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Title: Cover Crop and Tillage Effects on Irrigation Application Efficiency, Runoff Volume, Transport, Soybean Grain Yield and Net Returns

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Abstract

With numerous suggested improvements to production agriculture systems from properly applied soil health best management practices, many outside of the Midsouthern USA are perplexed by the relative lack of adoption of production systems to promote soil health. This study was conducted to determine the effect of conservation tillage (conventional, reduced, zone) with cover crops [cereal rye (*Secale cereale* L.), tillage radish (*Raphanus sativus* L.)], no cover crop] on irrigation application efficiency, offsite agrochemical transport, soybean [*Glycine max* (Merr.) L.] grain yield and net returns above specified costs. Seven treatments, conventional tillage/winter fallow (CT/WF), reduced tillage/winter fallow (RT/WF), reduced tillage/rye cover (RT/RC), reduced tillage/tillage radish (RT/TR), reduced tillage/sub-soiling (RT/SS), zone tillage/winter fallow (ZT/WF), and zone tillage/tillage radish (ZT/TR) were arranged in a randomized complete block design with three replications. Experimental units (8-m wide x 170-m long) instrumented to mass balance water, sediment, and agrochemical transport were planted with soybean at 345,935 seeds acre^{-1}. Pooled across years including a cover crop or sub-soiling in a reduced tillage system or switching to zone tillage systems increased irrigation application efficiency 32% while reducing total irrigation runoff volume 29% ($P < 0.0001$). Adopting ZT/WF, ZT/TR, RT/RC, or RT/SS production systems reduced total sediment transport 52% ($P = 0.0326$) whereas RT/TR and RT/RC reduced total N and P losses by 46% and 54%, respectively ($P \leq 0.0047$). Soybean grain yield and net returns above specified costs were increased by 9% and 23%, respectively, in a RT/SS production system ($P \leq 0.0152$). These data indicate that switching to a RT/SS Mid-Southern, USA soybean production system will maximize irrigation application efficiency, soybean grain yield, and net returns, while reducing total irrigation runoff volume, and agrochemical transport.

Introduction

Implementation of soil health production systems can benefit the entire agricultural system when conducted properly. Historically, erosion mitigation was the primary reason for adopting soil health BMPs (Lahmar, 2010), with recent focus placed on conserving soil moisture (Price et al., 2009). Soil health programs employ three principles conjunctively to improve soil physiochemical properties, reduce erosion, and offsite agrochemical transport, that is, decrease soil disturbance, increase soil coverage, and crop rotation (Lahmar, 2010). In some U.S. regions these principles are established independently of each other and not combined into one soil health system.

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The Mid-South, US is one region where soil health programs have not seen wide acceptance or implementation, yet could have a significant impact on production practices. Mid-South, US producers are skeptical of soil health programs due to associated production limitations, both perceived and actual. Irrigated agriculture in the Mid-South, US stands to reap the greatest benefits from soil health initiatives. Currently furrow irrigation is the prominent irrigation practice in the Mid-South, US. However, it is also one of the most inefficient uses of irrigation water. While many of these inefficiencies are inherent in the system itself, they are compounded by underlying soil issues.

Silt loam soils are some of the most productive soils in the region. These soils are plagued, however, by surface crusting which severely limits infiltration (Lado et al., 2004), while increasing runoff volumes (Endale et al., 2008) and erosion (Lahmar, 2010). Increases in runoff and soil loss also present the possibility of increased agrochemical transport. Past research, conducted at the Mississippi State Delta Research and Extension Center Stoneville, MS, indicates that irrigation application efficiencies may be increased through the use of surge valves or chemical soil amendments. Both of these approaches may add significant cost to producers.

Properly implemented soil health practices may increase furrow irrigation efficiency while simultaneously increasing producer returns through reduced inputs. Conservation tillage is a major component of soil health and has shown many benefits in regards to surface crusting, infiltration (Fageria et al., 2005), and agrochemical transport (Reddy et al., 2003). By definition, conservation tillage is any tillage operation that maintains 30% coverage of the soil surface by plant residue at planting (Lampurlanes and Cantero-Martinez, 2006). This definition leaves considerable variation in actual tillage operations performed, ranging from strict no-tillage (NT) to fall seed-bed preparation. Fall seed-bed preparation is the predominant tillage system in the Mid-South, US. While this system may accumulate significant plant residue amounts during the winter, the soil surface remains exposed for extended periods of time, potentially increasing soil crusting potential.

Fall cover crops are a soil health BMP that protect the soil surface during fallow periods (Dabney et al., 2001). Cover crops preserve soil structure from destructive forces that induce crusting, such as raindrop impact (Acuna and Villamil, 2014) and flowing water (Gabriels et al., 1997). Cover crops also increase surface porosity through root decomposition (Balkcom et al., 2007). Actively growing cover crops scavenge residual nutrients from the surrounding soil (Dabney et al., 2001), minimizing nutrient leaching and aiding in nutrient management (Olson et al., 2010). Potential negative impacts of cover crops include yield reductions (Clark et al., 2007; Dabney et al., 2001), delayed cash crop emergence (Acuna and Villamil, 2014), and soil water depletion (Blanco-Canqui et al., 2013).

Many investigators suggest a 3-5 year time period before soil health benefits are fully realized when switching to conservation practices (DeLaune et al., 2012; Raper et al., 2000; Reddy et al., 2009). Benefits associated with adopting soil health BMPs including improved soil physiochemical properties, reduced erosion, and decreased off-site agrochemical transport vary based upon geographic location and regional agricultural production practices (DeLaune et al., 2012). Therefore, the objective of this study was to determine the effect of conservation tillage (conventional, reduced, zone) with cover crops [cereal rye (*Secale cereale* L.), tillage radish (*Raphanus sativus* L.)], no cover crop] on irrigation application efficiency, offsite agrochemical transport, soybean [*Glycine max* (Merr.) L.] grain yield and net returns above specified costs.

Materials and Methods

This project was conducted at Mississippi State University's, Delta Research and Extension Center in Stoneville, MS from 2015-2018. Soils of the field consisted of Dubbs silt loam and Bosket very fine sandy loam (Soil Survey Staff, 2015). Twenty-one plots were established in 2003 by the USDA-ARS in Stoneville, MS. Field grade falls from North to South and West to East following precision leveling. Cotton (*Gossypium hirsutum*) was grown from 2003 to 2010, and from 2011 to 2014 corn (*Zea mays*) was grown. Beginning in the spring of 2015 continuous soybean was grown.

Experimental units were 8-rows wide by approximately 170-m long with 102-cm wide rows and were hydrologically separated by 3.1-m wide levees. Culverts were fitted with Teledyne Isco 2150 area velocity flow module sensors (Isco, Inc., Lincoln, Nebraska) and GLS Compact Composite Samplers (Isco, Inc., Lincoln, Nebraska) to measure runoff volume and capture water quality samples. A McCrometer flow tube with attached Mc®Propeller bolt-on saddle flowmeter (McCrometer Inc., Hemet, California) was installed on the riser to measure application volume.

Year one of the study was a transition year and consisted of four treatments with three replications arranged in randomized complete block design. Treatments included reduced tillage/winter fallow (RT/WF), reduced tillage/cereal rye cover (RT/RC), zone tillage/winter fallow (ZT/WF), and conventional tillage/winter fallow (CT/WF). Beginning in year two three additional treatments of reduced tillage/tillage radish cover (RT/TR), reduced tillage/sub-soiling (RT/SS), and zone tillage/tillage radish cover (ZT/TR) were added. Tillage operations were conducted as follows: Reduced tillage treatments were disked twice followed by bed formation in the fall after harvest. Zone tillage treatments were planted flat, and one pass was made with a sweep plow just prior to irrigation initiation for furrow creation. Conventional tillage treatments were disked twice in the fall after harvest and left flat through the winter, followed by one pass with a field cultivator and bed formation in the spring. One pass was made across RT and CT, with the exception of RT/RC, prior to irrigation initiation for furrow preparation. Rye and tillage radish were seeded using a Great Plains drill (Great Plains Manufacturing Inc. Salina, Kansas) at 67.2 kg ha^{-1} and 11.21 kg ha^{-1}, respectively.

All agronomic practices outside of tillage and irrigation scheduling were conducted according to Mississippi State University Extension service recommendations. Burn down of all plots was conducted on May 1st, April 26th, May 8th, and April 25th for 2015, 2016, 2017, and 2018, respectively. Tillage radish were chemically desiccated on February 10th, and March 21st, respectively, for 2016 and 2017, in 2018 winter kill was achieved and any regrowth continued until the April 25th burn down application. Rye cover crop was chemically desiccated with glyphosate at 1.26 kg ha^{-1} acid equivalent (ae) at the soft dough growth stage followed by rolling in the direction of planting using a four-row roller packer. Remaining treatments were desiccated using glyphosate and paraquat tank mixed at 1.26 and 1.55 kg ha^{-1} ae, respectively. Cover crop desiccation occurred two weeks prior to soybean planting on May 14th, May 11th, and May 9th, in 2015, 2016, 2017, and 2018 in accordance with recommendations described by Kornecki et al., (2012). Soybeans were planted directly into rye residue and any natural winter vegetation residue in other treatments. Soybean planting was achieved using a Monosem four row twin-row planter (Monosem® Inc./North America, Edwardsville, Kansas) at a rate of 345,935 seeds ha^{-1}.

Biomass samples were collected prior to cover crop termination. Biomass was determined by removing all cover crop residue from within 0.25-m^2 polyvinyl chloride squares (Kornecki et al., 2012) and drying for 72 hours at 60 C (Locke et al., 2005). Six samples were taken from the length of the plot to provide adequate representation along plot length. Percent ground cover was conducted on all plots just prior to soybean planting. Readings were calculated using the meterstick method (Hartwig and Laflen, 1978). Ten locations were randomly selected from the length of the plot.

The middle six rows of each plot were mechanically harvested and weighed using a portable weigh cart. Moisture content was determined and yields were adjusted to 130 g kg^{-1} moisture for analysis.

Irrigation was scheduled using FAO-56 and initiated at a 20.6 ha mm deficit, with 30.9 ha mm applied per irrigation event. Irrigation advance time was determined by:

$$A_T = T_2 - T_1$$

where A_T is the advance time; T_1 is irrigation start time; and T_2 is the time when the wetting front reached 170-m. Irrigation application efficiency was calculated by:

$$IAE = \frac{V_A - V_R}{V_A} \times 100$$

where IAE is irrigation application efficiency; V_A is irrigation volume applied (82,910-L $plot^{-1}$ $irrigation^{-1}$); and V_R is irrigation runoff volume.

Water samples were analyzed for total solids, filtered solids, suspended solids, ammonium (NH_4^+), nitrite (NO_2^-), nitrate (NO_3^-), total Kjeldahl nitrogen (TKN), total phosphorus (TP), ortho-phosphate, and total dissolved organic carbon (TDOC). Total and filtered solids were determined using American Public Health Association procedures (American Public Health Association, 1997a, 1997d), and suspended solids were determined by calculating the difference between total solids and filtered solids. Samples were vacuum filtered and filtrate was analyzed for NH_4^+, NO_2^-, NO_3^-, and soluble P (American Public Health Association, 1997b, 1997c, 2000a, 2000b; Locke et al., 2015). Ortho-phosphate was determined by digestion of unfiltered samples in H_2SO_4 with ammonium persulfate (American Public Health Association, 1997c). Analyses for filtered and digested samples were performed using a ThermoSpectronic Genesys™ 10 ultraviolet spectrophotometer (Spectronic Instruments) with a detection limit of 0.01 mg L^{-1} (Locke et al., 2015). Total phosphorus was determined by digesting unfiltered samples in H_2SO_4 with ammonium persulfate (American Public Health Association, 1997c). Total Kjeldahl nitrogen was determined with unfiltered runoff samples by digestion on a micro-Kjeldahl block digester followed by analysis with a Lachat QuickChem 8500 Series II autoanalyzer (Lachat Instruments) using Lachat Method 10-107-06-2-E (Locke et al., 2015). Samples were then filtered and analyzed using an Apollo 9000 combustion TOC analyzer (Teledyne Tekmar) to determine TDOC (Locke et al., 2015).

Economic analysis was calculated for net returns above specified costs (Table 1). Enterprise budgets were developed using Mississippi State University Delta Planning budgets for 2016, 2017, 2018, and 2019. Soybean prices were based on current cash value at Greenville, MS at the time of harvest. Results were analyzed using the GLIMMIX procedure in SAS (Statistical Analytical System Release 9.4; SAS Institute Inc. Cary, North Carolina) and means were separated using Fisher's Protected LSD at $\alpha \leq 0.05$.

Results and Discussion

Irrigation Application Efficiency

Pooled across years, production systems that promote soil health extended furrow advance times. Zone tillage with and without a cover crop and RT/RC increased furrow advance times by 62% and 42%, respectively, compared to all other treatments ($P < 0.0001$; Table 2). Similarly furrow advance times were reported to be at least 41 and 50% greater with a desiccated cover crop mulch and continuous cover crop, respectively (Gulick et al., 1994). Increasing furrow advance times allows irrigation water to remain in the furrow longer, potentially increasing infiltration and decreasing runoff volumes.

Total runoff volume was reduced by treatments which promote soil health benefits. Compared to CT/WF and the current regional standard RT/WF, irrigation runoff volume was reduced by at least 29% ($P < 0.0001$; Table 2). Others have reported that reduced tillage systems with a wheat or cereal rye cover crop reduced runoff by at least 10% relative to CT (Kaspar et al., 2001; Yoo et al., 1989). Production systems that reduce irrigation runoff have implications for irrigation application efficiency.

As expected irrigation application efficiency improvements were similar to reductions in runoff volume. All evaluated conservation production systems increased irrigation application efficiency by 32% compared to the CT/WF or our current regional standard RT/WF ($P < 0.0001$; Table 2). Irrigation application efficiencies calculated for RT/RC and ZT/WF exceed single application and cyclic application efficiencies of 38 and 55% respectively (Tyler et al., 1996) and approach the efficiency of high end drip irrigation systems which can reach 98% (Yohannes and Todesse, 1998). These data indicate that implementation of soil health production systems can increase furrow advance times, decrease irrigation runoff volumes, and improve irrigation application efficiency on a silt loam textured soil in the Mid-South US.

Offsite Agrochemical Transport

The majority of production systems which promote soil health reduced offsite transport of sediments. Switching to RT/RC, ZT/WF, RT/SS, or ZT/TR reduced total solids losses by at least 52% compared to CT/WF ($P = 0.0326$; Table 3). Decreased transport in in these treatments was attributed primarily to reductions in the loss of solids > 0.45 mm compared to CT/WF. Reductions in sediment transport of at least 52 and 88% have been reported for no-tillage and cover crops, respectively (Merten et al., 2015, Yoo et al., 1988). Therefore, it is possible to reduce the offsite transport of total solids on silt loam textured soils through implementation of best management practices that promote soil health.

The offsite transport of total P and Ortho-P was variable among treatments. Ortho-P transport from greatest in the ZT/WF and RT/WF treatments but was reduced by 65% in RT/TR systems ($P < 0.0001$; Table 3). Whereas, transport of total P from soybean fields was greatest in the RT/WF treatment and reduced by 52% in RT/TR treatments ($P = 0.0047$; Table 3). Off-site transport of Ortho-P in no-tillage increased from 1.3% to 58% relative to conventional tillage (Bertol et al., 2007; Franklin et al., 2012). Conversely, total P losses were 2.7-fold greater in conventional tillage than no-tillage (Franklin et al., 2012). These data indicate that soil health BMPs will not reduce the off-site transport of total P and Ortho-P on silt loam textured soils.

All soil health BMP reduced TKN transport compared to the regional standard RT/WF. Transport of TKN was reduced by at least 23% in ZT/WF, ZT/TR, RT/SS, RT/TR, and RT/RC treatments (P = 0.0002; Table 3). Others have reported reductions in TKN transport of at least 24% through no-tillage and 79% with a wheat cover crop (Franklin et al., 2012; Yoo et al., 1988). Franklin et al. (2012), reported TKN loss from conventional tillage was 3.4-fold greater than no-tillage. Our data indicates that implementation of soil health promoting BMP will reduce TKN losses from irrigation events.

Soybean Grain Yield

Soybean grain yield varied among all treatments. The greatest yields were produced in RT/SS systems but were reduced by at least 8% in ZT/WF, RT/WF, and RT/TR systems but were not different among CT/WF, ZT/TR, and RT/RC systems (P = 0.0152; Table 4). These data agree with similar studies which reported no differences in soybean grain yield following a cereal rye cover crop and reductions in a no-tillage system, which would be similar to the zone tillage treatments (Delate et al., 2011; Reddy et al., 2003; Ruffo et al., 2004; Smith et al., 2011). Long-term tillage studies have reported varied results in which soybean grain yield was not affected by tillage in some years and split evenly between no-tillage and conventional tillage in years where differences were observed (Watts and Torbert, 2011). These data indicate that a soil health BMP should have no effect on soybean grain yield in the Mid-South region, USA, compared to the current regional standard of RT/WF.

Economic Analysis

Net returns were influenced by conservation tillage and cover crops. The greatest returns were from the RT/SS system which was not different from the CT/WF, ZT/WF, or RT/WF systems, but was significantly greater than ZT/TR, RT/RC, and RT/TR. When RT/SS is compared to ZT/TR, RT/RC, and RT/TR net returns are decreased by at least 19% ($P < 0.0001$; Table 4). These data indicate that the additional costs associated with cover crop planting and desiccation can have a negative impact on net returns. Inclusion of a cereal rye cover crop in this system contained one additional cost of planting as desiccation occurred simultaneously with spring burn down of all no cover crop treatments. Conversely, tillage radish contains associated planting costs similar to cereal rye but must be desiccated with herbicide in some years. This herbicide application is generally too early in the season to be the spring burn down, resulting in two herbicide applications prior to planting. However, compared to the regional standard RT/WF, only RT/TR systems reduced net returns.

Conclusion

The objective of this study was to determine the effect of conservation tillage (conventional, reduced, zone) with cover crops [cereal rye (*Secale cereale* L.), tillage radish (*Raphanus sativus* L.)], no cover crop] on irrigation application efficiency, offsite agrochemical transport, soybean [*Glycine max* (Merr.) L.] grain yield and net returns above specified costs. Soybean productions systems which promote soil health are able to increase irrigation application efficiency across all years by 32%. Agrochemical transport, however, was much more sporadic. Reduced tillage production systems with either a cereal rye cover crop or sub-soiling, or implementing a zone tillage production system reduced total sediment losses by 52% compared to CT/WF. Transport of Ortho-P was greatest in ZT/WF and RT/WF treatments while total P transport was greatest from RT/WF treatments but both were reduced by at least 52% in RT/TR production systems. Zone tillage/winter fallow, ZT/TR, RT/SS, RT/TR, and RT/RC reduced TKN losses by 23% compared to the regional standard RT/WF production system. Soybean grain yield and net returns above specified costs were optimized by utilizing a RT/SS soybean production system.

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Table 1. Total specified treatment costs used in economic analysis of an irrigated conservation tillage/cover crop soybean study conducted in Stoneville, MS from 2015 through 2018 on a Dubbs silt loam.

Treatment	Total Specified Costs
	$ ha^{-1}
CT/WF†	847.53
RT/WF	806.83
RT/SS	845.75
RT/RC	938.68
RT/TR	901.82
ZT/WF	788.59
ZT/TR	855.21

† Treatment Designator: CT/WF = conventional tillage/winter fallow; RT/WF = reduced tillage/winter fallow; RT/SS = reduced tillage/sub-soiling; RT/RC = reduced tillage/rye cover; RT/TR = reduced tillage/tillage radish; ZT/WF = zone tillage/winter fallow; ZT/TR = zone tillage/tillage radish

Table 2. Furrow advance time (FAT), irrigation runoff volume (IRV), and irrigation application efficiency (IAE) from an irrigated conservation tillage/cover crop soybean study conducted in Stoneville, MS from 2015 to 2018 on a Dubbs silt loam.

Treatment	FAT	IRV	IAE
	min	L	%
CT/WF†	117 d‡	43,329 a	48 b
RT/WF	116 d	49,637 a	40 b
RT/SS	141 c	30,660 b	63 a
RT/RC	166 b	24,987 b	70 a
RT/TR	116 d	25,054 b	70 a
ZT/WF	194 a	28,591 b	66 a
ZT/TR	189 a	26,246 b	68 a

† Treatment Designator: CT/WF = conventional tillage/winter fallow; RT/WF = reduced tillage/winter fallow; RT/SS = reduced tillage/sub-soiling; RT/RC = reduced tillage/rye cover; RT/TR = reduced tillage/tillage radish; ZT/WF = zone tillage/winter fallow; ZT/TR = zone tillage/tillage radish

‡ Numbers followed by the same letter within a column are not different at the $\alpha = 0.05$ level of significance.

Table 3. Offsite transport of total solids (TS), total phosphorous (TP), ortho-phosphate (OP), and total Kjeldahl nitrogen (TKN) by irrigation water in a conservation tillage/cover crop soybean study conducted in Stoneville, MS from 2015 to 2018 on a Dubbs silt loam.

Treatment	TS	TP	OP	TKN
	kg ha^{-1}			
CT/WF[†]	211 a[‡]	0.24 ab	0.05 dc	0.81 ab
RT/WF	121 ab	0.30 a	0.09 ab	0.93 a
RT/SS	92 b	0.16 bc	0.05 dc	0.57 cd
RT/RC	61 b	0.15 c	0.06 dc	0.47 d
RT/TR	141 ab	0.14 c	0.04 d	0.50 d
ZT/WF	66 b	0.24 ab	0.11 a	0.71 bc
ZT/TR	101 b	0.18 bc	0.07 bc	0.63 bcd

[†] Treatment Designator: CT/WF = conventional tillage/winter fallow; RT/WF = reduced tillage/winter fallow; RT/SS = reduced tillage/sub-soiling; RT/RC = reduced tillage/rye cover; RT/TR = reduced tillage/tillage radish; ZT/WF = zone tillage/winter fallow; ZT/TR = zone tillage/tillage radish

[‡] Numbers followed by the same letter within a column are not different at the $\alpha = 0.05$ level of significance.

Table 4. Soybean grain yield and net returns above total specified costs for an irrigated conservation tillage/cover crop soybean study conducted in Stoneville, MS from 2015 to 2018 on a Dubbs silt loam.

Treatment	Yield	Returns
	kg ha^{-1}	\$ ha^{-1}
CT/WF[†]	3,879 ab	557 ab
RT/WF	3,621 bc	503 abc
RT/SS	3,971 a	579 a
RT/RC	3,733 abc	416 dc
RT/TR	3,507 c	341 d
ZT/WF	3,658 bc	548 ab
ZT/TR	3,769 ab	469 bc

[†] Treatment Designator: CT/WF = conventional tillage/winter fallow; RT/WF = reduced tillage/winter fallow; RT/SS = reduced tillage/sub-soiling; RT/RC = reduced tillage/rye cover; RT/TR = reduced tillage/tillage radish; ZT/WF = zone tillage/winter fallow; ZT/TR = zone tillage/tillage radish

[‡] Numbers followed by the same letter within a column are not different at the $\alpha = 0.05$ level of significance.