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Maintaining agronomics, economics, and furrow-irrigation efficiency in mid-southern USA soybean conservation production systems

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Maintaining agronomics, economics, and furrow-irrigation efficiency in mid-southern USA soybean conservation production systems

By

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Mid-southern USA soybean [*Glycine max* (L.) Merr.] producers are being pushed to increase adoption of conservation tillage systems as a means of increasing the application efficiency of gravity flow irrigation systems. This research was conducted to determine whether the efficiency of furrow-irrigation systems could be manipulated through conservation tillage systems while maintaining soybean productivity and profitability. Three experiments were conducted near Stoneville, MS on a Dubbs silt loam (Fine-silty, mixed, active, thermic Typic Hapludalfs) to determine the effects of reducing tillage and increasing ground cover residues on irrigation application efficiency, irrigation water use efficiency, soybean grain yield, and net returns above specified costs. In experiment 1, transitioning from conventional tillage to a conservation tillage system had no adverse effect on irrigation application efficiency, irrigation water use efficiency, soybean grain yield, or net returns above specified costs when subsoiling was included. For experiment 2, replacing subsoiling with a cereal rye or tillage radish cover crop in a conservation tillage system either had no effect or reduced irrigation application efficiency, irrigation water use efficiency, soybean grain yield, and net returns above specified costs up to 41%. In experiment 3, independent of cover crop, reducing tillage to only furrow creation had no adverse effect on irrigation application efficiency, irrigation water use efficiency, soybean grain yield, and net returns above specified costs relative to a conservation tillage system with subsoiling. Conservation tillage systems that include subsoiling maximize irrigation application efficiency and irrigation water use efficiency while minimizing adverse effects on yield and net returns relative to conservation tillage systems that further reduce tillage and/or increase ground coverage with cover crops. Our data indicate that soybean producers in the mid-southern USA maximize furrow-irrigation functionality, yield, and profitability while minimizing risk by transitioning from a conventional tillage system to a conservation tillage system with subsoiling.

DEDICATION

I am dedicating this work in love, honor, and memory of my father Dr. Kelly Bryant. He instilled a love for agricultural research in me which lead me to where I am now and without his guidance and encouragement this journey would have been much harder. He also set shining examples of how to be a true scientist while not losing touch with humanity and the people that help you along the way. The beginning is now over and I am on to fill his shoes as a scientist and mentor. The road goes on forever and the party never ends.

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INTRODUCTION

1.1 Conservation Tillage

Mid-southern USA soybean [*Glycine max* (L.) Merr.] producers are being pushed to adopt conservation tillage systems that include cover crops in hopes of capturing ecoservices benefits. According to the U.S. Soil Conservation Service, conservation tillage systems must leave 30% of the soil surface covered by residue after planting (Logan et al., 1991). However, mid-southern USA soybean production systems commonly include multiple surface tillage operations that leave less than 30% surface residue coverage at planting. Within the Delta region of Mississippi 536,000 hectares are intensively cultivated whereas 428,000 and 145,000 hectares are cultivated to reduced tillage or no-tillage standards, respectively (USDA-NASS, 2019). One method of increasing conservation tillage is through the use of a stale seed-bed soybean production system.

A common stale seed-bed system in the mid-southern USA involves surface tillage and raised seed-bed formation in the fall followed by chemical burn down and planting in the spring. Benefits of the stale seed-bed soybean production system include reducing tillage and labor inputs, mitigating planting delays during wet years, and realizing the full potential of the early soybean production system (ESPS), i.e., planting maturity group IV soybean in April instead of maturity group V or later in May or June (Heatherly, 1999a). Benefits of the ESPS are well documented for determinate, maturity group IV soybean on clay-textured soils (Elmore and

Heatherly, 1988; Heatherly and Elmore, 1983; Heatherly et al., 1990). The ESPS is the highest yielding and most profitable soybean production system for the mid-southern USA, but requires subsoiling to maximize yield and profitability when implemented on medium- to coarse-textured soils (Bryant et al., 2020; Heatherly et al., 1990; Popp et al., 2001; Salmeron et al., 2016). Excluding subsoiling from mid-southern USA conservation tillage systems can reduce soybean grain yield up to 13% (Bryant et al., 2020a). Means to increase ground coverage and reduce tillage in the ESPS is being advocated for by NRCS.

1.2 Cover Crops

The inclusion of a cereal rye (*Secale cereale* L.) cover crop in conservation tillage systems may be a means to increase ground coverage and reduce tillage in the ESPS. Cereal rye is desirable as a cover crop because it is winter hardy and can produce biomass in the range of 8.5 to 12 Mg ha^{-1} when terminated at the soft dough growth stage (Edmisten et al., 1998). Inclusion of a cereal rye cover crop in a conservation tillage system on loamy sand-textured soils improved cotton (*Gossypium hirsutum* L.) lint yield in five of six years in the coastal plains of South Carolina (Bauer et al., 2010). Furthermore, a cereal rye cover crop on a silt loam-textured soil in a conservation tillage system in the Tennessee River Valley of Alabama improved cotton seed and lint yield in the absence of subsoiling (Balkcom et al., 2006; Raper et al., 2000). The effects of a cereal rye cover crop on ground coverage, reducing tillage, and improving profitability in the ESPS have not been thoroughly evaluated in the mid-southern USA.

The adaptation of tillage radish (*Raphanus sativus* L. var. *longipinnatus*) as a cover crop provides another approach to increase ground coverage and reduce tillage in the mid-southern USA ESPS. Tillage radish is a desirable cover crop as it will winter kill at temperatures below -4^{o} C, produce aboveground biomass in a range of 1,306 to 4,026 kg ha^{-1}, and has a taproot that can penetrate compacted soils with bulk densities ranging from 1.3 to 1.75 Mg m^{-3} (Chen and Weil, 2010; Lawley et al., 2011; White and Weil, 2011). A tillage radish cover crop increased corn (*Zea mays* L.) silage yields but had no effect on corn grain yield in the mid-Atlantic USA; however, there was no effect on soil bulk density and increased penetration resistance (Chen and Weil, 2011; Lawley et al., 2011).

1.3 No-Tillage

As issues surrounding water quality, greenhouse gas emissions, and soil health continue to garner the national spotlight, the adoption of no-tillage (NT) practices by agriculture producers has been repeatedly touted as the best option to address all three concerns. No-tillage is a conservation tillage system defined as no soil disturbance other than the opening of a trench wide enough to accommodate seed placement (Depsch et al., 2014). Minimal adoption of NT is likely due to the need for raised seed-beds to achieve maximum soybean productivity in a region that is 80% gravity flow irrigated and where the frequency of high-intensity rainfall events is increasing (Dourte et al., 2015; Easterling et al., 2017; Huitink and Tacker, 2000; USDA-NASS, 2013).

Increased adoption of NT in the mid-southern USA is unlikely due to concerns over the effects of restrictive soil layers and seed-bed deterioration on soybean productivity and necessary irrigation and drainage. Strict adherence to NT standards excludes necessary subsoiling to remediate restrictive soil layers. No-tillage production systems on medium- to coarse-textured soils can reduce crop productivity up to 33% due to restrictive layers (Schwab et al., 2002; Watts and Torbert, 2011). Mid-southern USA soybean producers are also concerned that NT systems will have a negative effect on the efficacy of irrigation systems. Gravity flow irrigation delivery systems require furrows to effectively and efficiently direct water across production fields. On medium- to coarse-textured soils, the susceptibility of raised seed-beds to erode during a single growing season necessitates the creation of furrows on a yearly basis. However, it may be possible to garner some of the environmental benefits associated with NT while maintaining soybean productivity and profitability through modification of a zone-tillage system.

Modifying current zone tillage systems so that the tilled and untilled zones are inverted and including a deep-rooted cover crop may provide necessary furrows for irrigation and drainage purposes while alleviating restrictive soil layers and increasing ground cover. Traditional zone-tillage consists of tilling the seed row while the remaining soil surface remains untilled (Logan et al., 1991). In zone-tillage for furrow-irrigated environments the seed-row becomes the untilled portion while shallow furrows are created between seed-rows with a row-crop cultivator. Deep rooted cover crops such as the tillage radish can penetrate restrictive soil layers with bulk densities ranging from 1.3 to 1.75 Mg m^{-3} to a depth of 50 cm and are considered biological means of remediating restrictive soil layers (Chen and Weil, 2010; Weil et al., 2011).

1.4 Furrow-Irrigation Application Efficiency

In the mid-southern USA, water is supplied to 80% of irrigated land through gravity flow delivery systems (USDA-NASS, 2013) which is one of the least efficient irrigation systems available. Application efficiency of furrow-irrigation systems is typically near 65% while sprinkler and subsurface drip irrigation systems average application efficiencies of 85% and 95%, respectively (Lamm and Trooien, 2003). The mid-southern USA is well suited for furrow-irrigation due to the relatively low costs associated with setup and water lifting and the coupling of precision land-leveling with soils possessing low infiltration rates while the adoption of more efficient irrigation systems is hindered by environmental and economic factors (Brouwer et al., 1990; Massey et al., 2017).

By improving key components of irrigation application efficiency, such as increased infiltration and reduced runoff, conservation tillage systems may also be an ideal choice to improve furrow-irrigation application efficiency. The greatest benefit from conservation tillage systems is the ability of surface residues to increase furrow advance time and infiltration rates (Ashraf et al., 1999; Mailapalli et al., 2013; Trout, 1992; Yonts et al., 1991). Prolonged furrow advance times aid infiltration by extending the time water remains on the soil surface (Dabney, 1998; Gilley, 1995; Mailapalli et al., 2013). However, tillage may have a greater effect on furrow advance time than ground cover if surface coverage does not exceed 26% (Yonts et al., 1991). On silty clay loam-textured soils, when conservation tillage systems provided at least 44% ground cover, furrow advance time and infiltration increased up to 623% and 85%, respectively (Mailapalli et al., 2011). Conservation tillage systems with 60% ground cover increased furrow advance time and infiltration up to 37% and 50%, respectively, compared to a conventional tillage system on a sandy clay loam-textured soil (Ashraf et al., 1999). However, depending on in-flow rate and furrow length, ground cover residues exceeding 48% may prevent proper functioning of furrow irrigation (Yonts et al., 1991). By increasing furrow advance time and infiltration, runoff volumes are similarly reduced in conservation tillage systems (Dabney, 1998; Mailapalli et al., 2013). Runoff from furrow-irrigation was reduced up to 93% in conservation tillage systems on silt loam and silty clay loam-textured soils (Mailapalli et al., 2011, 2013). While the benefits from increasing ground cover and reducing tillage are convincing most of the previous work has evaluated incorporated residues or garnered data from only select irrigation events over a short period of time.

1.5 Research Justification

Conservation tillage systems have been well researched throughout the world and USA. However, there is a paucity of data specific to mid-southern USA soybean production. Prior research has also been limited to only one aspect of a production system instead of treating the system as a whole. Potential improvements to one aspect of the production system must not come at a cost to other aspects of the production system. Therefore, research was conducted from a systems approach to address four specific objectives.

Objective 1: Determine the effects of transitioning from conventional to conservation tillage on soybean grain yield, net returns above specified costs, and water use efficiency when implemented on medium- to coarse-textured soils in the mid-southern USA.

Objective 2: Determine the effects of replacing subsoiling with either a cereal rye or tillage radish cover crop in mid-southern USA soybean conservation tillage systems on soybean grain yield, net returns above specified costs, and water use efficiency.

Objective 3: Determine the effects of zone tillage with or without a cover crop on soybean grain yield, net returns above specified costs, and water use efficiency when implemented on medium- to coarse-textured soils in the mid-southern USA.

Objective 4: Determine the effects of conservation tillage systems on furrow-irrigation application efficiency for the duration of the soybean growing season on medium- to coarse-textured soils.

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CHAPTER II

CONSERVATION SOYBEAN PRODUCTION IN THE MID-SOUTHERN USA: I. TRANSITIONING FROM CONVENTIONAL TO CONSERVATION TILLAGE

2.1 Abstract

The adoption of production systems that leave greater than 30% residue coverage on the soil surface, i.e., conservation tillage, is limited in the mid-southern USA due to the development of restrictive layers and subsequent yield reductions. This research was conducted to determine if the inclusion of subsoiling in conservation tillage systems can maintain yield and profitability relative to that of conventional tillage. The effects of surface and subsurface tillage on soybean [*Glycine max* (L.) Merr.] grain yield, net returns above specified costs, and water use efficiency (WUE) were investigated near Stoneville, MS on a Dubbs silt loam (Fine-silty, mixed, active, thermic Typic Hapludalfs). Conservation tillage with subsoiling maintained or improved soybean grain yield, net returns above specified costs, and WUE up to 68% in three of four years ($P \leq 0.0002$). Conversely, conservation tillage alone either had no effect or decreased soybean grain yield up to 14%, decreased net returns above specified costs up to 20%, and decreased WUE up to 14% ($P \leq 0.0002$). Our data indicate that inclusion of subsoiling minimizes yield and net return declines commonly associated with conservation tillage systems and should be a component of the early soybean production system on medium- to coarse-textured soils.

2.2 Introduction

Mid-southern USA soybean [*Glycine max* (L.) Merr.] production systems commonly include multiple surface tillage operations that leave less than 30% surface residue coverage at planting. Within the Delta region of Mississippi 536,000 hectares are intensively cultivated whereas 428,000 and 145,000 hectares are cultivated to reduced tillage or no-tillage standards, respectively (USDA-NASS, 2019). In recent years there has been a renewed push to increase the number of hectares within the mid-southern USA managed under conservation tillage practices, that is, practices that leave at least 30% ground cover at the time of planting (Logan et al., 1991). One method of increasing conservation tillage is through the use of a stale seed-bed soybean production system.

A common stale seed-bed system in the mid-southern USA involves surface tillage and raised seed-bed formation in the fall followed by chemical burn down and planting in the spring. Benefits of the stale seed-bed soybean production system include reducing tillage and labor inputs, mitigating planting delays during wet years, and realizing the full potential of the early soybean production system (ESPS), i.e., planting maturity group IV soybean in April instead of maturity group V or later in May or June (Heatherly, 1999a). Benefits of the ESPS are well documented for determinate, maturity group IV soybean on clay-textured soils (Elmore and Heatherly, 1988; Heatherly and Elmore, 1983; Heatherly et al., 1990). In the last two decades, the ESPS has expanded onto medium- to coarse-textured soils, making the stale seed-bed more susceptible to degradation during the winter.

While adoption of the stale seed-bed soybean production system in the mid-southern USA has increased in recent years, numerous tillage operations are often employed prior to planting. One factor preventing the stale seed-bed soybean production system from being labeled conservation tillage is the allowance for tillage operations to be performed up to four weeks prior to planting (Heatherly, 1999b). For example, four to six weeks prior to planting, raised seed-beds that were eroded by winter rains are reshaped with a hipper (T. Irby, personal communication, 2019). Tillage performed this close to soybean planting does not allow for residue accumulation sufficient to satisfy the 30% ground cover requirement for conservation tillage (Logan et al., 1991).

A primary factor reducing the adoption of conservation tillage on medium- to coarse-textured soils in the mid-southern USA is reduced yield due to the development of a restrictive layer. In the Tennessee Valley Region of North Alabama, converting from conventional to conservation tillage increased restrictive layers and decreased yield, which were both corrected through use of vertical tillage (Raper et al., 2000, 2008). Thus, the objective of this study was to determine the effects of conservation tillage and in-row, subsoiling on soybean grain yield, net returns above specified costs, and water use efficiency (WUE).

2.3 Materials and Methods

2.3.1 Site Description and Experimental Design

Research was conducted from the 2015 through 2018 growing season on a field site at the Mississippi State University, Delta Research and Extension Center near Stoneville, MS that was originally established in the fall of 2003 to evaluate the effects of long-term conservation practices on agronomic and environmental parameters. Field soils consisted of Dubbs silt loam (Fine-silty, mixed, active, thermic Typic Hapludalfs) and Bosket very fine sandy loam (Fine-loamy, mixed, active, thermic Mollic Hapludalfs) (Soil Survey Staff, 2015). Continuous cotton (*Gossypium hirsutum* L.) was grown at the site from 2004 to 2010, and continuous corn (*Zea* mays L.) was grown from 2011 to 2014. The conventional tillage/winter fallow and reduced tillage/winter fallow treatments have not varied since field establishment while the reduced tillage/subsoiling treatment has always been reduced tillage the subsoiling component was added in the fall of 2014.

This research consisted of three replications of three treatments arranged in a randomized complete block design. Experimental units consisted of eight 1-m wide by 152-m long raised seed-beds. Tillage treatments are described as follows:

1. Conventional tillage/winter fallow – Experimental units were disked twice in the fall with a 4-m wide offset disk harrow to bury crop residue and remove existing seed-beds, then remained flat throughout the winter. Approximately one month prior to planting a single pass was made with a 6-m wide field cultivator followed by creation of raised beds with a four-row pan hipper. Seed-beds were created using a reel and harrow row conditioner immediately prior to soybean planting. A row crop cultivator with shallow flat sweeps was used prior to the first irrigation event in each crop year to prepare furrows. Conventional tillage/winter fallow was the most intensive tillage treatment and served as the control.
2. Reduced tillage/winter fallow – Experimental units were disked once in the fall with a 4-m wide offset disk harrow followed by seed-bed formation with a four-row pan hipper and pull type drum roller. Native vegetation was allowed to grow during the fallow period and chemically desiccated two weeks prior to soybean planting. Soybean planting utilized the stale seed-bed system (Heatherly, 1999b). A row crop cultivator with shallow flat sweeps was used prior to the first irrigation event in each crop year to prepare furrows.

3. Reduced tillage/subsoiling – Prior to any fall tillage operations, experimental units were subsoiled in-row to a depth of 56 cm with a four-row parabolic subsoiler. Remaining tillage operations were conducted in accordance with those described in reduced tillage/winter fallow.

The soybean growing season for each year of this project began the preceding fall and continued through soybean harvest. Dates for all field procedures are presented in Table 2.1.

2.3.2 Soybean Planting and Harvesting

Soybean planting occurred within the first two weeks of May in every crop year (Table 2.1). Soybean variety ASGROW 4632 (Monsanto Co., St. Louis, MO) was planted at 346,000 seeds ha^{-1} with a four-row Monosem twin row planter (Monosem Inc., Edwardsville, KS). At physiological maturity the center six rows were mechanically harvested for yield comparisons. Soybean seed weights were obtained with a grain cart with calibrated load cells attached. Moisture content was obtained from a GAC 2100b grain analysis computer (DICKEY-john, Auburn, IL) and adjusted to 130 g kg^{-1} for final yield determinations.

2.3.3 Cultural Management Practices

Management decisions related to pesticide application were conducted according to Mississippi State University Extension Service guidelines (Catchot et al., 2014; Mississippi State University, 2018b). Two weeks prior to soybean planting all winter vegetation was chemically desiccated. Applications of residual herbicides were made at planting and as needed throughout the season for weed control.

Irrigation events were scheduled using the climactic water-balance method FAO-56 as described by Allen et al. (1998). Irrigation initiated when a 5-cm soil deficit was reached. All experimental units were furrow-irrigated simultaneously and irrigations were delivered via lay-flat poly-ethylene tubing (Delta Plastics, Little Rock, AR). Computerized hole selection was calculated with the Pipe Hole and Universal Crown Evaluation Tool (PHAUCET) version 8.2.20 (USDA-NRCS, Washington, DC) as described by Bryant et al. (2017). Individual irrigation events applied 31 ha-mm at a rate of 19 L min^{-1} $furrow^{-1}$. A McCrometer flow tube with attached McPropeller bolt-on saddle flowmeter (McCrometer Inc., Hemet, CA) was installed at the field inlet to monitor application volumes and furrow flow rates.

2.3.4 Measured Parameters

In-season data were collected to monitor percent ground cover, soybean plant population, and WUE. Ground cover readings were obtained using the meter-stick method (Hartwig and Laflen, 1978). At the time of soybean planting ten locations were randomly selected and averaged across each experimental unit. Similarly, soybean plant populations were measured four weeks after planting within a 1-m section of row at 10 randomly selected locations and averaged across each experimental unit. Water use efficiency was calculated as described by Vories et al. (2005):

$$WUE = \frac{Y}{TWA} \quad \text{(Eq. 2.1)}$$

where WUE is water use efficiency (kg $ha\text{-}mm^{-1}$), Y is soybean grain yield (kg ha^{-1}), and TWA is irrigation and rainfall (ha-mm).

2.3.5 Economic Analysis

Economic analysis was conducted to determine net returns above specified costs. Costs associated with each treatment were obtained from Mississippi State University Delta Planning Budgets (Mississippi State University, 2015, 2016, 2017, 2018a) and adjusted on an annual basis for the 2015, 2016, 2017, and 2018 crop years (Table 2.2). Specified costs are on a per-hectare basis and include total direct costs and total fixed costs. Direct costs include per-hectare charges for operating inputs such as seed, pesticides, irrigation supplies, fuel, interest, labor, and repairs and maintenance. Fixed costs are annual capital recovery costs for machinery prorated by use, where use is calculated on a per-hectare basis. Soybean prices used in the study are the average daily reported spot price for #1 Grade soybeans delivered to Greenville, MS for the week of harvest (www.ams.usda.gov/mnreports/JK_GR110.txt). For per-hectare irrigation cost calculation, it was assumed that producers would be operating in a 65-hectare system. Equipment costs are based on assuming use of equipment sized for 96-cm seed-beds.

2.3.6 Statistical Analysis

All data were analyzed by ANOVA using the GLIMMIX Procedure in SAS 9.4 (Statistical Analytical System Release 9.4; SAS Institute Inc., Cary, NC). All fixed effects and interactions among fixed effects were tested using type III statistics. As plots were not re-randomized in every year, treatments were analyzed as repeated measures to determine change over time. Therefore, fixed effects included treatment, year, and the interaction of treatment and year. The LSMEANS statement was used to separate treatment means, and differences were considered significant at the $\alpha \leq 0.05$ level.

2.4 Results and Discussion

2.4.1 Seasonal Water Inputs and Field Measurements

Compared to the 10-yr average rainfall totals, and adjusted for yearly harvest dates, seasonal rainfall amounts varied during the study period (Table 2.3). Rainfall totals for the 2015 and 2017 growing seasons were 19% below the 10-yr average and are therefore considered dry years. Conversely, the 2016 and 2018 growing season rainfall totals were within 5% of the 10-yr average and are considered normal years. Regardless of rainfall totals all years required supplemental irrigation during crucial soybean growth stages (Table 2.3). The differences in number of irrigation events regardless of rainfall year designation is due to the timing of rains during the growing season.

Ground cover requirements for conservation tillage systems were satisfied in all years; however, soybean stands were reduced by planting into vegetative residue. Averaged across years, ground coverage for reduced tillage/winter fallow and reduced tillage/subsoiling was ≥ 42%, while ground coverage was less than 3% for conventional tillage/winter fallow. Relative to conventional tillage, soybean plant populations were reduced by 10% in conservation tillage systems regardless of year or subsoiling ($P = 0.0012$). Stand reductions were attributed to poor soil to seed contact (Olson et al., 2004) and are not expected to have an effect on soybean grain yield (Edwards and Purcell, 2005).

2.4.2 Soybean Grain Yield

The primary hypothesis of this research is that soybean productivity is reduced in conservation tillage systems due to the development of restrictive soil layers, but productivity can be maintained relative to that of conventional tillage/winter fallow by inclusion of subsoiling. Treatment interacted with year to have an effect on soybean grain yield ($P = 0.0002$; Table 2.4). As theorized, reducing surface tillage decreased soybean grain yield in reduced tillage/winter fallow up to 8% compared to that of conventional tillage/winter fallow in two of four years. In contrast, fracturing the restrictive soil layer by inclusion of subsoiling maintained or improved soybean grain yield in reduced tillage/subsoiling up to 18% of that reported for conventional tillage/winter fallow in 3 out of 4 growing seasons.

Our data indicate that adoption of conservation tillage has no effect on crop productivity if subsoiling operations are included in the system. These data are in agreement with others reporting that subsoiling as part of fall tillage operations on clay-textured soils in Mississippi and silt loam-textured soils in Arkansas maintained or improved soybean grain yield up to 380 kg ha^{-1} and 1,750 kg ha^{-1}, respectively (Heatherly and Spurlock, 2001; Popp et al., 2001). Conversely, a four-year cotton study on a Decatur silt loam in Alabama indicated that shallow fall tillage reduced seed cotton yield in two of four years and was not overcome when subsoiling was included (Raper et al., 2000).

2.4.3 Net Returns Above Specified Costs

A secondary hypothesis of this research is that cost savings associated with conservation tillage will not offset decreased income incurred through reduced soybean productivity. Treatment and year interacted to have an effect on net returns above total specified costs (P = 0.0002; Table 2.4). Relative to conventional tillage/winter fallow, reduced tillage/subsoiling maintained or improved net returns above specified costs up to 68% in three of four years, while reduced tillage/winter fallow maintained or decreased net returns above specified costs in all years. Our data indicate that if conservation tillage systems are implemented on medium- to coarse-textured soils in the mid-southern USA, then subsoiling should be included in the system to maximize net returns above specified costs. This conclusion is similar to that of Popp et al. (2001) who concluded that net returns from conservation tillage systems were maintained or increased up to \$380 ha^{-1} if subsoiling was conducted at a 45^{o} angle to the seed-bed.

2.4.4 Water Use Efficiency

We postulated that conservation tillage systems would decrease soybean WUE due to reduced soybean productivity. The interaction of treatment and year had an effect on WUE (P = 0.0001; Table 2.4). Relative to conventional tillage/winter fallow, reduced tillage/subsoiling maintained or improved WUE up to 16% in three of four years, while reduced tillage/winter fallow maintained or decreased WUE up to 14% in all years. These data indicate that subsoiling must be included to maximize WUE of conservation tillage system in the mid-southern USA.

2.5 Conclusions

The objective of this study was to determine the effects of conservation tillage and in-row, subsoiling on soybean grain yield, net returns above specified costs, and WUE. This research indicates that relative to conventional tillage, conservation tillage maintains or has an adverse effect on soybean grain yield, net returns above specified costs, and WUE. Inclusion of subsoiling in conservation tillage systems, however, maintains or improves soybean grain yield, net returns above specified costs, and WUE in three of four years. Our data indicate that subsoiling must be a component of conservation tillage systems to maximize soybean grain yield, net returns above specified costs, and WUE on medium- to coarse-textured soils in the mid-southern USA.

Table 2.1 Field operation dates for a furrow-irrigated, conservation tillage soybean [*Glycine max* (L.) Merr.] study conducted near Stoneville, MS from 2015 through 2018.

Operation	**2015**	**2016**	**2017**	**2018**
Fall Tillage	14 Oct	6 Oct	12 Oct	26 Oct
Spring Tillage	9 Apr	30 Mar	21 Mar	15 Mar
Cover Crop Planting	N/A	23 Oct	19 Oct	30 Oct
Burndown	30 Apr	*10 Feb; 26 Apr	26 Jan; 25 Apr	12 Jan; 25 Apr
Soybean Planting	14 May	11 May	09 May	09 May
Furrow Preparation	4 June	23 May	6 Jun	29 May
Soybean Harvest	24 Sep	27 Sep	17 Oct	05 Oct

* When two dates appear in the same cell the first is tillage radish desiccation and was applied only to treatments containing a tillage radish cover crop, and the second date is burndown prior to planting.

Table 2.2 Treatment total specified costs* used in economic analysis.

	CT/WF†	**RT/WF**	**RT/SS**	**Soybean Price**
Year	$ $ ha^{-1}$			$ $ kg^{-1}$
2015	845.95	804.48	841.75	0.34
2016	653.01	615.62	651.06	0.35
2017	697.59	662.48	697.59	0.35
2018	847.53	806.83	845.75	0.29

* Total specified costs include all tillage operations, pesticide applications, soybean planting and harvesting, soybean seed, irrigation supplies, irrigation water lifting, and pesticides.
† CT/WF = conventional tillage/winter fallow; RT/WF = reduced tillage/winter fallow; RT/SS = reduced tillage/subsoiling.

Table 2.3 Monthly rainfall (Rain) totals and 10-yr average (10-YAR) for Stoneville, MS and monthly irrigation totals (Irr).

	2015		2016		2017		2018		
	Rain*	Irr†	Rain	Irr	Rain	Irr	Rain	Irr	10-YAR
Month	ha-mm								
May	76.84		24.41		27.91		18.64		49.44
June	30.18		63.45	30.9	20.19		25.34	30.9	38.11
July	23.18	61.8	39.96	30.9	34.30	30.9	22.76	92.7	37.70
August	13.29	61.8	68.50		89.51		89.92	30.9	25.54
September	9.27		0.62		9.89		78.17		38.11
October					4.53				42.95
Total	**152.75**	**123.6**	**196.94**	**61.8**	**186.45**	**30.9**	**234.84**	**154.5**	**231.85**

* Rainfall totals for each year began the day of planting and end on the day of harvest.
† 30.9 ha-mm were applied at each furrow-irrigation event.

Table 2.4 Soybean [*Glycine max* (L.) Merr.] grain yield (Yield), net returns above specified costs (Returns), and water use efficiency (WUE) from a conservation tillage study conducted near Stoneville, MS from 2015 through 2018.

Year	**Tillage**[*]	**Yield** — $kg\ ha^{-1}$ —	**Returns** — $\$\ ha^{-1}$ —	**WUE** $kg\ ha\text{-}mm^{-1}$
2015	CT/WF	4542 a[†]	677.62 ab	14.78 a
	RT/WF	4455 a	689.96 a	14.50 a
	RT/SS	4331 a	611.19 b	14.10 a
2016	CT/WF	4333 a	875.25 a	16.75 a
	RT/WF	3735 b	701.83 b	14.44 b
	RT/SS	3872 b	714.82 b	14.97 b
2017	CT/WF	3488 a	525.08 ab	16.05 a
	RT/WF	3226 b	469.42 b	14.84 b
	RT/SS	3602 a	566.29 a	16.58 a
2018	CT/WF	3816 b	271.37 b	9.80 b
	RT/WF	3900 b	336.62 b	10.02 b
	RT/SS	4437 a	455.25 a	11.40 a

[*] CT/WF = conventional tillage/winter fallow; RT/WF = reduced tillage/winter fallow; RT/SS = reduced tillage/subsoiling.

[†] Numbers within a year in a column followed by the same letter are not different at $P \leq 0.05$.

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CHAPTER III

CONSERVATION SOYBEAN PRODUCTION IN THE MID-SOUTHERN USA: II. COVER CROPS AND CONSERVATION TILLAGE

3.1 Abstract

The adoption of cover crop production systems is lagging in the mid-southern USA due to concerns over yield stability and on-farm profitability. This research was conducted to determine if the inclusion of a cover crop in conservation tillage systems improves yield, profitability, and water use efficiency. The effects of replacing subsoiling with a cereal rye (*Secale cereale* L.) or tillage radish (*Raphanus sativus* L. var. *longipinnatus*) cover crop on soybean [*Glycine max* (L.) Merr.] grain yield, net returns above specified costs, and water use efficiency were evaluated in a conservation tillage system, i.e., surface residue ≥ 30% at planting, on a Dubbs silt loam (Fine-silty, mixed, active, thermic Typic Hapludalfs) from 2016 to 2018 near Stoneville, MS. Relative to the conservation tillage system with subsoiling, the replacement of subsoiling with a tillage radish cover crop reduced soybean grain yield, net returns above specified costs, and water use efficiency by up to 41% ($P \leq 0.0266$). Conversely, the replacement of subsoiling with a cereal rye cover crop had no effect on soybean grain yield or water use efficiency but reduced net returns above specified costs by 28% ($P \leq 0.0266$). In the mid-southern USA, a cereal rye cover crop can maintain soybean grain yield and water use efficiency relative to the regional standard, but widespread adoption of this production system is unlikely due to reduced profitability associated with additional seed and planting costs.

3.2 Introduction

In the mid-southern USA, planting an indeterminate maturity group IV soybean [*Glycine max* (L.) Merr.] in mid-April to Early-May into a stale seed-bed is referred to as the early soybean production system (ESPS). Under winter fallow conditions the stale seed-bed in the ESPS typically has surface residue coverage exceeding 30% and is, therefore, a conservation tillage system (Bryant et al., 2020). The ESPS is the highest yielding and most profitable soybean production system for the mid-southern USA, but requires subsoiling to maximize yield and profitability (Bryant et al., 2020; Heatherly et al., 1990; Popp et al., 2001; Salmeron et al., 2016). Excluding subsoiling from mid-southern USA conservation tillage systems can reduce soybean grain yield up to 13% (Bryant et al., 2020). Means to increase ground coverage and reduce tillage in the ESPS is being advocated for by NRCS.

The inclusion of a cereal rye (*Secale cereale* L.) cover crop in conservation tillage systems may be a means to increase ground coverage and reduce tillage in the ESPS. Cereal rye is desirable as a cover crop because it is winter hardy and can produce biomass in the range of 8.5 to 12 Mg ha^{-1} when terminated at the soft dough growth stage (Edmisten et al., 1998). Inclusion of a cereal rye cover crop in a conservation tillage system on loamy sand-textured soils improved cotton (*Gossypium hirsutum* L.) lint yield in five of six years in the coastal plains of South Carolina (Bauer et al., 2010). Furthermore, a cereal rye cover crop on a silt loam-textured soil in a conservation tillage system in the Tennessee River Valley of Alabama improved cotton seed and lint yield in the absence of subsoiling (Balkcom et al., 2006; Raper et al., 2000). The effects of a cereal rye cover crop on ground coverage, reducing tillage, and improving profitability in the ESPS have not been thoroughly evaluated in the mid-southern USA.

The adaptation of tillage radish (*Raphanus sativus* L. var. *longipinnatus*) as a cover crop provides another approach to increase ground coverage and reduce tillage in the mid-southern USA ESPS. Tillage radish is a desirable cover crop as it will winter kill at temperatures below -4^{o} C, produce aboveground biomass in a range of 1,306 to 4,026 kg ha^{-1}, and has a taproot that can penetrate restrictive soil layers with bulk densities ranging from 1.3 to 1.75 Mg m^{-3} (Chen and Weil, 2010; Lawley et al., 2011; White and Weil, 2011). A tillage radish cover crop increased corn (*Zea mays* L.) silage yields but had no effect on corn grain yield in the mid-Atlantic USA; however, there was no effect on soil bulk density and increased penetration resistance (Chen and Weil, 2011; Lawley et al., 2011). Based on minimal data and inconsistent effects of cover crops on production systems in the mid-southern USA, the objective of this research was to determine the effects of monoculture cereal rye or tillage radish cover crops on soybean grain yield, net returns above specified costs, and water use efficiency (WUE) in conservation tillage systems.

3.3 Materials and Methods

3.3.1 Site Description and Experimental Design

During the 2016 through 2018 soybean growing season continuous soybean research was conducted at the Mississippi State University Delta Research and Extension Center near Stoneville, MS. Field soils, production history, and experimental units are described previously (Bryant et al., 2020). Reduced tillage practices and the cereal rye cover crop were in place since the establishment of the field while subsoiling and tillage radish were added in the fall of 2014 and 2015, respectively. Three replications of three treatments were arranged in a randomized complete block design. Treatments are described as follows:

1. Reduced tillage/subsoiling – Experimental units were subsoiled in the row to a depth of 56 cm with a four-row parabolic subsoiler in the fall. Following subsoiling, experimental units were disked once with a 4-m wide offset disk harrow and seed-beds were created with a four-row pan hipper and pull type drum roller. Soybean was planted into native vegetation that was allowed to grow during the fallow period, and chemically desiccated two weeks prior to planting, utilizing the stale seed-bed system (Heatherly, 1999). Prior to the first irrigation event in each crop year, furrows were prepared with a row crop cultivator with shallow flat sweeps.
2. Reduced tillage/cereal rye – With the exception of eliminating subsoiling and furrow preparation, all tillage operations were performed in accordance with those described in reduced tillage/subsoiling. Immediately after seed-bed formation cereal rye was drill seeded using a Great Plains 4.5-m wide grain drill (Great Plains Manufacturing Inc., Salina, KS) with 19-cm row unit spacing at 67 kg ha^{-1}. Cereal rye was chemically desiccated at Feekes growth stage 11.1 or 01 May, whichever came first. Immediately prior to planting, cereal rye residue was rolled in the direction of planting with a four-row pull type drum roller.
3. Reduced tillage/tillage radish – With the exception of eliminating subsoiling, all tillage operations were performed in accordance with those described in reduced tillage/subsoiling. Immediately after seed-bed formation, tillage radish was drill-seeded using a Great Plains 4.5-m wide grain drill (Great Plains Manufacturing Inc., Salina, KS) with 19-cm row unit spacing at 11 kg ha^{-1} (Weil et al., 2011). Chemical desiccation occurred when tillage radish began bolting. initiated reproductive stages to prevent seed formation and potential summer weed issues.

The soybean growing season began the preceding fall and continued through harvest. Field procedure dates are presented in Table 3.1. Soybean planting and harvest information along with cultural field management practices are described in Bryant et al. (2020).

3.3.2 Measured Parameters

Percent ground cover, cover crop biomass production, soybean plant population, and WUE were monitored through in-season data collection. Ground cover measurements were determined at planting by the meter-stick method whereby ten locations were randomly selected and averaged across each experimental unit (Hartwig and Laflen, 1978). Dry biomass of both cereal rye and tillage radish was averaged across six randomly selected locations in each experimental unit and determined by standard methods (Kornecki et al., 2012). Biomass sampling occurred bimonthly, was initiated at desiccation, and terminated when biomass was no longer present or soybean growth prevented further sampling. Soybean plant populations were determined four weeks after planting when all emerged plants within a 1-m section of row were counted and averaged across ten randomly selected locations in each experimental unit. Water use efficiency was determined as described by Vories et al. (2005):

$$WUE = \frac{Y}{TWA} \qquad \text{(Eq. 3.1)}$$

where WUE is water use efficiency (kg ha-mm^{-1}), Y is soybean grain yield (kg ha^{-1}), and TWA is the sum of rainfall and irrigation (ha-mm).

3.3.3 Economic and Statistical Analysis

Net returns above specified costs were determined through economic analysis utilizing enterprise budgets. Costs were obtained from Mississippi State University Delta Planning Budgets (Mississippi State University, 2016, 2017, 2018; Table 3.2). Specified costs include total direct costs and total fixed costs on a per-hectare basis. Equipment costs were based on the assumption that equipment was sized for 96-cm seed-beds. Data were analyzed by ANOVA using the GLIMMIX Procedure in SAS 9.4 (Statistical Analytical System Release 9.4; SAS Institute Inc., Cary, NC) and differences were considered significant at the $\alpha \leq 0.05$ level. Further details regarding economic and statistical analysis procedures are provided in Bryant et al. (2020).

3.4 Results and Discussion

3.4.1 Seasonal Water Inputs and Field Measurements

Growing season rainfall totals along with the 10-yr average rainfall are presented in Table 3. Rainfall totals varied by year when adjusted for harvest dates and compared to the 10-yr average. The 2016 and 2018 growing seasons are classified as normal years where rainfall totals exceeded the 10-yr average by 4% and 1%, respectively, while the 2017 growing season is classified as dry as it received 19% less rainfall than the 10-yr average. Supplemental irrigation was required in all years. The number of irrigations required was two, one, and five in the 2016, 2017, and 2018 soybean growing seasons, respectively (Table 3.3). The timing of rainfall events during all growing seasons dictated the number of irrigation events required as noted by the normal year of 2018 requiring five events while the dry 2017 growing season only required one supplemental irrigation.

Treatment had an effect on percent ground cover at soybean planting but not on soybean plant populations (Table 3.4). Ground cover in all treatments satisfied conservation tillage requirements, but ground cover for reduced tillage/cereal rye was 57% and 64% greater than that of reduced tillage/subsoiling and reduced tillage/tillage radish, respectively (P = 0.0388). Soybean plant populations were not different among treatments (P = 0.6803).

Ground cover at soybean planting for reduced tillage/cereal rye was greater than reduced tillage/subsoiling and reduced tillage/tillage radish due to agronomic and environmental factors. Cereal rye produced 3,565 kg ha^{-1} of live biomass at termination with 3,509 kg ha^{-1} of biomass remaining at planting. Conversely, tillage radish produced 789 kg ha^{-1} of live biomass at termination and no biomass was present at planting. The biomass production of tillage radish was likely hampered by applications of fomesafen and fomesafen + S-metolachlor which is now known to reduce emergence up to 41% (Cornelius and Bradley, 2017). These herbicides were applied to provide pre- and post-emergence control of Palmer amaranth (*Amaranthus palmeri* S. Wats) resistant to glyphosate and acetolactate synthase inhibitors (Heap, 2019). Biomass of emerged tillage radish was further hindered by winter rains that resulted in frequent, short-term flooding and sustained periods of soil saturation (Weil et al., 2011). Moreover, ground cover for tillage radish at soybean planting was only native, cool-season weeds and not tillage radish because the later was terminated at bolting to prevent seed formation (Chen and Weil, 2011).

3.4.2 Soybean Grain Yield

The principle hypothesis of this research was that by including cover crops in conservation tillage systems, subsoiling could be eliminated while improving soybean productivity. Pooled across years, treatment had an effect on soybean grain yield ($P = 0.0266$; Table 3.4). Relative to reduced tillage/subsoiling, planting a fall cereal rye cover crop maintained soybean grain yield, while planting a fall tillage radish cover crop reduced soybean grain yield 12%. These data indicate that soybean grain yield can be maintained by replacing subsoiling with a cereal rye cover crop in conservation tillage systems.

The effect of a cereal rye cover crop on soybean grain yield is dependent on the ability to alleviate drought stress. In rainfed environments, cereal rye cover crops generally have a positive response on soybean grain yield if there is enough biomass to mitigate drought stress (Keene and Curran, 2016). It is most likely, therefore, that a cereal rye cover crop will maintain but not improve soybean grain yield in irrigated mid-southern USA production systems (Reddy, 2001, 2003; Zablotowicz et al., 2010).

The adverse effect of a tillage radish cover crop on soybean grain yield reported in this research is atypical for the literature. Across all reviewed literature, the tendency for tillage radish is to maintain soybean or corn yield by reducing restrictive soil layers and opening channels which allow succeeding crop roots to exploit soil water and nutrients deeper in the profile (Acuna and Villamil, 2014; White and Weil, 2011; Williams and Weil, 2004). Lawley et al. (2011) report reduced corn yield in one of seven years which was attributed to a reduction in tillage radish biomass production. Yield reductions in this study are similar to those of conservation tillage systems without subsoiling (Bryant et al., 2020) and are attributed to sub-optimal tillage radish growth which did not remediate restrictive soil layers.

3.4.3 Net Returns Above Specified Costs

We assumed that additional costs associated with cover crop seed and planting would be offset by eliminating subsoiling operations and that net returns would not be different between soybean production systems. Pooled across years, treatment had an effect on net returns above specified costs ($P = 0.0032$; Table 3.4). Contrary to our assumptions, net returns above specified costs were reduced in soybean production systems which included a cover crop. Including a tillage radish or cereal rye cover crop reduced net returns above specified costs by up to 41% relative to reduced tillage/subsoiling.

Additional costs associated with including a cover crop in conservation tillage systems cannot be recouped without positive influences on soybean grain yield. Averaged across years, the additional costs of cover crop seed and planting were \$61.45 ha^{-1} and \$93.24 ha^{-1} greater than the additional cost of subsoiling for tillage radish and cereal rye, respectively. Reduced tillage/tillage radish systems also contained costs for an additional herbicide application prior to planting. Similar research in the mid-southern USA determined that maximum net returns following cover crops did not offset the associated costs, and there is no economic benefit associated with cover crop adoption (Reddy, 2001; Snyder et al., 2016; Zablotowicz et al., 2010). These data indicate that subsoiling, instead of cover crops, maximizes net returns above specified costs in mid-southern USA conservation tillage systems.

3.4.4 Water Use Efficiency

A secondary hypothesis was that any reductions in soybean productivity would be exacerbated in soybean WUE. Treatment had an effect on WUE when pooled across years (P = 0.0266; Table 3.4). Compared to reduced tillage/subsoiling, planting a cereal rye or tillage radish cover crop had no effect or reduced soybean WUE by 11%, respectively. Water use efficiency was correlated with soybean grain yield. For example, a 12% reduction in soybean grain yield following a tillage radish cover crop resulted in an 11% reduction in WUE. Without positive yield effects following cover crops, WUE will not be improved in conservation tillage systems (Corak et al., 1991). These data support the findings of Bryant et al. (2020) that subsoiling must be included in mid-southern USA conservation tillage systems to maximize WUE.

3.5 Conclusions

The objective of this research was to determine the effects of monoculture cereal rye or tillage radish cover crops on soybean grain yield, net returns above specified costs, and water use efficiency in conservation tillage systems. These data indicate that relative to reduced tillage/subsoiling, soybean grain yield and WUE are maintained when subsoiling is replaced with a cereal rye cover crop but that tillage radish reduces soybean grain yield and WUE up to 12%. Replacing subsoiling with a cereal rye or tillage radish cover crop reduced net returns above specified costs up to 41%. Our data indicate that widespread adoption of cereal rye and tillage radish cover crops is unlikely in the mid-southern USA soybean production systems as profitability is reduced due to increased costs of cover crop seed and planting.

Table 3.1 Field operation dates for a furrow-irrigated, conservation tillage, with and without cover crops, soybean [*Glycine max* (L.) Merr.] study conducted near Stoneville, MS from 2016 through 2018.

Operation	**2016**	**2017**	**2018**
Fall Tillage	6 Oct	12 Oct	26 Oct
Spring Tillage	30 Mar	21 Mar	15 Mar
Cover Crop Planting	23 Oct	19 Oct	30 Oct
Burndown	[*]10 Feb; 26 Apr	26 Jan; 25 Apr	12 Jan; 25 Apr
Soybean Planting	11 May	09 May	09 May
Furrow Preparation	23 May	6 Jun	29 May
Soybean Harvest	27 Sep	17 Oct	05 Oct

[*] When two dates appear in the same cell the first is tillage radish desiccation and was applied only to treatments containing a tillage radish cover crop, and the second date is burndown prior to planting.

Table 3.2 Treatment total specified costs[*] used in economic analysis.

	RT/SS[†]	**RT/RC**	**RT/TR**	**Soybean Price**
Years		—— $ ha^{-1} ——		— $ kg^{-1} —
2016	651.06	733.71	754.62	0.35
2017	697.59	788.47	804.16	0.35
2018	845.75	938.68	901.82	0.29

[*] Total specified costs include all tillage operations, pesticide applications, soybean planting and harvesting, soybean seed, irrigation supplies, irrigation water lifting, and pesticides.
[†] RT/SS = reduced tillage/subsoiling; RT/RC = reduced tillage/cereal rye (*Secale cereale* L.) cover crop; RT/TR = reduced tillage/tillage radish (Raphanus sativus L. var. longipinnatus) cover crop.

Table 3.3 Monthly rainfall (Rain) totals and 10-yr average (10-YAR) for Stoneville, MS and monthly irrigation totals (Irr).

	2016		**2017**		**2018**		
	Rain*	**Irr†**	**Rain**	**Irr**	**Rain**	**Irr**	**10-YAR**
Month	ha-mm						
May	24.41		27.91		18.64		49.44
June	63.45	30.9	20.19		25.34	30.9	38.11
July	39.96	30.9	34.30	30.9	22.76	92.7	37.70
August	68.50		89.51		89.92	30.9	25.54
September	0.62		9.89		78.17		38.11
October			4.53				42.95
Total	**196.94**	**61.8**	**186.45**	**30.9**	**234.84**	**154.5**	**231.85**

* Rainfall totals for each year began the day of planting and end on the day of harvest.
† 30.9 ha-mm were applied at each furrow-irrigation event.

Table 3.4 Ground cover (GC), soybean [*Glycine max* (L.) Merr.] plant population (SPP), soybean grain yield (Yield), net returns above specified costs (Returns), and water use efficiency (WUE) from a conservation tillage and cover crop study conducted near Stoneville, MS from 2016 through 2018.

	GC	**SPP**	**Yield**	**Returns**	**WUE**
Treatment*	— % —	Plants m^{-1}	kg ha^{-1}	— \$ ha^{-1} —	kg $ha\text{-}mm^{-1}$
RT/SS	44 b†	24 a	3971 a	578.79 a	14.31 a
RT/RC	69 a	20 a	3733 ab	415.92 b	13.52 ab
RT/TR	42 b	20 a	3507 b	340.81 b	12.73 b

* RT/SS = reduced tillage/subsoiling; RT/RC = reduced tillage/cereal rye (*Secale cereale* L.) cover crop; RT/TR = reduced tillage/tillage radish (Raphanus sativus L. var. longipinnatus) cover crop..
† Numbers in a column followed by the same letter are not different at $P \leq 0.05$.

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CHAPTER IV

CONSERVATION SOYBEAN PRODUCTION IN THE MID-SOUTHERN USA: III. ZONE TILLAGE FOR FURROW-IRRIGATION SYSTEMS

4.1 Abstract

Mid-southern USA soybean producers are being pushed to adopt no-tillage systems to capture the associated environmental benefits; however, adoption is minimal due to the need for raised seed-beds for irrigation and drainage purposes. This research was conducted to determine if zone tillage systems, with and without a tillage radish (*Raphanus sativus* L. var. *longipinnatus)* cover crop, can maintain yield, profitability, and water use efficiency relative to that of a conservation tillage system with subsoiling. The effects of conservation systems on soybean [*Glycine max* (L). Merr.] grain yield, net returns above specified costs, and water use efficiency were investigated near Stoneville, MS on a Dubbs silt loam (Fine-silty, mixed, active, thermic Typic Hapludalfs). Relative to a conservation tillage system with subsoiling, switching to a zone tillage system with or without a cover crop had no effect on soybean grain yield, net returns above specified costs, or water use efficiency ($P \geq 0.4694$). Our data indicate that mid-southern USA soybean productivity and profitability are maintained in zone-tillage systems.

4.2 Introduction

As issues surrounding water quality, greenhouse gas emissions, and soil health continue to garner the national spotlight, the adoption of no-tillage (NT) practices by agriculture producers has been repeatedly touted as the best option to address all three concerns. No-tillage is a conservation tillage system defined as no soil disturbance other than the opening of a trench wide enough to accommodate seed placement (Depsch et al., 2014). Within the mid-southern USA, however, intensive tillage systems remain the cultural norm (Bryant et al., 2020a; USDA-NASS, 2019). The Delta region of Mississippi currently has only 145,000 hectares of production land managed according to NT standards (USDA-NASS, 2019). Minimal adoption of NT is likely due to the need for raised seed-beds to achieve maximum soybean [*Glycine max* (L) Merr.] productivity in a region that is 80% gravity flow irrigated and where the frequency of high-intensity rainfall events is increasing (Dourte et al., 2015; Easterling et al., 2017; Huitink and Tacker, 2000; USDA-NASS, 2013).

Typical mid-southern USA conservation production systems include planting soybean on a raised, stale seed-bed into chemically desiccated winter fallow residues during the 01 April to 15 April planting window (Bryant et al., 2020b; Heatherly, 1999a; Salmeron et al., 2016). On medium- to coarse-textured soils this system must include subsoiling to maximize soybean productivity and profitability (Bryant et al., 2020a; Heatherly et al., 1990; Popp et al., 2001). Mid-southern USA conservation tillage systems that do not include subsoiling can reduce soybean grain yield by at least 10% (Bryant et al., 2020a). However, regional producers are being pushed to increase adoption of soybean production systems which further reduce tillage operations and increase ground cover to capture the associated ecoservices.

Increased adoption of NT in the mid-southern USA is unlikely due to concerns over the effects of restrictive soil layers and seed-bed deterioration on soybean productivity and necessary irrigation and drainage. Strict adherence to NT standards excludes necessary subsoiling to remediate restrictive soil layers. No-tillage production systems on medium- to coarse-textured soils can reduce crop productivity up to 33% due to restrictive soil layers (Schwab et al., 2002; Watts and Torbert, 2011). Mid-southern USA soybean producers are also concerned that NT systems will have a negative effect on the efficacy of irrigation systems. Gravity flow irrigation delivery systems require furrows to effectively and efficiently direct water across production fields. On medium- to coarse-textured soils, the susceptibility of raised seed-beds to erode during a single growing season necessitates the creation of furrows on a yearly basis. However, it may be possible to garner some of the environmental benefits associated with NT while maintaining soybean productivity and profitability through modification of a zone-tillage system.

Modifying current zone tillage systems so that the tilled and untilled zones are inverted and including a deep-rooted cover crop may provide necessary furrows for irrigation and drainage purposes while alleviating restrictive soil layers and increasing ground cover. Traditional zone-tillage consists of tilling the seed row while the remaining soil surface remains untilled (Logan et al., 1991). In zone-tillage for furrow-irrigated environments the seed-row becomes the untilled portion while shallow furrows are created between seed-rows with a row-crop cultivator. Deep rooted cover crops such as the tillage radish (*Raphanus sativus* L. var. *longipinnatus*) can penetrate restrictive soil layers with bulk densities ranging from 1.3 to 1.75 Mg m^{-3} to a depth of 50 cm and are considered biological means of remediating restrictive soil layers (Chen and Weil, 2010; Weil et al., 2011). Thus, the objective of this study was to determine the effect of zone-tillage systems with and without a tillage radish cover crop on soybean grain yield, net returns above specified costs, and water use efficiency (WUE) relative to a mid-southern USA conservation tillage system with subsoiling.

4.3 Materials and Methods

4.3.1 Site Description and Experimental Design

Continuous soybean research was conducted during the 2016 through 2018 soybean growing seasons at the Mississippi State University Delta Research and Extension Center near Stoneville, MS. Field details such as soil texture, production history, and experimental units are described previously (Bryant et al., 2020a). Prior to this research, reduced tillage was practiced from field establishment and subsoiling was added to the treatment in the fall of 2014. Zone tillage/winter fallow was a long-term no-tillage treatment until the summer of 2015 and zone tillage/tillage radish was converted from reduced tillage standards in the fall of 2014 with tillage radish planted the first time in the fall of 2015. Three replications of three treatments were arranged in a randomized complete block design. Treatments are described as follows:

1. Reduced tillage/subsoiling – In-row subsoiling was performed to a depth of 56 cm using a four-row parabolic subsoiler in the fall. Experimental units were then disked once with a 4-m wide offset disk harrow and raised seed-beds were created with a four-row pan hipper and pull type drum roller. Native vegetation grew throughout the fallow period and was chemically desiccated two weeks prior to planting. Soybean was planted utilizing the stale seed-bed system (Heatherly, 1999b). Furrows were prepared for irrigation with a row crop cultivator with shallow flat sweeps attached.
2. Zone tillage/winter fallow – No tillage operations were conducted in the fall or spring of any crop year. Soybean was planted flat into native winter vegetation that was chemically desiccated two weeks prior to planting. Shallow furrows were created every

year to facilitate furrow-irrigation using a row crop cultivator with shallow flat sweeps. At a depth of approximately 5 cm these furrows did not create raised seed-beds.

3. Zone tillage/tillage radish – Experimental units were subjected to the same tillage and furrow creation standards as zone tillage/winter fallow treatments. Following soybean harvest tillage radish was drill-seeded using a Great Plains 4.5-m wide grain drill (Great Plains Manufacturing Inc., Salina, KS) with 19-cm row unit spacing at 11 kg ha^{-1} (Weil et al., 2011). Tillage radish was chemically desiccated once it began to bolt.

The soybean growing season began the preceding fall and continued through soybean harvest. Field procedure dates are presented in Table 4.1. Soybean planting and harvesting details along with cultural field management practices are described in Bryant et al. (2020a).

4.3.2 Measured Parameters

Percent ground cover at planting, cover crop biomass production, soybean plant population, and WUE were measured by in-season data collection. Ground cover measurements were recorded using the meter-stick method (Hartwig and Laflen, 1978) and dry biomass of tillage radish was determined by standard methods (Kornecki et al., 2012). Soybean stand establishment was determined by counting all emerged plants within a 1-m section of row and WUE was determined as described by Vories et al. (2005):

$$WUE = \frac{Y}{TWA} \qquad \text{(Eq. 4.1)}$$

where WUE is water use efficiency (kg ha-mm^{-1}), Y is soybean grain yield (kg ha^{-1}), and TWA is the sum of rainfall and irrigation (ha-mm). Sample timing, frequency, and intensity are described in Bryant et al. (2020b).

4.3.3 Economic and Statistical Analysis

Enterprise budgets were prepared to determine net returns above specified costs. Costs associated with all field procedures were obtained from Mississippi State University Delta Planning Budgets for the 2016, 2017, and 2018 crop years (Mississippi State University, 2016, 2017, 2018; Table 4.2). Total fixed costs and total direct costs on a per-hectare basis are included in specified costs. Assumptions regarding equipment costs were based on equipment sized for 96-cm seed-beds. Data were analyzed by ANOVA using the GLIMMIX Procedure in SAS 9.4 (Statistical Analytical System Release 9.4; SAS Institute Inc., Cary, NC) with differences considered significant at the $\alpha \leq 0.05$ level. Economic and statistical analysis procedures are discussed at length in Bryant et al. (2020a).

4.4 Results and Discussion

4.4.1 Seasonal Water Inputs and Field Measurements

Rainfall during the growing season varied by year during the study period (Table 4.3). Rainfall during the 2016 and 2018 growing seasons are classified as normal as rainfall amounts exceeded the 10-year average by 4% and 1%, respectively. Rainfall received during the 2017 growing season was 19% below the 10-year average and the growing season is classified as dry. In all years of the study, however, supplemental irrigation was required during critical soybean growth stages. The 2016, 2017, and 2018 growing seasons required two, one, and five supplemental irrigation events, respectively (Table 4.3). Rainfall timing had a greater influence on number of irrigation events than did rainfall total. Only one irrigation was required in the dry growing season as less intense rains occurred more frequently.

Pooled across years, treatment had an effect on percent ground cover and soybean plant populations (Table 4.4). At soybean planting, all treatments satisfied requirements for conservation tillage, but ground cover in zone tillage/winter fallow was 64% greater than reduced tillage/subsoiling and reduced tillage/tillage radish (P = 0.0015). The ground cover for zone tillage/tillage radish was reduced relative to zone tillage/winter fallow due to application of glyphosate and 2,4-D in the former. Glyphosate and 2,4-D were applied 12 to 14 weeks prior to soybean planting to prevent seed formation and subsequent weed infestation by tillage radish (Chen and Weil, 2011). No tillage radish residues were present at soybean planting, but native, cool-season weeds provided ground cover. Planting soybean flat, with or without a cover crop, reduced soybean plant populations by 21% relative to reduced tillage/subsoiling (P = 0.0144). Superior plant stands in reduced tillage/subsoiling relative to the flat systems was attributed to better drainage and reduced water logging in the former (Huitink and Tacker, 2000). Differences in soybean plant populations among treatments were great enough to potentially have an effect on grain yield (Edwards and Purcell, 2005).

Biomass production from tillage radish was reduced relative to values reported in the literature (Chen and Weil, 2010; Lawley et al., 2011, 2012; White and Weil, 2011). Live biomass production was 240 kg ha^{-1} and did not persist longer than six weeks after desiccation. Reduced production of biomass by tillage radish in mid-southern USA conservation systems was described previously and is attributed to fomesafen and fomesafen + S-metolachlor carryover and extended periods of soil saturation (Bryant et al., 2020b; Cornelius and Bradley, 2017; Weil et al., 2011).

4.4.2 Soybean Grain Yield

A core hypothesis of this research was that planting flat and not on a raised seed-bed would reduce soybean grain yield. Contrary to the hypothesis, planting flat, with or without a cover crop, had no effect on soybean grain yield (P = 0.4986; Table 4.4). Pooled across treatments and years, soybean grain yield was 3,799 kg ha^{-1}. Lack of soybean response to tillage system and cover crop is most likely due to a combination of soybean sensitivity to tillage and irrigation.

Across the mid-southern USA, soybean response to NT has varied. In rainfed environments soybean grain yield is either decreased or maintained relative to tillage system (Reddy, 2001, 2002, 2003; Reddy et al., 2003; Verkler et al., 2009; Zablotowicz et al., 2010). Reduced soybean grain yield in NT is attributed to reduced soybean plant populations and drought during the growing season (Reddy, 2001; Verkler et al., 2009). Conversely, soybean grain yield in irrigated NT systems is maintained relative to a tilled system as irrigation mitigates the effects of drought (Verkler et al., 2009; Watts and Torbert, 2011). Therefore, it is most likely that irrigation masked any potential differences in soybean grain yield associated with tillage or plant populations in this research as is common in the mid-southern USA (Pringle and Martin, 2003; Pringle et al., 2017).

Lack of a negative yield response to cover crop was especially surprising as a reduced tillage system with a tillage radish cover crop reduced soybean grain yield 12% in a larger component of this same research (Bryant et al., 2020b). In the mid-southern USA, soybean grown in a NT system with either a cereal rye or hairy vetch (*Vicia villosa* Roth) cover crop grain yield is either reduced or maintained relative to a no cover crop system (Reddy, 2003; Reddy et al., 2003; Zablotowicz et al., 2010). The effects of tillage radish on soybean grain yield have been evaluated more in other regions of the USA. In the northern Atlantic and Mid-West USA regions tillage radish maintains or improves soybean grain yield relative to NT without a cover crop (Dagel et al., 2014; Williams and Weil, 2004). Increased soybean grain yield following tillage radish is attributed to alleviation of restrictive soil layers and the creation of rooting channels allowing the succeeding soybean crop to easily exploit soil water and nutrients (Williams and Weil, 2004).

While these data indicate that a modified zone-tillage system is agronomically viable through the duration of this study, that may not be the case in all years. Anecdotal evidence suggests that planting date and soybean plant population may be negatively influenced in some years. In this research, soybean was planted in the early- to mid-May planting window; however, the optimum planting window is 01 April to 15 April and soybean grain yields will decrease by 0.13% day^{-1} between 15 April and 01 May and then decrease by 0.27% day^{-1} between 01 May and 15 May (Salmeron et al., 2016). Visual field observations indicated that during many years of this research lack of a raised seed-bed had a negative effect on drainage and would have delayed soybean planting beyond the optimal window. Furthermore, in year one of the succeeding study, utilizing the same treatments, 72 mm of rainfall were received 7-days after planting and reduced soybean populations to 30% of desired final plant population (Data not shown). Emerged soybean then had to be chemically desiccated and replanted 14-days after the desired planting date.

4.4.3 Net Returns Above Specified Costs

We hypothesized that removing multiple tillage inputs from the production system would increase on-farm profitability, relative to reduced tillage/subsoiling. This was not true as treatment and the interaction of treatment and year had no effect on net returns above specified costs (P = 0.3724; Table 4.4). Net returns above specified costs were \$532.92 ha^{-1}, pooled across treatments and years. The lack of response is attributed to the relatively low costs of removed tillage operations, relative to remaining inputs, and an absence of yield response (Reddy, 2001, 2002). Averaged across years, costs associated with subsoiling, disking, and seed-bed formation were \$80.23 ha^{-1} while costs for inputs shared between all soybean production systems were \$651.23 ha^{-1}. Zone tillage/tillage radish production systems included average additional input costs of \$140.25 ha^{-1} over zone tillage/winter fallow and \$60.02 ha^{-1} over reduced tillage/subsoiling for cover crop seed, planting, and desiccation. These data indicate that so long as input costs and soybean grain yield are similar net returns above specified costs will be maintained. Zone tillage systems were economically viable during this research; however, the previously discussed agronomic issues of the subsequent study will also influence the economics. Based upon 2018 costs and not accounting for any potential replant rebates, the additional costs of replanting are \$183.84 ha^{-1} (Mississippi State University, 2018). These additional costs would then increase the risk associated with net returns from zone tillage systems but may be offset by rebates offered through soybean seed companies and/or crop insurance payouts.

4.4.4 Water Use Efficiency

Based on our hypothesis that planting flat would reduce soybean grain yield we expected WUE to be decreased when planting flat, with or without a cover crop. As expected, WUE results mirrored yield, but were not different due to lack of yield response (P = 0.5652; Table 4.4). Pooled over treatments and years, soybean WUE was 14 kg ha-mm^{-1}. Greater WUE from soybean is important because it maximizes net returns of both rainfall and irrigation (Schneekloth et al., 1991). Typically, increased WUE from tillage and cover crop studies are identified in rainfed studies where one system was able to protect crop yield during drought (Darapuneni et al., 2017; Verkler et al., 2009). It is most likely that the use of irrigation in this research masked any potential WUE differences.

4.5 Conclusions

The objective of this study was to determine the effect of zone-tillage systems with and without a tillage radish cover crop on soybean grain yield, net returns above specified costs, and water use efficiency (WUE) relative to a mid-southern USA conservation tillage system with subsoiling. The zone-tillage system for furrow-irrigated environments with or without a cover crop was able to maintain soybean grain yield, net returns above specified costs, and WUE relative to a reduced tillage/subsoiling production system. Our data indicate that mid-southern USA soybean producers wanting to capture some of the environmental benefits associated with NT production systems could implement this system while being able to continue important regional practices. However, the potential risks associated with adoption of this system on soybean planting date and grain yield in a region with frequent heavy spring rains should be carefully considered.

Table 4.1 Field operation dates for a furrow-irrigated, conservation tillage, with and without cover crops, soybean [*Glycine max* (L.) Merr.] study conducted near Stoneville, MS from 2016 through 2018.

Operation	**2016**	**2017**	**2018**
Fall Tillage	6 Oct	12 Oct	26 Oct
Spring Tillage	30 Mar	21 Mar	15 Mar
Cover Crop Planting	23 Oct	19 Oct	30 Oct
Burndown	*10 Feb; 26 Apr	26 Jan; 25 Apr	12 Jan; 25 Apr
Soybean Planting	11 May	09 May	09 May
Furrow Preparation	23 May	6 Jun	29 May
Soybean Harvest	27 Sep	17 Oct	05 Oct

* When two dates appear in the same cell the first is tillage radish desiccation and was applied only to treatments containing a tillage radish cover crop, and the second date is burndown prior to planting.

Table 4.2 Treatment total specified costs* used in economic analysis.

	RT/SS†	**ZT/WF**	**ZT/TR**	**Soybean Price**
Years		$ ha^{-1}		$ kg^{-1}
2016	651.06	573.15	712.14	0.35
2017	697.59	620.32	762.01	0.35
2018	845.75	760.23	900.33	0.29

* Total specified costs include all tillage operations, pesticide applications, soybean planting and harvesting, soybean seed, irrigation supplies, irrigation water lifting, and pesticides.
† RT/SS = reduced tillage/subsoiling; ZT/WF = zone tillage/winter fallow; ZT/TR = zone tillage/tillage radish (Raphanus sativus L. var. longipinnatus) cover crop.

Table 4.3 Monthly rainfall (Rain) totals and 10-yr average (10-YAR) for Stoneville, MS and monthly irrigation totals (Irr).

	2016		2017		2018		
	Rain*	**Irr†**	**Rain**	**Irr**	**Rain**	**Irr**	**10-YAR**
Month	ha-mm						
May	24.41		27.91		18.64		49.44
June	63.45	30.9	20.19		25.34	30.9	38.11
July	39.96	30.9	34.30	30.9	22.76	92.7	37.70
August	68.50		89.51		89.92	30.9	25.54
September	0.62		9.89		78.17		38.11
October			4.53				42.95
Total	**196.94**	**61.8**	**186.45**	**30.9**	**234.84**	**154.5**	**231.85**

* Rainfall totals for each year began the day of planting and end on the day of harvest.
† 30.9 ha-mm were applied at each furrow-irrigation event.

Table 4.4 Ground cover (GC), soybean [*Glycine max* (L.) Merr.] plant population (SPP), soybean grain yield (Yield), net returns above specified costs (Returns), and water use efficiency (WUE) from a conservation tillage and cover crop study conducted near Stoneville, MS from 2016 through 2018.

	GC	**SPP**	**Yield**	**Returns**	**WUE**
Treatment*	— % —	Plants m^{-1}	kg ha^{-1}	— \$ ha^{-1} —	kg ha-mm^{-1}
RT/SS	44 b†	24 a	3971 a	578.79 a	14.31 a
ZT/WF	72 a	19 b	3658 a	557.10 a	13.21 a
ZT/TR	54 b	19 b	3769 a	453.88 a	13.65 a

* RT/SS = reduced tillage/subsoiling; ZT/WF = zone tillage/winter fallow; ZT/TR = zone tillage/tillage radish (Raphanus sativus L. var. longipinnatus) cover crop.
† Numbers in a column followed by the same letter are not different at $P \leq 0.05$.

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CHAPTER V

FURROW-IRRIGATION APPLICATION EFFICIENCY IN MID-SOUTHERN USA CONSERVATION TILLAGE SYSTEMS

5.1 Abstract

Approximately 80% of mid-southern USA irrigation requirements are supplied through gravity flow delivery systems with inherently low application efficiency. This research was conducted to determine whether the efficiency of furrow-irrigation systems could be manipulated through conservation tillage systems. Three experiments were conducted near Stoneville, MS on a Dubbs silt loam (Fine-silty, mixed, active, thermic Typic Hapludalfs) to determine the effects of reducing tillage and increasing ground cover residues on irrigation application efficiency and irrigation water use efficiency. In experiment 1, transitioning from conventional tillage to a conservation tillage system had no adverse effect on irrigation application efficiency and irrigation water use efficiency when subsoiling was included. For experiment 2, replacing subsoiling with a cereal rye or tillage radish cover crop in a conservation tillage system either had no effect or reduced irrigation application efficiency and irrigation water use efficiency up to 10%. In experiment 3, independent of cover crop, reducing tillage to only furrow creation had no adverse effect on irrigation application efficiency or irrigation water use efficiency relative to a conservation tillage system with subsoiling. Conservation tillage systems that include subsoiling maximize irrigation application efficiency and irrigation water use efficiency while minimizing adverse effects on yield and net returns relative to conservation tillage systems that

further reduce tillage and/or increase ground coverage with cover crops. Our data indicate that soybean producers in the mid-southern USA maximize furrow-irrigation functionality, yield, and profitability while minimizing risk by transitioning from a conventional tillage system to a conservation tillage system with subsoiling.

5.2 Introduction

In the mid-southern USA, water is supplied to 80% of irrigated land through gravity flow delivery systems (USDA-NASS, 2013) which is one of the least efficient irrigation systems available. Application efficiency of furrow-irrigation systems is typically near 65% while sprinkler and subsurface drip irrigation systems average application efficiencies of 85% and 95%, respectively (Lamm and Trooien, 2003). Center pivots with low energy precision application packages are 95% efficient and subsurface drip irrigation systems near 99% when deep percolation and soil evaporation are properly managed (Amosson et al., 2011; Lamm and Trooien, 2003). Because of the comparatively low efficiency, many within the US agricultural community, but outside of the mid-southern USA, are mystified by the continued use of furrow-irrigation.

The mid-southern USA is well suited for furrow-irrigation due to the relatively low costs associated with setup and water lifting and the coupling of precision land-leveling with soils possessing low infiltration rates while the adoption of more efficient irrigation systems is hindered by environmental and economic factors (Brouwer et al., 1990; Massey et al., 2017). Sprinkler irrigation systems often become stuck in the predominating clay soils and the presence of iron (Fe) in water sources clogs emitters of drip irrigation systems (Clark et al., 1996; Heatherly and Pringle, 1991; Stevens et al., 2017). While these issues can be corrected it is not considered economical in a region where total irrigation costs are currently \$0.99 ha-mm^{-1} (Mississippi State University, 2017). Therefore, the most practical solution is to identify methods of increasing the application efficiency of furrow-irrigation systems by practices which fit into regional systems without drastic changes or costs.

Many approaches to increasing furrow-irrigation efficiency have focused on chemical soil amendments or changes to water input methods. Polyacrylamide is a water soluble, synthetic organic polymer that improve infiltration by stabilizing the soil structure, thereby, decreasing runoff volumes and increasing application efficiency (Lentz and Sojka, 2009; McNeal et al., 2017). Application of polyacrylamide as either a granule on the soil surface or through irrigation water increases furrow advance time and infiltration up to 37% and 35%, respectively, while decreasing runoff volume up to 44% (Bjorneberg and Sojka, 2008; Lentz and Sojka, 2009; McNeal et al., 2017; Sojka et al., 1998). Surge irrigation is another method to increase infiltration, reduce runoff, and improve irrigation application efficiency by splitting a field into two sections and applying water in an alternating fashion as short pulses (Wood et al., 2017). Surge irrigation can reduce runoff volume, deep percolation losses, and total water applied up to 57%, 64%, and 31%, respectively, while increasing irrigation application efficiency up to 209%, compared to continuous flow irrigation and depending upon soil texture (Goldhamer et al., 1987; Mattar et al., 2017; Musick et al., 1987). While neither of these approaches to increasing application efficiency of gravity flow irrigation systems requires significant monetary investment there are considerable increases to labor and management to ensure that all aspects are functioning properly. A better approach to increasing application efficiency may be adjustments to the production system rather than to the irrigation delivery system.

Agronomic production systems which increase ground cover, i.e., conservation tillage systems, can increase key components of irrigation application efficiency. The greatest benefit from conservation tillage systems is the ability of surface residues to increase furrow advance time and infiltration rates (Ashraf et al., 1999; Mailapalli et al., 2013; Trout, 1992; Yonts et al., 1991). Prolonged furrow advance times aid infiltration by extending the time water remains on the soil surface (Dabney, 1998; Gilley, 1995; Mailapalli et al., 2013). However, tillage may have a greater effect on furrow advance time than ground cover if surface coverage does not exceed 26% (Yonts et al., 1991). On silty clay loam-textured soils, when conservation tillage systems provided at least 44% ground cover, furrow advance time and infiltration increased up to 623% and 85%, respectively (Mailapalli et al., 2011). Conservation tillage systems with 60% ground cover increased furrow advance time and infiltration up to 37% and 50%, respectively, compared to a conventional tillage system on a sandy clay loam-textured soil (Ashraf et al., 1999). However, depending on in-flow rate and furrow length, ground cover residues exceeding 48% may prevent proper functioning of furrow irrigation (Yonts et al., 1991). By increasing furrow advance time and infiltration, runoff volumes are similarly reduced in conservation tillage systems (Dabney, 1998; Mailapalli et al., 2013). Runoff from furrow-irrigation was reduced up to 93% in conservation tillage systems on silt loam and silty clay loam-textured soils (Mailapalli et al., 2011, 2013). While the benefits from increasing ground cover and reducing tillage are convincing most of the previous work has evaluated incorporated residues or garnered data from only select irrigation events over a short period of time.

There is a paucity of data evaluating conservation tillage from a systems approach through the duration of a soybean growing season in furrow-irrigated environments. In the mid-southern USA, specifically, there is no data to indicate what effects reducing tillage and increasing ground cover will have on furrow-irrigation functionality and application efficiency. Thus, the objective of this research was three fold: To determine if furrow advance time, infiltration and runoff volumes, irrigation application efficiency (IAE), and irrigation water use efficiency (IWUE) can be manipulated by; 1) Converting from conventional to conservation tillage; 2) Replacing subsoiling a cereal rye or tillage radish cover crop in conservation tillage; 3) Switching to a modified zone tillage system.

5.3 Materials and Methods

5.3.1 Site Description and Experimental Design

Continuous soybean research was conducted during the 2015 through 2018 soybean growing seasons for objective one and during the 2016 through 2018 growing seasons for objectives two and three at the Mississippi State University Delta Research and Extension Center in Stoneville, MS. Field soil was a Bosket very fine sandy loam (Fine-loamy, mixed, active, thermic Mollic Hapludalfs) in the East transitioning to a Dubbs silt loam (Fine-silty, mixed, active, thermic Typic Hapludalfs) in the West (Soil Survey Staff, 2015). The field was established in the fall of 2003 to evaluate long-term conservation practices in regard to agronomics, runoff volume, and water quality. Experimental units were precision land-leveled to a uniform slope of 0.2% and separated by 3-m wide earthen levees to prevent cross contamination of runoff. Prior to this research cotton was grown from 2004 to 2010 and corn was grown from 2011 to 2014. The 2015 growing season was a transition year to facilitate implementation of all treatments and was the first year of soybean production. Conventional tillage/winter fallow, reduced tillage/winter fallow, and reduced tillage/cereal rye treatments were original treatments implemented in 2003. The remaining reduced tillage treatments adhered to the same tillage standards from 2003; however, subsoiling was added to one treatment in the fall of 2014 and a tillage radish cover crop was added to the other in the fall of 2015. Zone tillage/winter fallow was long-term no-tillage from the fall of 2003 until the summer of 2015 and zone tillage/tillage radish was a reduced tillage treatment from the fall of 2003 until the fall of 2014 when tillage standards were changed and the tillage radish cover crop was added in the fall of 2015. This research consisted of three replications of seven treatments arranged in a randomized complete block design. Experimental units consisted of eight 1-m wide by 152-m long raised seed-beds. Treatments are described as follows:

1. Conventional tillage/winter fallow – In the fall, experimental units were disked twice with a 4-m wide offset disk harrow and remained flat through the winter. In the spring, approximately one month prior to planting, experimental units were tilled once with a 6-m wide field cultivator followed by creation of raised beds with a four-row pan hipper. Seed-beds were created immediately prior to soybean planting with a reel and harrow row conditioner. Furrows were prepared for irrigation with a row crop cultivator with shallow flat sweeps attached prior to canopy closure. This treatment served as our control as it was the most tillage intensive.
2. Reduced tillage/winter fallow – Seed-bed preparation occurred in the fall to facilitate the stale seed-bed production system. Experimental units were disked once with a 4-m wide offset disk harrow and raised seed-beds were created with a four-row pan hipper and pull type drum roller. Native, cool season vegetation grew during the fallow period and was chemically desiccated two weeks prior to planting. Prior to canopy closure, furrows were prepared for irrigation with a row crop cultivator with shallow flat sweeps attached.
3. Reduced tillage/subsoiling – Tillage, with the exception of adding subsoiling, and fallow period management was as described for reduced tillage/winter fallow. In-row subsoiling to a depth of 56 cm was performed prior to disking and seed-bed formation with a four-row parabolic subsoiler.
4. Reduced tillage/cereal rye – Tillage and fallow period management was conducted in accordance with reduced tillage/winter fallow standards with the exception of eliminating

furrow preparation. Cereal rye was drill seeded into fresh seed-beds with a Great Plains 4.5-m wide grain drill (Great Plains Manufacturing Inc., Salina, KS) with 19-cm row unit spacing at 67 kg ha^{-1}. Cereal rye was chemically desiccated at Feekes growth stage 11.1 or 01 May, whichever came first, to allow maximum biomass production without extending soybean planting beyond 15 May. Immediately prior to soybean planting, cereal rye biomass was rolled in the direction of planting with a four-row pull type drum roller.

5. Reduced tillage/tillage radish – Tillage and fallow period management was conducted according to reduced tillage/winter fallow standards. Tillage radish was drill seeded into fresh seed-beds with a Great Plains 4.5-m wide grain drill (Great Plains Manufacturing Inc., Salina, KS) with 19-cm row unit spacing at 11 kg ha^{-1} (Weil et al., 2011). To prevent seed formation and potential summer weed problems, tillage radish was chemically desiccated once it began to bolt (Chen and Weil, 2011).
6. Zone tillage/winter fallow – Experimental units were not subjected to any tillage in the fall or spring of any crop year. Native, cool season vegetation grew during the fallow period and was chemically desiccated two weeks prior to soybean planting. Soybean was planted flat in to fallow period plant residue. Prior to canopy closure, shallow furrows were created between seed rows using a row crop cultivator with shallow flat sweeps. At a depth of 5 cm these furrows did not create raised seed-beds and were created to facilitate furrow-irrigation.
7. Zone tillage/tillage radish – Experimental units were subjected to the same tillage and fallow period standards as zone tillage/winter fallow. After soybean harvest, tillage radish was drill seeded with a Great Plains 4.5-m wide grain drill (Great Plains

Manufacturing Inc., Salina, KS) with 19-cm row unit spacing at 11 kg ha^{-1} and was chemically desiccated once it began to bolt.

For this research the soybean growing season began the preceding fall and continued through soybean harvest. Dates for all field procedures are listed in Table 5.1.

5.3.2 Soybean Planting and Harvesting

In all crop years, soybean was planted in the first two weeks of May depending on cereal rye desiccation date (Table 5.1). Soybean variety ASGROW 4632 (Monsanto Co., St. Louis, MO) was planted with a four-row Monosem twin row planter (Monosem Inc., Edwardsville, KS) at 346,000 seeds ha^{-1}. The six center rows were mechanically harvested for yield comparisons at physiological maturity. Seed weights were obtained from a grain cart with calibrated load cells while moisture content was obtained with a GAC 2100b grain analysis computer (DICKEY-john, Auburn, IL). Moisture was adjusted to 130 g kg^{-1} for final yield determinations. Soybean grain yield is presented in Bryant et al. (2020a, 2020b, 2020c).

5.3.3 Irrigation Scheduling and Delivery

Irrigation was initiated when the climactic water-balance method FAO-56 (Allen et al., 1998) indicated a 5-cm soil deficit was reached. Irrigation was delivered via lay-flat poly-ethylene tubing (PolyTubing) (Delta Plastics, Little Rock, AR) and all experimental units were furrow-irrigated simultaneously. Irrigation was applied to every furrow in an experimental unit and hole size for each furrow was calculated with Pipe Hole and Universal Crown Evaluation Tool (PHAUCET) version 8.2.20 (USDA_NRCS, Washington, DC) as described by Bryant et al. (2017). Thirty-one ha-mm at a rate of 19 L min^{-1} furrow^{-1} were applied at individual irrigation timings. Application volumes and furrow, flow rates were monitored with a McCrometer flow tube with attached McPropeller bolt-on saddle flowmeter (McCrometer Inc., Hemet, CA) installed on the field inlet. Flow rate for individual experimental units was verified by catching water for one furrow for 15 seconds and calculating volume applied in one minute.

5.3.4 Measured Parameters

In-season data collection was used to calculate percent ground cover, cover crop biomass, furrow advance time, runoff volume, infiltration volume, irrigation application efficiency, and irrigation water use efficiency. At soybean planting, percent ground cover was calculated with the meter-stick method (Hartwig and Laflen, 1978) by averaging across 10 randomly selected locations within each experimental unit. Live biomass of cereal rye and tillage radish was averaged across six randomly selected locations within each experimental unit and calculated by clipping all plant material within a 0.25 m^2 area at the soil surface and drying at 60^o C for 72 hours (Kornecki et al., 2012). Furrow advance time was calculated by:

$$A_T = T_2 - T_1 \quad \text{(Eq. 5.1)}$$

where A_T is furrow advance time (min), T_2 is the time when the wetting front reached 152 m (min), and T_1 is irrigation start time (min). Runoff volume was recorded by Teledyne Isco 2150 area velocity flow module sensors (Teledyne ISCO, Lincoln, NE) installed in the drain of individual experimental units. For this research, evaporation during irrigation events was considered negligible; therefore, infiltration is calculated by:

$$V_I = V_A - V_R \quad \text{(Eq. 5.2)}$$

where V_I is infiltration volume (L), V_A is irrigation volume applied (L), and V_R is irrigation runoff volume (L). Irrigation application efficiency was calculated by:

$$IAE = \frac{V_A - V_R}{V_A} * 100 \quad \text{(Eq. 5.3)}$$

where IAE is irrigation application efficiency (%), V_A is irrigation volume applied (82,910 L experimental unit^{-1} irrigation^{-1}), and V_R is irrigation runoff volume (L). Irrigation water use efficiency was calculated as described by Vories et al. (2005):

$$IWUE = \frac{Y}{IWA} \qquad \text{(Eq 5.4)}$$

where IWUE is irrigation water use efficiency (kg ha-mm^{-1}), Y is soybean grain yield (kg), and IWA is irrigation water applied (ha-mm). Runoff volumes were not recorded from the single irrigation event of 2017 preventing calculations of infiltration volume and irrigation application efficiency due to equipment failure; thus, presented results for these variables are from the seven irrigation events of 2016 and 2018.

5.3.5 Statistical Analysis

Data from all years were analyzed by ANOVA using the GLIMMIX Procedure in SAS 9.4 (Statistical Analytical System Release 9.4; SAS Institute Inc., Cary, NC). All fixed effects and interactions among fixed effects were tested using type III statistics. Treatments were analyzed as repeated measures to determine change over time as experimental units were not re-randomized every year. Treatment means were separated by the LSMEANS statement and differences were considered significant at the $\alpha \leq 0.05$ level.

5.4 Results and Discussion

5.4.1 Seasonal Water Inputs and Field Measurements

Growing season rainfall and irrigation data are discussed in Bryant et al. (2020a; Table 5.2). Briefly, rainfall for the 2016 and 2018 growing seasons were ≤ 5% over the 10-yr average and are considered normal, while rainfall for the 2017 growing season was 19% below the 10-yr average and is considered dry. Irrigation was required in all years regardless of cumulative rainfall, and the number of irrigation events in a growing season was controlled more by rainfall frequency than amount.

5.4.2 Converting from Conventional to Conservation Tillage

Ground cover at the time of planting must meet or exceed 30% to be defined as a conservation tillage system by the United States Department of Agriculture, Natural Resource Conservation Service. In all years and for all treatments, conservation tillage ground cover requirements were satisfied. Pooled across years, ground cover in reduced tillage/winter fallow and reduced tillage/subsoiling was 42% and 44%, respectively, while ground cover in conventional tillage/winter fallow was < 5% (Bryant et al., 2020a). For all treatments, ground cover at soybean planting consisted of chemically desiccated residues of native, cool-season weeds. Decreased ground cover in conventional tillage/winter fallow relative to the two reduced tillage systems was due to spring tillage in the former, which was conducted 4- to 6-weeks prior to soybean planting.

We theorized that greater ground cover in conservation tillage systems would improve irrigation application efficiency relative to conventional tillage because greater plant residue in the former would slow furrow advance time, reduce cumulative runoff, and promote infiltration, regardless of sub-soiling. Contrary to our hypothesis, however, conservation tillage systems either had no effect or decreased irrigation application efficiency up to 29% (Table 5.3). No positive effect of conservation tillage systems on irrigation application efficiency is attributed to agricultural management practices that ensure furrow integrity.

Reduced irrigation application efficiency in reduced tillage/winter fallow relative to conventional tillage/winter fallow was attributed to maintaining furrow integrity by cultivating prior to the first irrigation. In the mid-southern USA, furrow integrity is maintained in gravity flow irrigation systems by cultivating to a depth of approximately 5 cm with a row-crop cultivator prior to the initial irrigation or canopy closure. Ensuring furrow integrity with a row-crop cultivator removes all plant residue from the flow pathway. Without plant residues to provide hydraulic roughness furrow advance time is not slowed and the potential for infiltration is decreased, as was the case in this research (Mailapalli et al., 2010; Trout, 1992; Table 5.3). Furthermore, elapsed time since primary tillage of reduced tillage/winter fallow was sufficient for soil particles to reconsolidate, collapsing macropores and preventing infiltration into the subsoil (Lampurlanes and Cantero-Martinez, 2006). These issues can be mitigated when subsoiling is included in conservation tillage systems.

Relative to conventional tillage/winter fallow, irrigation application efficiency was maintained in reduced tillage systems when subsoiling was included (Table 5.3). In the mid-southern USA, subsoiling is incorporated in agricultural production systems to remediate restrictive soil layers on medium- to coarse-textured soils (Bryant et al., 2020a). Mechanically fracturing plow-pans creates large, semi-stable channels which facilitate water movement into the subsoil (Taylor and Olsson, 1987). The creation of large, semi-stable channels in reduced tillage/subsoiling is likely why infiltration was similar to conventional tillage/winter fallow and 73% greater than reduced tillage/winter fallow (Table 5.3). The ability to maintain or improve irrigation application efficiency in reduced tillage systems with subsoiling may have a positive effect on irrigation water use efficiency.

The effect of reduced tillage systems on irrigation water use efficiency is dependent on subsoiling. In the absence of subsoiling, conservation tillage reduced irrigation water use efficiency up to 14% in two of four years relative to conventional tillage/winter fallow (Table 5.4). Conversely, the inclusion of subsoiling in conservation tillage maintained or improved irrigation water use efficiency up to 14% in three of four years relative to CT/WF (Table 5.4). Since the inclusion of subsoiling in conservation tillage systems maintains or improves irrigation application efficiency and irrigation water use efficiency relative to conventional tillage systems, reduced tillage/subsoiling is likely to be adopted so long as there are no negative effects on soybean productivity and profitability.

These data indicate that mid-southern USA soybean producers can maintain or improve irrigation application efficiency and irrigation water use efficiency by transitioning to conservation tillage system but subsoiling is required. Moreover, our agronomic and economic data indicate that the inclusion of subsoiling in conservation tillage systems maintains or increases soybean grain yield and net returns up to 68% relative to conventional tillage/winter fallow (Bryant et al., 2020a). Collectively, these agronomic, economic, and environmental data indicate that mid-southern USA soybean producers can adopt a conservation tillage system that includes subsoiling with no adverse effects.

5.4.3 Replacing subsoiling with a cereal rye or tillage radish cover crop

Ground cover and cover crop biomass data for this research were previously reported (Bryant et al., 2020b). Briefly, ground cover exceeded 30% in all treatments and met the requirements for conservation tillage systems. With the exception of cereal rye, ground cover was provided by native, cool-season weeds and declined in the order of 69% for reduced tillage/cereal rye > 42% for reduced tillage/tillage radish = 44% for reduced tillage/subsoiling. Cover crop biomass at termination was not different between cereal rye, 3,565 kg ha^{-1}, and tillage radish, 789 kg ha^{-1}. However, at soybean planting, there were no tillage radish residues present due to desiccation at bolting, while there were 3,509 kg ha^{-1} of cereal rye biomass remaining.

We postulated that replacing subsoiling with a cover crop in mid-southern USA conservation tillage systems would maintain or improve irrigation application efficiency relative to reduced tillage/subsoiling due to the effects of plant residue on soil water dynamics. As postulated, replacing subsoiling with a cover crop had no effect on irrigation application efficiency (P = 0.9384; Table 5.5). These data indicate that tillage may be further reduced in mid-southern USA conservation tillage systems by replacing subsoiling with a cereal rye or tillage radish cover crop.

Cover crops were likely able to maintain irrigation application efficiency relative to reduced tillage/subsoiling by increasing macropore flow along decaying root channels and/or increasing hydraulic roughness in the furrow. Decaying roots from cereal rye and tillage radish cover crops should have provided paths of preferential flow which would increase infiltration, as was noted in this research (Dabney et al., 1998; Table 5.5). Additionally, in the case of cereal rye, furrows were not cultivated prior to irrigation which increased plant residues, provided greater hydraulic roughness, retarded water flow, increase soil dwell time and wetted perimeter, and ultimately, infiltration (Aarstad and Miller, 1978; Table 5.5). The ability to remove subsoiling from conservation tillage system while maintaining irrigation application efficiency may positively influence irrigation water use efficiency as well.

The effects of cover crop on irrigation water use efficiency in conservation tillage systems is species dependent. Replacing subsoiling with a tillage radish cover crop reduced irrigation water use efficiency 10% relative to reduced tillage/subsoiling (Table 5.5). Conversely, replacing subsoiling with a cereal rye cover crop maintained irrigation water use efficiency relative to reduced tillage/subsoiling (Table 5.5). These data indicate that only a cereal rye cover crop should be considered for inclusion in mid-southern USA furrow-irrigated production systems as they have no adverse effects on irrigation application efficiency and irrigation water use efficiency.

This research validates that some cover crops can maintain irrigation application efficiency and irrigation water use efficiency in conservation tillage systems but adoption will be hindered by effects on yield and/or economics. Replacing deep tillage with a brassica cover crop reduced soybean grain yield and net returns up to 41% relative to reduced tillage/subsoiling (Bryant et al., 2020b). Moreover, replacing subsoiling with a cereal rye cover crop maintained soybean grain yield but reduced net returns 28% relative to reduced tillage/subsoiling. Since the exclusion of subsoiling and inclusion of cover crops never improved irrigation application efficiency or irrigation water use efficiency but, rather decreased yield and/or net returns, we submit that the most productive and environmentally conscious production system is reduced tillage/subsoiling on medium- to coarse-textured soils. There is a need, however, to evaluate the effects of eliminating tillage and including of cover crops on agronomic, economic, and environmental services relative to conservation tillage systems that receive subsoiling.

5.4.4 Switching to a modified zone tillage system

Ground cover and cover crop biomass data for this research were previously reported (Bryant et al., 2020c). Briefly, at soybean planting, ground cover in all treatments was provided by native, cool-season weed species and increased in the order of 44% for reduced tillage/subsoiling = 54% for zone tillage/tillage radish < 72% for zone tillage/winter fallow. Tillage radish biomass was 240 kg ha^{-1} at termination but did not persist until soybean planting.

We hypothesized that eliminating all subsoil and surface tillage, with the exception of furrow creation, would maintain or improve irrigation application efficiency relative to reduced tillage/subsoiling due to the effects of tillage on soil water dynamics. Moreover, we assumed that the positive effects of no-tillage on application efficiency would be amplified by a cover crop (Smith, 2016). However, regardless of cover crop, minimizing tillage to only furrow creation had no effect on irrigation application efficiency (*P* = 0.9895; Table 5.6). These data indicate that tillage can be reduced to only furrow creation while maintaining furrow-irrigation functionality similar to that of reduced tillage/subsoiling.

Zone tillage systems likely maintained irrigation application efficiency by increasing the wetted perimeter due to exclusion of raised seed-beds. In typical gravity flow irrigation systems, the wetted perimeter is constrained to the limits of the furrow and is controlled by inflow rates (Trout, 1992). In the zone tillage systems, shallow furrows without raised seed-beds allowed water to flow across plant rows, thereby, increasing the wetted perimeter, which should have increased infiltration, as noted in this research (Aarstad and Miller, 1978; Yonts et al., 1991; Table 5.6). It is possible that reducing tillage to an absolute minimum may also have positive effects on irrigation water use efficiency.

We theorized that reducing tillage to an absolute minimum and including a cover crop would increase irrigation water use efficiency in zone tillage systems because of improvements in soil health (Smith, 2016). In contrast, zone tillage systems, with or without a cover crop, maintained irrigation water use efficiency relative to reduced tillage/subsoiling (Table 5.6). As zone tillage systems had no adverse effect on irrigation application efficiency or irrigation water use efficiency, they may be considered for adoption in mid-southern USA furrow-irrigated production systems.

These data indicate that tillage can be reduced to only furrow creation on medium- to coarse-textured soils in the mid-southern USA without negative effects on irrigation application efficiency and irrigation water use efficiency. Zone tillage systems are further validated as viable conservation soybean production systems as they have no negative effects on soybean grain yield and net returns (Bryant et al., 2020c). However, there is anecdotal evidence that planting soybean in a flat, zone tillage configuration increases the risk for replants and subsequent yield loss relative bedded systems when high-intensity rainfall events occur during emergence and establishment. In 2019, 72 mm of rainfall occurred seven days after planting which reduced soybean plant populations to 30% of desired stand. Based on the average yields for this study, the estimated costs for replanting zone tillage and the yield drag associated with delayed planting is \$233.47 ha^{-1}, i.e., a 54% reduction in net returns relative to reduced tillage/subsoiling (Bryant et al., 2020c). Moreover, climate scientists are predicting that the frequency of high-intensity rainfall events will increase due to climate change (Dourte et al., 2015; Easterling et al., 2017). It is unlikely, therefore, that mid-southern USA agronomists and crop consultants will recommend a zone tillage system due to increased risk for replant and yield loss relative to reduced tillage/subsoiling.

5.5 Conclusions

The objective of this research was three fold: To determine if furrow advance time, infiltration and runoff volumes, irrigation application efficiency (IAE), and irrigation water use efficiency (IWUE) can be manipulated by; 1) Converting from conventional to conservation tillage; 2) Replacing subsoiling a cereal rye or tillage radish cover crop in conservation tillage; 3) Switching to a modified zone tillage system. On medium- to coarse-textured soils, mid-southern USA soybean producers can transition away from conventional tillage systems and adopt reduced tillage systems but must include subsoiling in order to sustain irrigation application efficiency and profitability. In reduced tillage systems subsoiling can be replaced with a cereal rye cover crop without having an adverse effect on irrigation application efficiency and soybean productivity but is unlikely to be adopted due to negative effects on profitability. Independent of cover crop, tillage may be further reduced while maintaining irrigation application efficiency and soybean productivity and profitability relative to reduced tillage with subsoiling through adoption of a zone tillage system but producers must understand the extra risk associated. Our data indicate that soybean producers in the mid-southern USA maximize furrow-irrigation functionality, yield, and profitability while minimizing risk by transitioning from a conventional tillage system to a conservation tillage system with subsoiling.

Table 5.1 Field operation dates for a furrow-irrigation application efficiency in conservation tillage systems study conducted near Stoneville, MS from 2015 through 2018.

Field Operations	**2015**	**2016**	**2017**	**2018**
Fall Tillage	14 Oct	6 Oct	12 Oct	26 Oct
Spring Tillage	9 Apr	30 Mar	21 Mar	15 Mar
CC Planting	N/A	23 Oct	19 Oct	30 Oct
Burndown	30 Apr	10 Feb*; 26 Apr	26 Jan; 25 Apr	12 Jan; 25 Apr
Soybean Planting	14 May	11 May	09 May	09 May
Furrow Preparation	04 June	23 May	06 June	29 May
Soybean Harvest	24 Sep	27 Sep	17 Oct	05 Oct

* When two dates appear in the same cell the first is tillage radish desiccation and was applied only to treatments containing a tillage radish cover crop, and the second date is burndown prior to planting.

Table 5.2 Monthly rainfall (Rain) totals and 10-yr average (10-YAR) for Stoneville, MS and monthly irrigation totals (Irr).

	2015		**2016**		**2017**		**2018**		
	Rain*	**Irr†**	**Rain**	**Irr**	**Rain**	**Irr**	**Rain**	**Irr**	**10-YAR**
Month	ha-mm								
May	76.84		24.41		27.91		18.64		49.44
June	30.18		63.45	30.9	20.19		25.34	30.9	38.11
July	23.18	61.8	39.96	30.9	34.30	30.9	22.76	92.7	37.70
Aug	13.29	61.8	68.50		89.51		89.92	30.9	25.54
Sep	9.27		0.62		9.89		78.17		38.11
Oct					4.53				42.95
Total	**152.75**	**123.6**	**196.94**	**61.8**	**186.45**	**30.9**	**234.84**	**154.5**	**231.85**

* Rainfall totals for each year began the day of planting and end on the day of harvest.
† 30.9 ha-mm were applied at each furrow-irrigation event.

Table 5.3 Furrow advance time (Advance), infiltration, runoff, and irrigation application efficiency (IAE) from a furrow-irrigated soybean [*Glycine max* (L.) Merr.] conservation tillage study conducted near Stoneville, MS from 2015 through 2018 on a silt loam-textured soil.

	Advance	**Infiltration**	**Runoff**	**IAE**
Treatment	min	—— L ——		%
CT/WF*	119 b†	45,839 a	37,071 b	55 a
RT/WF	111 b	32,401 b	50,509 a	39 b
RT/SS	130 a	55,994 a	26,916 b	68 a

* CT/WF = conventional tillage/winter fallow; RT/WF = reduced tillage/winter fallow; RT/SS = reduced tillage/subsoiling.

† Numbers within a column followed by the same letter are not different at the $P \leq 0.05$ level of significance.

Table 5.4 Soybean [*Glycine max* (L.) Merr.] irrigation water use efficiency from a furrow irrigated conservation tillage study conducted near Stoneville, MS from 2015 through 2018 on a silt loam-textured soil.

	2015	**2016**	**2017**	**2018**
Treatment	—— $kg\ ha\text{-}mm^{-1}$ ——			
CT/WF*	15 a†	70 a	113 b	25 b
RT/WF	15 a	60 b	104 c	25 b
RT/SS	14 a	63 b	117 a	29 a

* CT/WF = conventional tillage/winter fallow; RT/WF = reduced tillage/winter fallow; RT/SS = reduced tillage/subsoiling.

† Numbers within a column followed by the same letter are not different at the $P \leq 0.05$ level of significance.

Table 5.5 Furrow advance time (Advance), infiltration, runoff, irrigation application efficiency (IAE), and irrigation water use efficiency (IWUE) from a furrow-irrigated soybean [*Glycine max* (L.) Merr.] conservation tillage with a cereal rye (*Secale cereale* L.) or tillage radish (*Raphanus sativus* L. var. *longipinnatus*) cover crop in place of subsoiling conducted near Stoneville, MS from 2016 through 2018.

	Advance	**Infiltration**	**Runoff**	**IAE**	**IWUE**
Treatment	min	——— L ———		%	kg ha-mm^{-1}
RT/SS*	132 b†	51,486 a	31,425 a	62 a	69 a
RT/RC	153 a	54,306 a	28,604 a	65 a	65 ab
RT/TR	102 c	52,642 a	30,269 a	63 a	62 b

* RT/SS = reduced tillage/subsoiling; RT/RC = reduced tillage/rye cover; RT/TR = reduced tillage/tillage radish.

† Numbers within a column followed by the same letter are not different at the $P \leq 0.05$ level of significance.

Table 5.6 Furrow advance time (Advance), infiltration, runoff, irrigation application efficiency (IAE), and irrigation water use efficiency (IWUE) from a furrow-irrigated soybean [*Glycine max* (L.) Merr.] zone tillage system with or without a tillage radish (*Raphanus sativus* L. var. *longipinnatus*) cover crop conducted near Stoneville, MS from 2016 through 2018.

	Advance	**Infiltration**	**Runoff**	**IAE**	**IWUE**
Treatment	min	——— L ———		%	kg ha-mm^{-1}
RT/SS*	132 a†	51,486 a	31,425 a	62 a	69 a
ZT/WF	189 a	52,527 a	30,384 a	63 a	64 a
ZT/TR	167 a	51,658 a	31,253 a	62 a	67 a

* RT/SS = reduced tillage/subsoiling; ZT/WF = zone tillage/winter fallow; ZT/TR = zone tillage/tillage radish.

† Numbers within a column followed by the same letter are not different at the $P \leq 0.05$ level of significance.

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