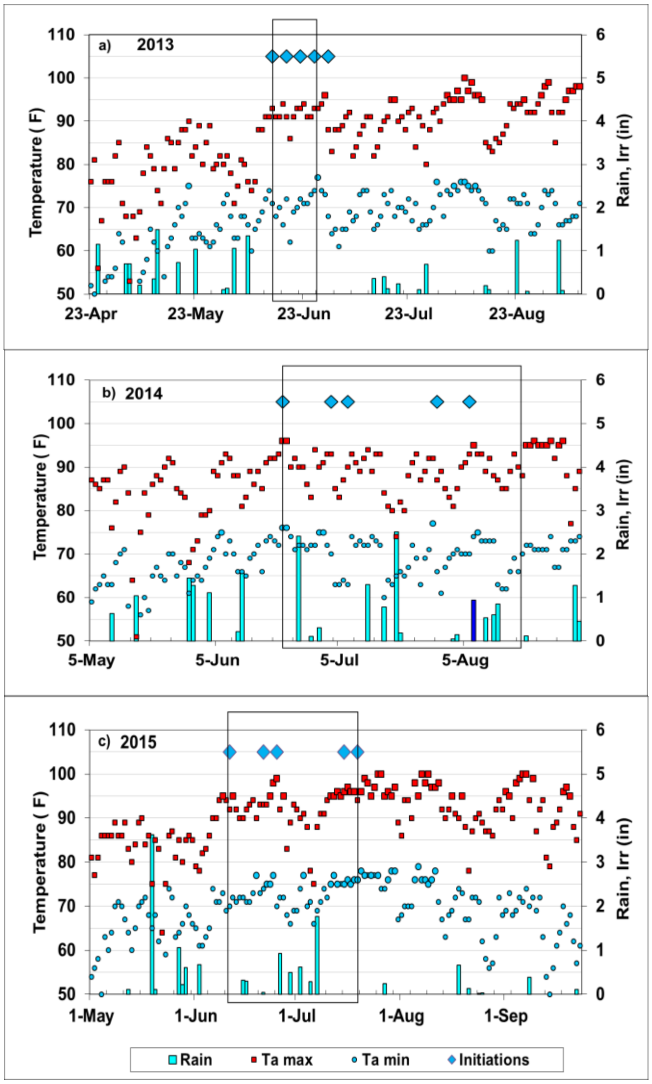

Figure 11. Daily maximum and minimum air temperature, rainfall and irrigation initiation date for a soybean irrigation initiation study, sprinkler irrigated, on a Bosket/Dundee soil, Stoneville, Mississippi, for 2013-2015. Highlighted area represents the window of opportunity (WOP) which indicates times of initiation where no significant differences among yield and economic net returns were observed.

In 2015, at site 1, the MG 4.6 and MG 4.9 varieties responded differently. The 17 June initiation, SWP 51 kPa; SWD 1.9 in. (fig. 2d, 5d) was the optimum initiation for the MG 4.6 variety and occurred just ahead of a 2 d period with high $T_{a\ max}$ of 95°F and high $T_{a\ min}$ of 75.5°F (fig. 9d). The 18 July initiation, SWP 96 kPa; SWD 6.5 in. (fig. 2d, 5d) at site 1 which was on the drier side of the WOP for the MG 4.9 variety occurred the day before a 24 d EHP with high average $T_{a\ max}$ of 96.1°F and 6 d after a 18 day EHP with high average $T_{a\ min}$ of 75.8°F started. The 14 July, SWP 79 kPa; SWD 4.7 in. (fig. 3c, 6c) and 18 July, SWP 79 kPa; SWD 5.3 in. (fig. 4c, 7c) initiations on the drier side of the WOP for the later planted MG 4.6 soybean at site 2 and 3, respectively, experienced a similar EHPs (fig. 10c and 11c). The optimum initiation of MG 4.6 at site 1, 17 June, occurred a month earlier than the other varieties is likely due to higher sensitivity to heat (Puteh et al., 2013).

Irrigation initiation timing was influenced by the presence of an EHP with $T_{a\ max}$ of >=95°F or combined with $T_{a\ min}$ of >=75°F at site 1 in 2012, 2013, 2014 (MG 4.9), and 2015, and at site 2 and 3 in 2015, while initiation timing was not influenced by the presence of an EHP at site 1 in 2014 (MG 4.6) and at sites 2 and 3 in 2013 and 2014. An EHP with only a $T_{a\ min}$ of >=75°F occurred 5 d ahead of an EHP with high average $T_{a\ max}$ and $T_{a\ min}$ in 2015, but it is not clear if the EHP with $T_{a\ min}$ of >=75°F influenced initiation timing.

In the presence of an EHP, SWP and SWD values at initiation on the drier side of WOP, occurring in the middle of the EHP, were as low as 48 kPa and 2.6 in. at site 1, in 2012. In 2013–2015, SWP and SWD values at initiation, occurring ahead of or at the onset of an EHP, were 49, 80, and 96 kPa and 4.6, 6.0, and 6.5 in., respectively. In the absence of an EHP at site 1 for the MG 4.6 and MG 4.9 varieties, SWP and SWD values climbed as high as 113 and 121 kPa, respectively, and 5.1 in., in 2014, before a rainfall events rewet the soil. This data suggests that in the presence of an EHP, SWP and SWD trigger values likely need to be lower than SWP and SWD trigger values in the absence of an EHP at site 1.

At sites 2 and 3a, in the presence of an EHP, SWP and SWD values at initiation on the drier side of the WOP, occurring ahead of the EHP, were 79 and 79 kPa and 4.7 and 5.3 in., respectively, in 2015. In the absence of an EHP, at sites 2 and 3b, in 2014, SWP and SWD values climbed as high as 114, and 70 kPa, and 4.7 and 4.7 in., respectively, before rainfall rewet the soil. However, in 2013, for sites 2 and 3a, SWP and SWD values at initiation on the drier side of the WOP were 78 and 62 kPa and 3.6 and 4.2 in., respectively. The data from 2014 in the absence of an EHP and 2015 in the presence of an EHP of sites 2 and 3 are similar to results at site 1, but the 2013 data with its low SWP values in the absence of an EHP is contradictory. So there is not enough data at this time to make a recommendation on these soils. Other weather parameters need to be explored, such as humidity, heat index, solar radiation, and wind, to determine if there is a quantifiable condition that existed which caused the yield reducing stress in 2013 in the absence of an EHP.

Using EHP in irrigation initiation scheduling at site 1 along with SWP or SWD will result in a dual threshold recommendation. There would be a heat induced threshold (in the presence of an EHP) and a drought induced threshold (in the absence of EHP). The heat induced threshold for site 1, a Sharkey soil, would initiate irrigations at a SWP of 50 kPa or a SWD of 2.6 in. if an on-going EHP or at a SWP of >= 50 kPa or a SWD of >=2.6 in. at the onset of an EHP and rainfall is not imminent. From the data at site 1, a drought induced threshold would delay irrigation initiations until SWP of 113-121 kPa or a SWD of 5.1 in. have been reached in the absence of an on-going or forecasted EHP and rainfall is not imminent. It is likely that the drought induced threshold is more aligned with the strategy of irrigating at 50% AWHC (Kranz and Specht, 2012) and the threshold would be higher than given as it approaches the SWP value representing 50% AWHC (196 kPa) for this Sharkey soil. To use EHP in irrigation initiation scheduling, forecasted temperatures will need to be reasonably accurate. Generally, EHP with high $T_{a\ max}$ are associated with high pressure systems that linger in a region and should be forecastable.

Using EHP where valid would improve recommendations over using SWP or SWD alone, while initiating irrigations timely when a yield reducing heat stress is occurring and while capturing and utilizing more rainfall during the growing season in the absence of a heat stress. Maximizing yield while minimizing irrigation water applied.

These recommendations may not work as well on shallower soils, or in a year when winter rainfall does not recharge the soil profile. Initiating irrigations immediately ahead of a significant rainfall events has reduced yield in this study (7 July initiation in 2012, site 1; 11 July, 2013, site 1; and 24 June in 2015, site 3). These recommendation are a starting point if irrigating just one field or set but is an ending point if irrigating multiple fields or sets with the same well. Producers will need to furrow irrigate all their soybean fields irrigated by the same well before the last field or set to be irrigated reaches this recommendation or ending point. The initiation of the first field or set to be irrigated would then have to be initiated earlier, depending on how long it takes to irrigate all fields in question and taking into consideration soil differences.

Conclusions

Irrigation increased soybean yields three of the four years of the study for the MG 4.6 varieties and all four years for the MG 4.9 variety at all three sites. We describe a window of opportunity where initiating irrigations will produce maximum yields and net returns that are similar. Stress conditions that reduce yield can occur at any time from late vegetative stages to full seed on these deep soils. Initiating irrigations immediately ahead of significant rainfall events has reduced yields.

Irrigation initiation of the deep Sharkey silty clay soil, was influenced by the presence or absence of an extended heat period (three or more days of maximum air temperature >= 95°F, EHP). Using a dual threshold recommendation with soil water potential (SWP) or soil water deficit (SWD), whether in the presence (heat induced) or absence (drought induced) of an EHP is better than using SWP or SWD alone and results in recommendations with more complete information. Thus, the heat induced threshold for a furrow irrigated Sharkey SiC soil, would be to initiate irrigations at a SWP of 50 kPa or a SWD of 2.6 in. if an on-going EHP or at a SWP of >= 50 kPa or a SWD of >=2.6 in. at the onset of an EHP and rainfall is not imminent. The drought induced threshold for this soil would delay irrigation initiations until at least a SWP of 113-121 kPa or a SWD of 5.1 in. has been reached in the absence of an on-going or forecasted EHP and rainfall is not imminent.

There was not enough data to give a concise irrigation initiation recommendation for the deep Bosket/Dubbs silt loam, Bosket/Commerce loam and Dundee/Forestdale silty clay loam soil in these studies. Other weather parameters need to be examined to quantify conditions that could potentially cause a yield reducing stress.

Irrigation initiations may have to be initiated earlier than the above recommendation when taking into account multiple fields irrigated by the same well and the time it takes to irrigate all fields or sets, and taking into consideration soil differences within these fields and sets. Further irrigation initiation research needs to be conducted over years with different varieties on multiple soil types and in different regions to increase the validity and breadth of these recommendations. Research needs to evaluate temperature forecasts to determine if they are accurate enough for use in irrigation scheduling.

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References

Allen, R.G., Pereira, L.S., Raes, D. & Smith, M. (1998). Crop evapotranspiration: Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper No. 56, FAO, Rome.

Board, J. E., & Kahlon, C. S. (2011). *Soybean yield formation: what controls it and how it can be improved*. INTECH Open Access Publisher.

Evett, S. R. (2007). Soil Water and Monitoring Technology. *Irrigation of Agricultural Crops*, (irrigationofagr2), 25-84.

Fisher D. K. (2012). Open-source hardware is a low-cost alternative for scientific instrumentation and research. *Modern Instrumentation*, *2012*.

Fisher, D. K., & Pringle III, H. C. (2013). Evaluation of alternative methods for estimating reference evapotranspiration. *Agricultural Sciences*, 4: No. 8A: 51-60. *2013*.

Frederick, J.R., Camp, C.R., & Bauer, P.J. (2001). Drought-stress effects on branch and mainstream seed yield and yield components of determinate soybean. *Crop Sci.* 41:759-763.

Gibson, L. R., & Mullen, R. E. (1996). Influence of day and night temperature on soybean seed yield. *Crop Science*, *36*(1), 98-104.

Heatherly, L.G., & Ray, J.D. (2007). Soybean and Corn. In *Irrigation of agricultural crops*, 2nd Edition. 477-533. R.J. Lascano and R.E. Sojka, ed. Agron. Monogr. 30. ASA, CSSA, and SSSA, Madison, Wisc.

Hiler, E.A., & Howell, T.A. (1983). Irrigation options to avoid critical stress: an overview. In *Limitations to efficient water use in crop production*. 479-497. Taylor, H.M., Jordan, W.R., & Sinclair, T.R,. ed. ASA. Madison, Wisc.

Huxley, P. A., Summerfield, R. J., & Hughes, A. P. (1976). Growth and development of soyabean cv. TK5 as affected by tropical daylengths, day/night temperatures and nitrogen nutrition. *Annals of Applied Biology*, *82*(1), 117-133.

Irmak, S., Payero, J.O., Eisenhauer, D.E., Kranz, W. L., Martin, D.L., Zoubek, G.L., . . . Leininger, D. (2006). Watermark granular matrix sensor to measure soil matric potential for irrigation management. EC783. Cooperative Extension, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln.

Koger, T., Catchot, A., Allen, T., Zhang, L., Eubank, T., Blessitt, B., Smith, J., & Owen, L. (2010). Guide to soybean growth stages. Pub. 2588. Miss. State Univ., Ext. Ser. Mississippi State, Mississippi.

Kranz, W. L., & Specht, J. E. (2012). *Irrigating soybean*. G1367. Cooperative Extension, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln.

McCann, I.R., Kincaid, D.C., & Wang, D. (1992). Operational characteristics of the watermark model 200 soil water potential sensor for irrigation management. *Appl. Eng. in Agric. ASABE* 8(5):603-609.

MSU. (2009-2012). Delta Planning Budgets, Various Issues, Department of Agric. Economics Budget Reports. Mississippi State University.

Peters, D. B., Pendleton, J. W., Hageman, R. H., & Brown, C. M. (1971). Effect of night air temperature on grain yield of corn, wheat, and soybeans. *Agronomy Journal*, *63*(5), 809-809.

Puteh, A. B., ThuZar, M., Mondal, M. M. A., Abdullah, N. A., & Halim, M. R. A. (2013). Soybean [Glycine max (L.) Merrill] seed yield response to high temperature stress during reproductive growth stages. *Australian Journal of Crop Science*, *7*(10), 1472.

Saxton, K.E., Rawls, W.J., Romberger, J.S., & Papendick, R.L. (1986). Estimating generalized soil water characteristics from texture. *Trans. ASAE* 50(4):1031-1035.

Schlenker, W., & Roberts, M. J. (2009). Nonlinear temperature effects indicate severe damages to US crop yields under climate change. *Proceedings of the National Academy of sciences*, *106*(37), 15594-15598.

Stegman, E.C. (1983). Irrigation options to avoid critical stress: Irrigation scheduling-some applied concepts. In *Limitations to efficient water use in crop production*. 499-505. Taylor, H.M., Jordan, W.R., & Sinclair, T.R,. ed. ASA. Madison, Wisc.

Thuzar, M., Puteh, A. B., Abdullah, N. A. P., Lassim, M. M., & Jusoff, K. (2010). The effects of temperature stress on the quality and yield of soya bean [(Glycine max L.) Merrill.]. *Journal of Agricultural Science*, *2*(1), 172.

Tupper, G.R. (1995). Low-till parabolic subsoiler: A new design for reduced soil surface disturbance and power requirement. In *Proc. 1995 Southern Conservation Tillage Conference for Sustainable Agriculture*, Sp. Bull. 88-7. 90-92. Mississippi State University, Mississippi State, Miss.

Wesley, R.A., Heatherly, L.G., Elmore, C.D., & Spurlock, S.R. (1994). Effects of irrigation on corn, sorghum, and soybean in the Mississippi river alluvial plain: An economic analysis. USDA Agricultural Research Service, ARS-118, 16 pp.

YMD. (2006). Water level survey 2006 results and long term aquifer trends in the Mississippi Delta. Yazoo Mississippi Delta Joint Water Mgmt. District. Retrieved from http://www.ymd.org/pdfs/wateruse/2006%20Handout%203.pdf.

USDA NRCS OSD. Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Official Soil Series Descriptions (OSDs). Retrieved from http://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/soils/home/?cid=nrcs142p2_053587.

USDA SCS. (1974). Conservation Irrigation Guide for Mississippi. USDA Soil Conservation Service, Jackson, Miss. pp 86.

USDA. (1986). Urban hydrology for small watersheds (PDF). Technical Release 55 (TR-55) (Second ed.). NRCS, Conservation Engineering Division. Retrieved from http://www.cpesc.org/reference/tr55.pdf.

USDA AMS. Mississippi Daily Grain Report. Grain prices at Country Elevators. Various Issues. Mississippi Dept. of Agric. - USDA Market News, Jackson, Miss. Retrieved from http://www.ams.usda.gov/mnreports/JK_GR110.txt.

IMPACTS AND BENEFITS TO MISSISSIPPI SOYBEAN PRODUCERS

Stress conditions that reduce yield can occur at any time from late vegetative stages to full seed on the deep soils in this study. Initiating irrigations immediately ahead of significant rainfall events reduced yields. Results from this project determined more concise trigger value recommendations for a Sharkey silty clay soil to avoid conditions causing a yield reducing stress, using soil water potential or soil water deficit data along with maximum air temperature data. There was not enough data to give a concise irrigation initiation recommendation for the deep Bosket/Dubbs silt loam, Bosket/Commerce loam and Dundee/Forestdale silty clay loam.

Other weather parameters need to be examined to quantify conditions that could potentially cause a yield reducing stress. The purpose of this project is to improve irrigation initiation recommendations on Mississippi soils to initiate irrigations with Watermark soil water potential sensors and irrigation scheduling programs in order to more efficiently apply water to maximize yields economically while using the least amount of water, thus 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 $10.27/acre.

END PRODUCTS-COMPLETED OR FORTHCOMING

A manuscript “Yield and Economic Response of Soybean to Irrigation Initiation in Mississippi” has been prepared to submit for publication.

Delta States Irrigation Conference, Miner Missouri, Irrigation Scheduling – Using Various Moisture Sensors, December 17-18, 2014.

Soybean and Corn Field Day, Stoneville, MS, July 18, 2013.

Results have been referred to in support of other work by Jason Krutz in Irrigation Symposiums: Tunica, February 10; Stoneville, February 26. Delta Area Water Conservation Meetings: Cleveland, February 17; Sumner, February 18; Indianola, February 20; Belzoni, February 21. Mississippi, Arkansas, and Louisiana Extension Agent In-Service-Training Stoneville, Mississippi, February 24-25, 2013.

Soybean and Corn Field Day, Stoneville, MS, July 19, 2012.