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Conservation Management Improves Runoff Water Quality: Implications for Environmental Sustainability in a Glyphosate-Resistant Cotton Production System

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Studies suggest that coincidental adoption of both herbicide-resistant genetically modified crops (GMC) and conservation management may be mutually complementary, but integrated conservation systems with GMCs need to be assessed to balance production goals with environmental concerns. Genetically modified glyphosate-resistant cotton (*Gossypium hirsutum* L.) was managed on replicated experimental plots as either no-till (NT) or minimum tillage (MT) and with either no cover (NC) or rye (*Secale cereal* L.) cover crop (CC) from 2001 to 2007 near Stoneville, MS. Rainfall simulations in 2007 were used to evaluate water quality in runoff as influenced by management at two critical times: (i) 24 h after fertilizer application in the spring; and (ii) 24 h after tillage following crop harvest. With the exception of MT-NC in the spring (with the lowest surface plant residue coverage, 2%), runoff was higher in fall than spring. Suspended solids and turbidity in runoff were higher for tilled soil (MT) and areas with no cover crop, particularly in the fall. Tillage in the fall was the largest contributor to erosion loss. Similarly, total orthophosphate and total Kjeldahl N losses were greatest with tillage in the fall, while the lowest dissolved organic C losses in runoff were in fall with NT. Overall, NT and CC treatments reduced nutrient and solids losses. Major factors contributing to these results include recent tillage (in the fall) and coverage of the soil surface by plant residues (NT > MT, CC > NC). This study demonstrated the effectiveness of integrating cover crop and conservation tillage in reducing runoff and nutrient losses in a GMC system.

Abbreviations: CC, cover crop; DOC, dissolved organic carbon; DS, dissolved solids; FOP, filtered orthophosphate; GMC, genetically modified crop; M3-P, Mehlich 3 extractable phosphorus; MT, minimum tillage; NC, no cover crop; NT, no-till; SS, suspended solids; TC, total carbon; TKN, total Kjeldahl nitrogen; TOP, total orthophosphate; TS, total solids.

Numerous studies have demonstrated the benefits derived from agronomic practices such as cover crops and minimum tillage that conserve water and soil (Zobeck and Schillinger, 2010). Cover crops provide protection to the soil surface from sediment runoff loss (Mutchler and McDowell, 1990), and decomposing cover crop residues can improve physical and biological attributes of the soil (Locke and Bryson, 1997). Reducing tillage operations helps to preserve and improve soil structure (e.g., increased macropores and infiltration) (Castellanos-Navarrete et al., 2012) and reduces susceptibility to erosion (Prasuhn, 2012; Zhang et al., 2007; Zhang, 2012). Therefore, from the perspective of erosion control and sediment loss in runoff, increased adoption of conservation measures in agricultural landscapes is a positive step toward addressing environmental con-

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cerns such as degrading soil and water resources. Relating positive or negative effects of conservation management on nutrient export in watershed systems is more complicated and varied (Sprague and Gronberg, 2012). Although significant research has been conducted on the impacts of conservation management on soil characteristics and erosion control, relatively few studies have addressed the impacts from those practices on nutrient losses in runoff, and results have been mixed (McDowell and McGregor, 1980; Mostaghimi et al., 1988; Owens and Edwards, 1993; Daverede et al., 2003; Tiessen et al., 2010). The dynamics of nutrient export are influenced by a number of factors, including cropping system, topography, specific practices, hydrology, nutrient chemistry, and weather patterns, and research on quantifying the effects and processes influencing nutrient fate in conservation systems is sorely needed.

Genetically modified crops (GMCs) with tolerance to herbicides such as glufosinate [2-amino-4-(hydroxymethylphosphinyl) butanoic acid] and glyphosate [*N*-(phosphonomethyl)glycine] are commonly used, and crops with tolerance for other herbicides (e.g., 2,4-D [2-(2,4-dichlorophenoxy)acetic acid] or dicamba [3,6-dichloro-2-methoxybenzoic acid]) are being developed. Integrating GMCs with herbicide tolerance into farming systems provides flexibility with respect to the management of conservation practices, for example, increased windows of time available for planting and herbicide application (Graef et al., 2007) and minimizing the need for post-planting cultivation. Studies have suggested that the coincidental increase in adoption of both herbicide-resistant GMCs and conservation management may be mutually complementary (National Research Council, 2010). Because herbicide-resistant GMCs are often integrated with conservation management systems, concerted assessments of environmental risks in the context of conservation systems need to be undertaken. However, relatively little effort has been expended in assessing the impacts on soils or soil processes in these integrated systems (Locke et al., 2008).

Some of the impacts on soil may not be directly attributed to the GMC itself but rather to the way in which the GMC system is managed. For example, one of the most prevalent environmental issues concerning herbicide-resistant GMCs is that of herbicide-resistant weeds. Reports of weed species shifts due to the use of glyphosate-resistant GMCs are rapidly increasing (e.g., Webster and Nichols, 2012). The agricultural community is struggling to find ways to curtail the spread of herbicide-resistant weeds, and management recommendations include diversified and closely monitored approaches (Norsworthy et al., 2012). The judicious use of tillage in ways that minimize soil disturbance may be an acceptable option for managing some herbicide-resistant weeds. However, because of the detrimental effects of erosion due to tillage, a return to widespread and repeated use of tillage to manage weeds should be avoided.

Studies have shown that chemical losses are often associated with the time lapsed after application (Wauchope, 1978), and chemical and sediment losses are associated with the length of time since tillage (Auerswald, 1993; Wilson et al., 2004). Because chemical and sediment losses are associated with tillage and cover cropping practices, understanding how implementing managed tillage to control weeds in herbicide-resistant GMC production influences losses is an important management question. In a previous study related to the research presented here, Krutz et al. (2009) demonstrated the mitigation effects of tillage and a cover crop on solids and herbicide runoff loss in a simulation conducted in the spring soon after planting genetically modified glyphosate-resistant cotton. In this study, we investigated the effects of tillage and a cover crop on nutrient and associated sediment losses using rainfall simulations at two critical times with respect to management: (i) 24 h after fertilizer application in the spring (the same time period as Krutz et al., 2009); and (ii) 24 h after tillage following crop harvest in the fall.

MATERIALS AND METHODS

Site Description

A cotton field experiment was established on a Dundee silt loam (a fine-silty, mixed, active, thermic Typic Endoaqualf) at the USDA–ARS Crop Production Systems Research Unit farm near Stoneville, MS, in the fall of 2000. A detailed account of the methods used was reported by Locke et al. (2013). Briefly, the experiment was arranged as a split plot with four blocks. The main experimental effect was tillage (no-till [NT] or minimum tillage [MT]), and cover crop was the split-effect treatment. Although the full experiment consisted of two cover crop treatments (rye and balansa clover [*Trifolium michelianum* Savi var. *balansae* Boiss. Azn.]) compared with a no-cover-crop treatment (Locke et al., 2013), only the rye cover crop (hereafter designated CC) and no cover crop (NC) treatments were utilized for the simulated rainfall study described here. The area for each experimental field plot was 0.026 ha.

The MT plots were disked and row beds were formed after harvest each year. This was the only tillage operation other than smoothing the tops of the beds in the spring before planting cotton. The MT treatment is defined in comparison to conventional tillage in this region, which consists of multiple tillage operations each year. The NT plots were never tilled, and cotton was planted directly into the row beds from the previous cotton crop. The rye cover crop was planted in the fall after cotton harvest and tillage (in the case of MT). The rye was killed with 1.12 kg a.i. ha^{-1} glyphosate applied on 16 Apr. 2007, 1 mo before cotton was planted (16 May). Nitrogen as liquid urea–NH_4NO_3 was applied at a rate of 134 kg N ha^{-1} 1 d before planting cotton. This experimental management schedule was repeated for 7 yr.

Rainfall Simulations

Two rainfall simulations were conducted in 2007 to evaluate nutrient and associated sediment runoff: (i) 1 d after N fertilizer application (1, 8, 9, and 15 May for Blocks 1–4, respectively); and (ii) after plots were disked following cotton harvest in the fall (30–31 October, 1–2 November).

One day following cotton planting and fertilizer application in the spring, 0.0002-ha microplots were established for rainfall simulations within each experimental field plot (NT-NC, MT-NC, NT-CC, and MT-CC) (Krutz et al., 2009). Dimensions of the microplots were 1 m wide by 2.43 m long, and they were centered over one cotton row bed. Aluminum frames were pressed into the soil surface (to approximately 10-cm depth) along the border of each microplot to provide hydrologic isolation during the rainfall simulation. A calibrated dual oscillating nozzle rainfall simulator (41.4 kPa at the nozzles) delivering a nominal rainfall intensity of 60 mm h^{-1} was used for the experiment (Meyer and Harmon, 1979). The nozzles were 3.2 m above the soil surface, and a plastic tarp was wrapped around the rainfall simulator apparatus to minimize disturbance from wind. Rainfall simulations were initiated and continued until 60 min of runoff was generated per microplot.

For the rainfall simulation conducted after cotton harvest in the fall, the MT plots were disked and rowed into beds by block on 29, 30, and 31 October and 1 November. Immediately after land preparation for MT plots within each block, microplots were established on all experimental field plots, and rainfall simulations were conducted as described above.

Runoff Sample Collection, Processing, and Analysis

For both spring and fall rainfall simulations, all runoff generated during the simulation flowed through an outlet flume positioned at the downslope end of the microplot. All water and sediment were captured in a holding tank. Runoff rates were determined by manually recording the water height (cm) in the holding tank at 60-s intervals. Runoff samples were collected in 1-L glass bottles from the flume outlet for nutrient and sediment analysis at 5, 10, 15, 20, 30, 40, 50, and 60 min after runoff initiation. All glass bottles were sealed with Teflon-lined screw caps and placed on ice until transport to the National Sedimentation Laboratory, Oxford, MS, where they were either immediately processed or frozen until processing.

Analyses of runoff samples was done in accordance with procedures developed from the American Public Health Association. Physical analyses of runoff samples included total solids (TS) and total dissolved solids (DS), which include all nonaggregated fine solids <0.45 mm (American Public Health Association, 1997a, 1997d). To determine TS, 100 mL of well-shaken runoff sample was measured into a tared evaporating dish, and the sample weight was recorded after drying for 48 h at 105°C. To determine DS, sample bottles were manually shaken to resuspend the sediment, a 100-mL sample was vacuum filtered (0.45 mm), and the filtrate residue weight was determined after drying for 24 h at 105°C. Total suspended solids (SS) (solids >0.45 mm) were calculated by the difference between TS and DS. Turbidity (in nephelometric turbidity units, NTU) was measured on unfiltered samples using the nephelometric method with a Hach 2100P turbidimeter (American Public Health Association, 2001).

Runoff samples were vacuum filtered (0.45 mm), and the filtrate was analyzed for NH_4^+, NO_3^-, NO_2^-, and soluble reactive P, i.e., orthophosphate, according to American Public Health Association (1997b, 1997c, 2000a, 2000b). Total orthophosphate (TOP) was determined by digesting 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 GenesysTM 10 ultraviolet spectrophotometer (Spectronic Instruments) with a detection limit of 0.01 mg L^{-1}. Unfiltered runoff samples were processed for total Kjeldahl N (TKN) by digesting unfiltered samples on a micro-Kjeldahl block digester (H_2SO_4 with HgO and K_2SO_4) followed by analysis with a Lachat QuickChem 8500 Series II autoanalyzer (Lachat Instruments) using Lachat Method 10-107-06-2-E. Dissolved organic C (DOC) was measured on filtered samples using an Apollo 9000 combustion TOC analyzer (Teledyne Tekmar).

Soil Characteristics and Plant Residue

Soil samples were collected from each field experimental plot coincidental with the rainfall simulations in the spring and fall. In the spring, the soil was sampled at depths of 0 to 2 and 2 to 5 cm (Krutz et al., 2009). The soil was sampled in the fall at one depth interval, from 0 to 7.6 cm, when bulk density measurements were made (see below).

Soil particle size analysis for these field plots is reported elsewhere (Krutz et al., 2009; Locke et al., 2013). Soil total C (TC) and total N (TN) concentrations were determined on duplicate air-dried samples (30 mg oven-dried basis) using a Vario Max CNS (Elementar). Soil pH was determined in 0.01 mol L^{-1} $CaCl_2$ (1:2 soil/solution), and electrical conductivity was measured in a saturated paste extract (1:1 soil/solution). Soils were assessed for Mehlich 3 extractable P (M3-P) (Mehlich, 1984; Sims, 2009) and $CaCl_2$–extractable P ($CaCl_2$–P) (Soltanpour et al., 1974; Self-Davis et al., 2009). Briefly, 0.5 g of air-dried soil was added to a 15-mL polypropylene centrifuge tube and the samples were shaken for either 1 h ($CaCl_2$–P) or 5 min (M3-P) and then filtered (0.45 mm). Filtered extracts were analyzed colorimetrically according to procedures described by Murphy and Riley (1962) using a BiotekELX 808 absorbance microplate reader (Biotek Instruments).

Bulk density and antecedent moisture content were determined on samples collected during the spring and fall experiments from the 0- to 7.6-cm depth on the top of plant rows at two randomly selected locations within each plot and using methods similar to those described by Blake and Hartge (1986). Soils were dried, and bulk density was calculated from the total dry weight of the soil and the volume of the coring device. Infiltration was measured only in the spring using a cylinder infiltrometer (Bouwer, 1986). Residue coverage at the time of the simulated rainfall was determined by visual estimates on a 1- by 2.43-m-long area on a scale of 0 (no coverage) to 100% (complete coverage).

To compare the spring and fall soil results and to present the data on an area (e.g., Mg N or C ha^{-1}) basis using bulk density measurements, the spring soil sample data from the 0- to 2- and

2- to 5-cm depths were recalculated to a 0- to 5-cm basis. Results for TC, TN, M3-P, and CaCl_2–P are presented as concentrations in soil (g kg^{-1} or mg kg^{-1}) or on an area basis (Mg N or C ha^{-1}) using bulk density measurements.

Statistical Analysis

Analysis of variance and mean separation were performed using Proc Mixed (SAS Version 9.2, SAS Institute). Treatment means were separated at appropriate levels of significance using Fisher's protected LSD test. Means were typically considered significantly different at $P < 0.05$ or $P < 0.01$, but if a greater P value was considered to be important, the exact value is given. Regression and correlation analyses (Proc Corr and Proc GLM) were used to determine simple linear relationships between independent and dependent variables (SAS Version 9.2).

RESULTS AND DISCUSSION

Soil Characteristics and Plant Residue

Details of the soil particle analysis were reported by Krutz et al. (2009), and statistical comparisons among the tillage, cover crop, and soil depths showed no statistical differences in the sand, silt, or clay fractions. Soil particle data pooled among the tillage, cover crop, and depth intervals averaged 216, 495, and 289 g kg^{-1} for sand, silt, and clay, respectively. Homogeneity of the silt loam texture indicated that blocking adequately controlled a known textural gradient in the experimental area, and runoff differences among treatments were not attributed to inherent variability in soil texture among plots (Krutz et al., 2009).

The management of soil and cover crops at the time of each rainfall simulation event greatly influenced some soil characteristics and surface conditions but had marginal or no effect on others (Tables 1–3). In the spring, the cover crop and other winter plants had been killed with herbicide 2 to 4 wk before the rainfall simulations. Plant residues covered 88% or more of the soil surface on CC plots for both tillage treatments at the spring rainfall simulation (Krutz et al., 2009), while the MT treatment with no cover crop had the least residue coverage (Table 1). Plant residue coverage in MT plots after fall tillage was fourfold less than that of NT plots regardless of cover crop (Table 1).

For soil chemistry parameters, statistical comparisons between simulation runoff events (spring vs. fall) were not made because the analyses for spring were determined on samples collected from the 0- to 5-cm soil depth increment, while fall samples were collected from the 0- to 7.6-cm depth increment. In both spring and fall, the main effects of tillage and cover crop indicated that soil C and N concentrations were enhanced for NT and CC (Table 2). There was also a significant interaction between tillage and cover crop for total soil C and N in both fall and spring rainfall simulation events (Table 2). At both spring and fall sampling times, no difference in total soil N concentration was observed between cover crop treatments in MT,

Table 1. Effect of no-till (NT) or minimum tillage (MT) and cover crop (CC) or no cover crop (NC) on the soil surface cover by plant residues in the spring and fall.

Tillage	Cover crop	Soil surface cover	
		Spring	Fall
		%	
NT	CC	91 a†	71
NT	NC	60 b	60
MT	CC	88 a	24
MT	NC	2c	9
NT		75.4 a	65.6 a
MT		44.9 b	16.4 b
	CC	89.6 a	47.5 a
	NC	30.6 b	34.6 b
		ANOVA *P* values	
Tillage		<0.001	<0.001
Cover		<0.001	0.09
Tillage × cover		<0.001	NS‡

† For spring or fall and interaction or main effects, means followed by the same letter are not significantly different.

‡ NS, for fall means, not significant at $P \leq 0.05$.

Table 2. Effect of no-till (NT) or minimum tillage (MT) and cover crop (CC) or no cover crop (NC) on various soil chemical parameters for the spring and fall rainfall simulations, including total C concentration (TC), total N concentration (TN), C/N ratio, Mehlich 3 extractable P (M3-P), and CaCl_2–extractable P (CaCl_2–P).

Tillage	Cover	TC	TN	C/N ratio	M3-P	CaCl_2–P
		g kg^{-1}			mg kg^{-1}	
Spring (0–5-cm depth)						
NT	CC	17.0 a†	1.40 a	12.0 a	82.5	12.4
NT	NC	11.7 c	1.05 b	11.2 b	93.2	10.7
MT	CC	13.2 b	1.08 b	12.2 a	64.7	9.53
MT	NC	13.3 b	1.11 b	12.0 a	92.3	10.7
NT		14.4 a	1.22 a	11.6 b	–	–
MT		13.3 b	1.09 b	12.1 a	–	–
	CC	15.1 a	1.24 a	12.1 a	73.6 b	
	NC	12.5 b	1.07 b	11.6 b	92.8 a	
				ANOVA *P* values		
Tillage		<0.027	<0.001	<0.03	NS‡	NS
Cover		<0.001	<0.001	<0.02	<0.043	NS
Tillage × cover		<0.001	<0.001	0.18	NS	NS
Fall (0–7.6-cm depth)						
NT	CC	15.2a	1.23 a	12.3 a	57.9 b	6.98 ab
NT	NC	11.6b	1.02 b	11.4 c	58.7 b	5.78 b
MT	CC	12.6b	1.06 b	11.8 b	62.8 b	7.38 ab
MT	NC	12.0b	1.02 b	11.8 b	85.7 a	8.78 a
NT		13.4a	1.13 a		58.3 b	6.38 b
MT		12.3b	1.04 b		74.2 a	8.08 a
	CC	13.9a	1.15 a	12.0 a	60.3 b	–
	NC	11.8b	1.02b	11.6 b	72.2 a	–
				ANOVA *P* values		
Tillage		<0.05	<0.03	NS	<0.045	<0.043
Cover		<0.002	<0.004	<0.003	0.12	NS
Tillage × cover		<0.013	<0.04	<0.005	0.14	0.11

† For each parameter within a season and interaction or main effect, means followed by the same letter are not significantly different.

‡ NS, not significant at $P \leq 0.05$.

while total soil N for NT CC was higher than that of NT NC. Similarly, soil C in NT CC was higher than any other tillage or cover crop treatment in both spring and fall samplings (Table 2). For the present study area, Locke et al. (2013) reported that although elevated surface (0–2 cm) concentrations of soil C were observed in NT with respect to MT (study period 2001–2006), throughout the entire 15-cm plow layer (Mg ha^{-1} basis) TC was the same for both tillage treatments. For soil samples collected in 2007, the lower soil C and N observed in NT NC treatments in both spring and fall (Table 2) might be a consequence of stratification and dilution of the C and N by soil mixing. Therefore, it was not unexpected that C/N ratios followed a similar pattern, with the highest C/N ratio observed in NT CC and the lowest in NT NC (Table 2). Tillage did not significantly influence M3-P in the spring sampling, but M3-P was higher in the MT soils in the fall (Table 2). Lower M3-P was measured in the CC soil in both spring and fall but only at $P = 0.12$ in the fall, presumably because fall tillage in MT diluted the effect of the cover crop. Similarly, $CaCl_2$–P was higher for MT in the fall, but neither tillage nor cover crop influenced $CaCl_2$–P in the spring (Table 2). Tillage weakly influenced soil pH (Table 3), tending toward a higher pH in the MT soil. In both spring and fall, the pH was higher in the NC soil (Table 3). Neither tillage nor cover crop influenced the electrical conductivity at either sampling time (Table 3).

Neither tillage nor cover crop influenced the bulk density in either the spring or the fall (Table 3). Although similar trends have been reported elsewhere (e.g., Rhoton et al., 2002), it was anticipated that the recently fall-tilled MT soils would have a lower bulk density. Infiltration rates in the spring (not measured in the fall) measured within the crop row position were significantly higher than in the furrow positions (15.9 mm h^{-1} for row vs. 3.1 for furrow positions, $P < 0.05$). The row vs. furrow effect on the infiltration rate was probably due to compaction (Liebig et al., 1993; Locke et al., 2013). Within the row, infiltration in the spring was higher for MT and NC (Table 3). Krutz et al. (2009) reported that the soil water content before the spring rainfall simulation was slightly elevated in NT and CC soils. Similarly, for the fall rainfall simulation event, tillage and the lack of a cover crop reduced the soil water content (0.25 vs. 0.23 kg kg^{-1} in NT vs. MT, $P < 0.05$; 0.25 vs. 0.23 kg kg^{-1} in CC vs. NC, $P < 0.01$).

Several observations can be made from the soils data. Total soil C reflects the surface accumulation of crop residues on the soil surface that is typical of conservation management systems, particularly for the CC treatment. Similarly, total N concentrations were elevated in CC and NT surface soils. These effects were important in the spring, before crop residues from the winter months had decomposed, but were still evident in the fall, although diminished because of recent tillage. Higher C/N ratios were observed in the CC soil in both spring and fall, but the lowest C/N ratio occurred in the NT NC soil. Lower M3-P in the CC soil in both spring and fall might be indicative of P immobilization in crop residues. Higher M3-P and $CaCl_2$–P in the MT soils in fall might reflect disturbance and mixing from tillage.

Hydrology

Evaluation of the hydrology for the spring rainfall simulation was reported in detail by Krutz et al. (2009). For the spring rainfall simulation, the rye cover crop significantly increased the time lapse from initiation of rainfall until runoff began (Table 4). The increased time to runoff for the CC soil was attributed to greater plant residues slowing runoff (Reddy et al., 1994) and potentially increasing the moisture retention capacity in the shallow soil surface (Blanco-Canqui and Lal, 2007). When the spring and fall time lapses were compared, the cover crop effect continued regardless of the long-term tillage treatment (Table 4). However, while there was not an effect of tillage on time to runoff in the spring, the recently tilled soils in the fall exhibited more delay in runoff than the NT soils (Wilson et al., 2004). Recent tillage would have impaired surface crusting, disrupting established shallow flow paths into the surface soil profile and increasing surface roughness, thus temporarily impeding surface flow before runoff commenced (Daverede et al., 2003). The volume of rainfall retained and potentially infiltrated into the shallow surface of CC soils during the interim before runoff inception was 2.63 mm greater than in NC soils. Simulated rainfall

Table 3. Effect of no-till (NT) or minimum tillage (MT) and cover crop (CC) or no cover crop (NC) on soil bulk density (BD), electrical conductivity (EC), and pH for the spring and fall rainfall simulations and infiltration rate in the row (IR-Row) for the spring.

Tillage	Cover	BD	EC	pH	IR-Row
		Mg m^{-3}	μS cm^{-1}		mm h^{-1}
Spring					
NT	CC	1.14	728	5.71	2.52
NT	NC	1.16	660	5.78	14.9
MT	CC	1.17	502	5.75	15.2
MT	NC	1.16	561	6.03	28.6
NT			694 a†	5.75 b	8.69 b
MT			532 b	5.89 a	21.9 a
	CC		–	5.73 b	8.88 b
	NC		–	5.91 a	21.7 a
			ANOVA *P* values		
Tillage		NS‡	0.12	0.13	0.11
Cover		NS	NS	0.08	0.12
Tillage × cover		NS	NS	NS	NS
Fall					
NT	CC	1.11	345	5.91 bc	–
NT	NC	1.16	351	6.18 ab	–
MT	CC	1.10	350	5.71 c	–
MT	NC	1.17	340	6.32 a	–
	CC	1.11 b	–	5.81 b	–
	NC	1.16 a	–	6.25 a	–
			ANOVA *P* values		
Tillage		NS	NS	NS	
Cover		0.16	NS	<0.001	
Tillage × cover		NS	NS	0.09	

† For each parameter within a season and interaction or main effect, means followed by the same letter are not significantly different.

‡ NS, not significant at $P \leq 0.05$.

Table 4. Effect of no-till (NT) or minimum tillage (MT) and cover crop (CC) or no cover crop (NC) on the time to inception of runoff across two seasons.

Season	Tillage	Cover crop	Time to runoff
			min
Spring	NT		13.9 a†
	MT		15.1 a
Fall	NT		7.00 b
	MT		15.3 a
Across seasons	NT		10.5 b
	MT		15.2 a
		CC	14.1 a
		NC	11.5 b
		ANOVA *P* values	
Tillage		<0.001	
Cover		<0.03	
Season × tillage		<0.005	
Season × cover		NS‡	

† For each treatment effect, means followed by the same letter are not significantly different. Means for the interaction of season and cover are not shown because the interaction was not significant at $P \leq 0.05$

‡ NS, not significant at $P \leq 0.05$.

retained in the fall MT soil was 7.25 mm greater than in the NT soils.

Pooled across both seasons, there was a significant main effect of tillage and cover crop for the rate of runoff, with faster runoff measured from the MT and NC plots (Table 5). The pattern of runoff rate during the spring and fall simulated rainfall events was similar for all tillage and cover crop treatments, with runoff increasing more rapidly during the first 5 to 30 min and then reaching a gradual or more steady-state rate during the final 30 min. There was a cover crop × time after runoff inception interaction for runoff rate ($P < 0.0001$) (Fig. 1). The runoff rate for NC and CC in spring and fall was the same for the first 20 min of runoff, and then the runoff rate in the NC plots was faster than that in the CC plots for the duration of the simulations (Fig. 1). There was also a significant season × tillage × cover crop interaction for runoff rate (Table 5). In the spring, the runoff rate for NT CC and MT CC were the same, but the runoff rate for MT NC was higher than that of NT NC, indicating that the cover crop helped to offset the negative effects of tillage on the runoff rate in the spring. In the fall, the runoff rate for NT CC was less than that for MT CC due to recent tillage in the MT plots. The runoff rate for MT CC in the fall was equivalent to both NC treatments regardless of tillage, indicating that recent tillage before the rainfall simulation in the fall cancelled the positive effects of a cover crop in the fall. The highest runoff rates for both spring and fall were observed in plots that were tilled and had no cover crop. The decreased runoff rates from CC and NT plots were attributed to increased surface plant residues absorbing rainfall and physically impeding surface flow until shallow pores filled.

Table 5. Main effects and interactions of no-till (NT) or minimum tillage (MT) and cover crop (CC) or no cover crop (NC) for cumulative runoff and rate of runoff across the two seasons.

Season	Tillage	Cover	Runoff rate	Cumulative runoff
			mm h^{-1}	mm
Spring	NT	CC	24.1 d†	27.6 d
Fall	NT	CC	28.4 cd	34.7 cd
Spring	MT	CC	25.4 d	27.9 d
Fall	MT	CC	38.3 a	44.3 ab
Spring	NT	NC	31.4 bc	35.6 bcd
Fall	NT	NC	35.2 ab	42.4 abc
Spring	MT	NC	40.2 a	45.2 a
Fall	MT	NC	35.7 ab	43.8 ab
Across seasons	NT		29.8 b	35.1 b
	MT		34.9 a	40.3 a
		CC	29.1b	33.6 b
		NC	35.6 a	41.8 a
			ANOVA *P* values	
Tillage			<0.001	<0.020
Cover			<0.001	<0.001
Season × cover			<0.001	<0.041
Season × tillage × cover			<0.001	<0.046

† For each interaction or main effect, means followed by the same letter are not significantly different.

The main effects of tillage and cover crop averaged across seasons indicated that cumulative runoff was greater in tilled plots with no cover (Table 5). The interactions among season, tillage, and cover crop were also significant (Table 5). Similar to the runoff rate, cumulative runoff did not differ between NT and MT with cover crops in the spring, but for those plots with no cover crop, greater runoff was measured for MT than NT (Table 5). In the fall, more runoff occurred in all tilled plots and those with no cover crop. These trends were also observed in the significant interactions of season × cover crop × time for cumulative runoff ($P < 0.0485$) (Fig. 2A). After 15 min of runoff, cumulative runoff for the spring CC remained lower than cumulative runoff for spring NC for the duration of the simulation event (Fig. 2A). Similarly, when cumulative runoff for spring CC was compared with fall CC, runoff was lower in the spring beginning at 20 min after runoff initiation until runoff termination (Fig. 2A). Cumulative runoff for NC and CC in the fall was the

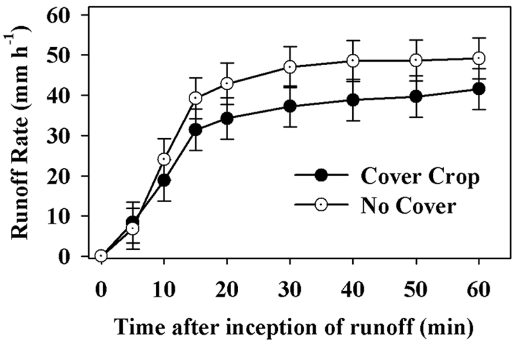

Fig. 1. Runoff rate pooled across spring and fall rainfall simulations (season) to show the effect of a cover crop during runoff. Symbols represent the mean of 16 replicates. Error bars denote Fisher's $LSD_{0.05}$ (cover crop × time).

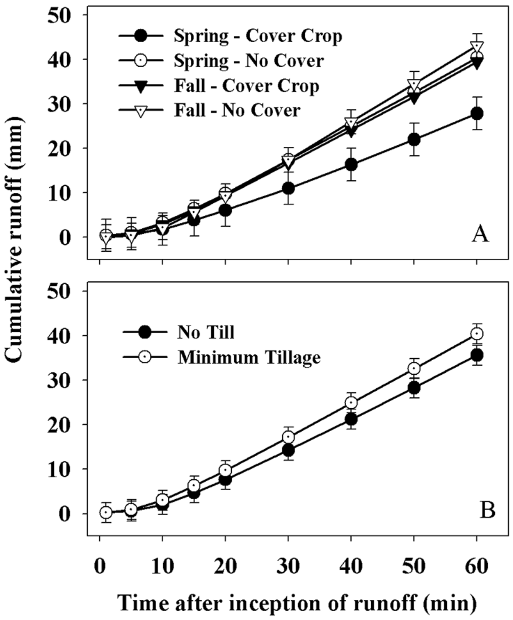

Fig. 2. (A) Cumulative runoff during the time of runoff as influenced by cover crop: no cover crop in the spring, cover crop in the spring, no cover crop in the fall, and cover crop in the fall; and (B) cumulative runoff pooled across spring and fall rainfall simulations (season) to show the effect of tillage (no-till or minimum tillage) during the time of runoff. Symbols represent the means of 8 and 16 replicates in (A) and (B), respectively. Error bars denote Fisher's LSD$_{0.05}$ for season × cover crop × time for (A) and tillage × time for (B).

same except for the final measurement at 60 min when NC was greater than CC. Cumulative runoff did not differ between spring NC and fall NC for any sampling time. The reduction in runoff volume for CC plots was attributed to surface plant residue coverage because there was a strong negative correlation ($r = -0.76$, $P < 0.0001$) between residue coverage and cumulative runoff, and residue coverage in CC plots was greater than that in NC at both simulation events (Table 1).

Averaged across the two rainfall simulation events (seasons), there was an interaction between tillage and time since runoff inception ($P < 0.005$) for cumulative runoff (Fig. 2B). From 20 min of runoff until the end of the simulation, cumulative runoff from MT was greater than that from NT (Fig. 2B). Whether the soil had been recently tilled (fall tillage before the rainfall simulation) or 7 mo before the rainfall simulation (spring simulation), cumulative runoff was less for NT. Although this pattern was consistent for the present study, results in the literature have been mixed (Van Doren et al., 1984). The length of time since establishment of the NT soils was 7 yr, which should have allowed development of a more stable structure (Locke et al., 2013), and the NT soil was characterized by higher soil organic C (Table 1). In addition, the higher surface plant residue cover in NT plots should have provided more resistance to surface water flow.

Solids Transport

Both tillage and cover crop had a significant influence on solids loss in both rainfall simulation events (Table 6). Cumulative TS and SS losses and average turbidity in the runoff were greater in MT than in NT averaged across both rainfall simulation events (Table 6). However, inspection of the interaction indicates that this difference occurred only in the fall after recent tillage (Table 6).

Table 6. Main effects and interactions of no-till (NT) or minimum tillage (MT) and cover crop (CC) or no cover crop (NC) for total solids (TS), suspended solids (SS), dissolved solids (DS), and average turbidity (in nephelometric turbidity units, NTU) in runoff.

Season	Treatment	TS	SS	DS	Turbidity
		kg ha^{-1}			NTU
Tillage					
Spring	NT	717 b†	708 b	–	2050 b
Fall	NT	502 b	483 b	–	2042 b
Spring	MT	1469 b	1450 b	–	3138 b
Fall	MT	5076 a	5039 a	–	8660 a
Across seasons	NT	609 b	595 b	14.1 b	1967 b
	MT	3272 a	3244 a	28.0 a	5899 a
	CC	1183 b	1161 b	–	2688 b
	NC	2699 a	2679 a	–	5178 a
		ANOVA *P* values			
Tillage		<0.01	<0.01	<0.01	<0.01
Cover		<0.01	<0.01	NS‡	<0.01
Season × tillage		<0.01	<0.01	NS	<0.01

† For each parameter and interaction or main effect, means followed by the same letter are not significantly different.

‡ NS, not significant at $P \leq 0.05$.

Cumulative TS and SS losses and average turbidity were less in CC than in NC in both spring and fall (Table 6). These results were attributed to the lack of tillage in NT and protection from erosion by surface plant residues in both CC and NT (Cogo et al., 1984; Laflen et al., 1978; Mannering and Meyer, 1963; McGregor et al., 1975, 1990), as indicated by strong negative correlations between runoff loss of TS and SS and surface plant residue cover ($r = 0.78$, $P < 0.001$ for both TS and SS). Across both rainfall simulation events, there was a significant interaction between cover crop and time of runoff for cumulative SS ($P < 0.001$) (Fig. 3). Cumulative SS in NC was greater than that in CC from 20 min after runoff initiation until the end (Fig. 3). There was a season × tillage × time interaction for cumulative SS ($P < 0.0001$) (Fig. 4A). As might be expected in an area that

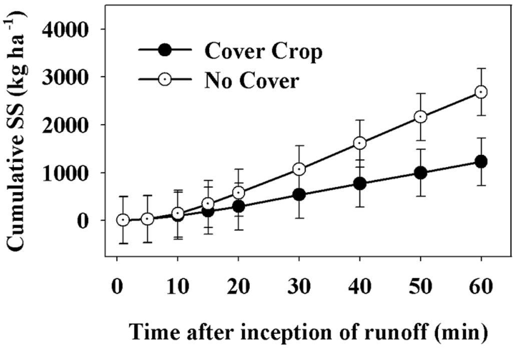

Fig. 3. Cumulative suspended solids (SS) loss in runoff pooled across spring and fall rainfall simulations (season) to show the effect of a cover crop during the time of runoff. Symbols represent the mean of 16 replicates. Error bars denote Fisher's LSD$_{0.05}$ (cover crop × time).

was recently tilled (Van Doren et al., 1984), the highest cumulative SS was lost from MT plots in the fall, and differences were observed after 15 min of runoff until the termination of runoff sampling (Fig. 4A; Table 6). The magnitude of difference in runoff loss among the other treatments was much less and was not observed until later in the runoff simulation. Cumulative SS in fall and spring NT plots did not differ at any time after runoff inception, and cumulative SS did not differ between NT and MT until the final sampling at 60 min (Fig. 4A; Table 6).

Dissolved solids comprised only a minor proportion of the TS lost in runoff. Averaged across rainfall simulation events (seasons), cumulative DS loss in MT plots was greater than that in NT (Table 6). Across rainfall simulation events, cumulative DS in runoff was influenced by an interaction between tillage and time after runoff inception ($P < 0.0001$) (Fig. 4B). After 15 min of runoff, DS in NT was less than that in MT for the remainder of the rainfall simulation event. No effect of cover crop was observed for DS loss in runoff (Table 6).

With respect to implications for herbicide-resistant GMC systems, the NT plots in this study with glyphosate-resistant GMC cotton were managed as such for 7 yr, with annual applications of glyphosate to kill winter plant residues in preparation for planting and with post-planting applications to control weeds that might inhibit cotton growth and production (Locke et al., 2013). Refraining from tillage reduced both runoff and erosion in this study. Similarly, using a cover crop reduced runoff and erosion, and including a cover crop mitigated those losses even in MT, where the soil was tilled in the fall. It was beyond the scope of this study to assess the benefits of a cover crop with respect to weed control by competition or shading, but based on other reports (Teasdale et al., 2007), using a cover crop sometimes may allow producers to minimize or eliminate herbicide use.

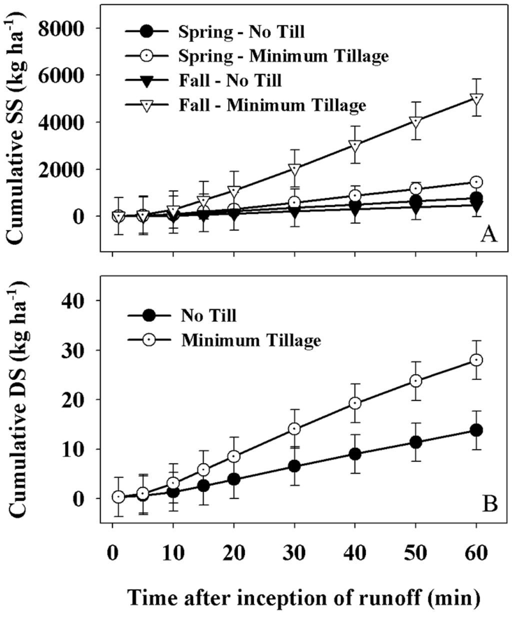

Fig. 4. (A) Effect of tillage on cumulative suspended solids (SS) loss in runoff: no-till in the spring, minimum tillage in the spring, no-till in the fall, and minimum tillage in the fall; and (B) effect of tillage on cumulative dissolved solids (DS) loss in runoff pooled across spring and fall rainfall simulations (season) to show the effect of tillage (no-till or minimum tillage) during the time of runoff. Symbols represent the means of 8 and 16 replicates in (A) and (B), respectively. Error bars denote Fisher's $LSD_{0.05}$ for (A) season × tillage × time and (B) for tillage × time.

Nutrient Transport

A significant main effect of tillage averaged across the two rainfall simulation events (seasons) indicated a greater cumulative loss of TOP, particulate P, and FOP in runoff from MT plots (Table 7). For TOP and particulate P, there was also a significant season × tillage interaction. In the spring rainfall simulation event, tillage did not influence the overall cumulative TOP and particulate P in runoff (Table 7). However, in the fall, cumulative loss of the P constituents in runoff was greater in MT than in NT (Table 7). There was also a significant interaction between tillage and time after runoff inception for cumulative TOP and particulate P loss in runoff (Fig. 5A and 5B). After 20 min of runoff during the fall simulation, loss of both TOP and particulate P was greater in MT than in NT. During the spring simulation, greater losses of TOP and particulate P in MT did not occur until after 40 min of runoff (Fig. 5A and 5B). Also, there was an interaction of tillage × time after runoff inception for FOP averaged across the two rainfall simulation events (Fig. 5C). Differences between FOP runoff between NT and MT did not emerge until late in the rainfall simulation (after 40 min).

When data were pooled across rainfall simulation events (seasons), cumulative TOP and particulate P runoff loss was greater in NC than in CC (Table 7). There was also an interaction between cover crop and time for cumulative TOP and particulate P loss in runoff (Fig. 6). After 15 min of runoff, loss of both P constituents was greater in the NC plots for the duration of the rainfall simulation.

Table 7. Main effects and interactions of no-till (NT) or minimum tillage (MT) and cover crop (CC) or no cover crop (NC) for cumulative total orthophosphate (TOP), particulate P, filtered orthophosphate (FOP), and dissolved organic C (DOC) in runoff.

Season	Treatment	TOP	Particulate P	FOP	DOC
		kg ha^{-1}			
Tillage					
Spring	NT	0.77 b†	0.36 b		3.27 a
Fall	NT	1.27 b	0.38 b		1.59 b
Spring	MT	1.15 b	0.62 b		3.06 a
Fall	MT	2.49 a	1.40 a		2.79 a
Across seasons	NT	1.02 b	0.37 b	0.65 b	
	MT	1.82 a	1.01 a	0.81 a	
Cover crop					
Across seasons	CC	1.18 b	0.50b		
	NC	1.65 a	0.88a		
			ANOVA *P* values		
Tillage		<0.01	<0.01	<0.05	NS‡
Cover		<0.05	<0.05	NS	NS
Season × tillage		<0.05	<0.001	NS	<0.05

† For each parameter and interaction or main effect, means followed by the same letter are not significantly different.

‡ NS, not significant at $P \leq 0.05$.

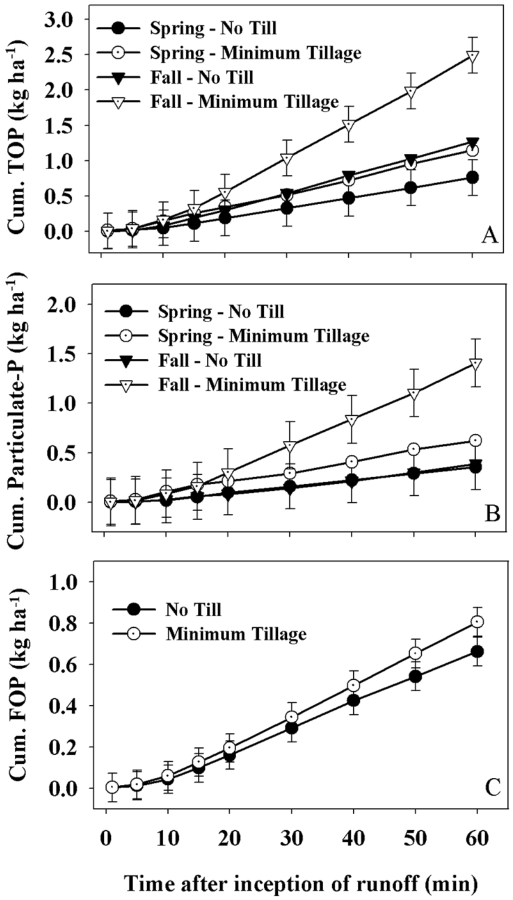

Fig. 5. Cumulative (Cum.) (A) total orthophosphate (TOP), (B) particulate P, and (C) filtered orthophosphate (FOP) showing the effects of tillage on loss in runoff. For TOP and particulate P, error bars denote $LSD_{0.05}$ showing the season × tillage × time of runoff interaction, and each symbol represents the mean of eight replicates; FOP is pooled across rainfall simulations (season), error bars denote $LSD_{0.05}$ showing the tillage × time of runoff interaction, and each symbol represents the mean of 16 replicates.

Several observations can be made from the P runoff results. Both tillage and cover crop practices helped to mitigate P losses. This effect was observed at both simulations, although the positive effects of cover crops on mitigation diminished for the fall event because of the recent tillage in MT plots. The lack of tillage in NT plots at either rainfall simulation provided a significant measure of protection from erosion. Even in the MT plots, the long interval since tillage the previous year (approximately 8 mo) provided the time needed for the soil to settle and stabilize, probably mitigating erosion and nutrient loss during the spring rainfall simulation. In both NT and CC plots, plant residues also afforded protection from erosion and runoff loss. The effects of tillage and residue cover on solids loss in runoff influenced the P runoff results. Runoff losses of both the soluble P (FOP) and the P associated with solids were enhanced in MT and NC, where erosion was higher. This is consistent with the results of others (Laflen and Tabatabai, 1984; McDowell and McGregor, 1984; Tiessen et al., 2010) who observed strong associations between soil loss and P loss that resulted in reduced losses of particulate P in conservation tillage. Plant residue cover was negatively correlated with TOP, particulate P, and FOP ($r = -0.74$, $P < 0.001$; -0.66, $P < 0.006$; and -0.50, $P < 0.047$, respectively) in runoff. No P fertilizer was applied to these soils because the available soil P level was relatively high. Higher M3-P in the MT and NC soils may have further enhanced the vulnerability of these soils to loss of P in runoff. Total orthophosphate in runoff from the fall rainfall simulation was correlated with soil $CaCl_2$–P ($r = 0.53$, $P < 0.037$) but not with M3-P. The FOP in runoff was correlated with $CaCl_2$–P in both the spring ($r = 0.57$, $P < 0.025$) and fall ($r = 0.43$, $P < 0.10$) simulations and with M3-P in the fall simulation ($r = 0.58$, $P < 0.018$). Inconsistent relationships between soluble P in runoff and soil test P have also been reported elsewhere (Pote et al., 1996; Hooda et al., 2000). Particulate P comprised the great majority of TOP lost in runoff, but it was not correlated with M3-P and was weakly related with $CaCl_2$–P only in the fall ($r = 0.45$, $P < 0.08$). Particulate P was strongly correlated with SS in both the spring ($r = 0.75$, $P < 0.001$) and fall ($r = 0.77$, $P < 0.0005$) simulations (Andraski et al., 1985; Owens and Edwards, 1993). Similarly, TOP and particulate P were correlated with the average runoff turbidity in both spring ($r = 0.71$, $P < 0.003$; and $r = 0.77$, $P < 0.001$, respectively) and fall ($r = 0.58$, $P < 0.02$; and $r = 0.55$, $P < 0.03$, respectively) (Udeigwe and Wang, 2007). The correlation of particulate P with DS ($r = 0.55$, $P < 0.029$) was observed only in the fall rainfall simulation, presumably associated with the recent tillage. The only relationship observed for FOP was a correlation with DS in the fall ($r = 0.67$, $P < 0.005$).

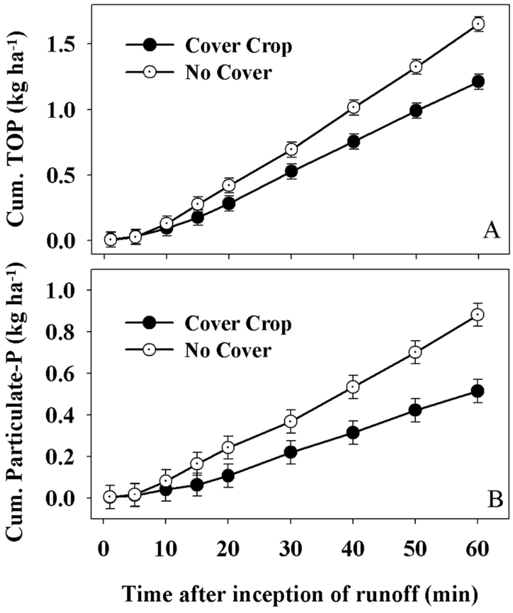

Fig. 6. Cumulative (Cum.) (A) total orthophosphate (TOP) and (B) particulate P runoff losses pooled across spring and fall rainfall simulations to show the interaction of cover crop and time of runoff. Symbols represent the mean of 16 replicates. Error bars denote $LSD_{0.05}$ (cover crop × time after runoff inception).

The effects of tillage on the soluble N constituents in the runoff, cumulative NH_4, NO_3, and NO_2, were only significant in the fall rainfall simulation, with losses from MT greater than those from NT (Table 8). No effect of cover crop was ob-

Table 8. Main effects of no-till (NT) or minimum tillage (MT) and cover crop (CC) or no cover crop (NC) for cumulative total Kjeldahl N (TKN), NH_4, NO_3, and NO_2 in runoff.

Treatment	TKN	NH_4	NO_3	NO_2
	kg ha^{-1}			
Fall only				
NT	1.19 b†	0.003 b	0.024 b	0.002 b
MT	3.57 a	0.027 a	0.060 a	0.008 a
CC	1.66 b			
NC	3.10 a			
	ANOVA *P* values‡			
Tillage	<0.001	<0.001	<0.002	<0.023
Cover	<0.013	NS§	NS	NS
Across seasons				
NT	3.18b			
MT	5.51a			
	ANOVA *P* values¶			
Tillage	<0.001			
Cover	NS			

† For each parameter main effect, means followed by the same letter are not significantly different.

‡ Analysis of variance performed for separate seasons.

§ NS, not significant at $P \leq 0.05$.

¶ Analysis of variance performed on data pooled across seasons.

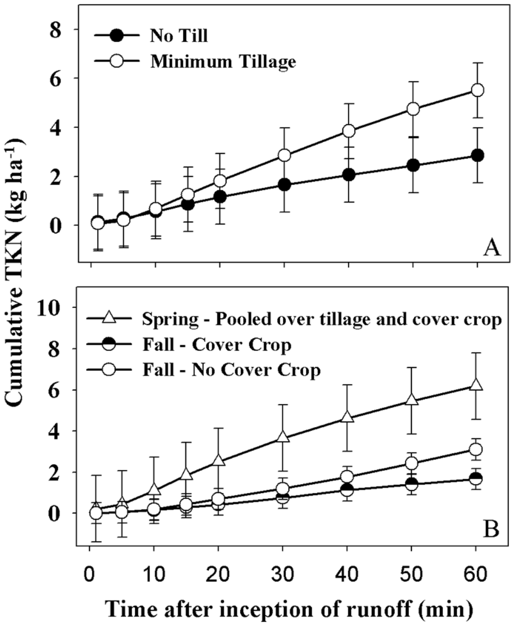

Fig. 7. Cumulative total Kjeldahl N (TKN) loss in runoff: (A) interaction of tillage and time during runoff pooled across rainfall simulation (season); error bars denote Fisher's $LSD_{0.05}$ showing the tillage × time of runoff interaction, and each symbol represents the mean of 16 replicates; (B) interaction of cover crop and time during runoff for fall only (with and without a cover crop) and the pattern of TKN loss in runoff during the spring rainfall simulation (pooled across all tillage and cover crop treatments); for the fall data, error bars denote Fisher's $LSD_{0.05}$ showing the season × cover crop × time of runoff interaction, and each symbol represents the mean of eight replicates; for the spring data, error bars denote Fisher's $LSD_{0.05}$ showing the change in TKN with time, and each symbol represents the mean of 32 replicates.

served for NH_4, NO_3, or NO_2 in runoff. Averaged across the two rainfall simulation events, cumulative TKN losses in runoff were also greater in the MT plots (Table 8). Pooled across the two simulation events, there was a significant interaction for cumulative TKN between tillage and time after runoff inception (Fig. 7A). There was no tillage difference in TKN in runoff until after 20 min, when TKN in MT was greater than that in NT and remained so for the duration of the experiment (Fig. 7A). In the fall rainfall simulation, there was a cover crop × time after runoff inception interaction for cumulative TKN in runoff (Fig. 7B), but there was no cover crop effect on TKN in the spring simulation even though N fertilizer was applied just before the spring rainfall simulation (Table 8; Fig. 7B). However, cumulative TKN losses were greater in the spring ($P < 0.05$) (Fig. 7B).

There was a significant interaction between tillage and rainfall simulation events (seasons) on cumulative DOC lost in the runoff (Table 7). More DOC was lost in runoff from the NT plots in spring than from NT in the fall. There was not a tillage effect on DOC in spring, but in the fall, more DOC was lost from MT than from NT. This is consistent with other studies showing increasing C loss with increased tillage (Truman et al., 2007).

Several observations can be made from the N and DOC results. Fertilizer N applied just before the spring rainfall simulation did not appear to have a major effect on soluble N lost in runoff. Injecting the fertilizer into the soil should have provided some protection from rainfall and subsequent surface runoff. Applying it in a band rather than broadcasting also may have reduced vulnerability to runoff loss. Although the TKN loss was greater in the spring than the fall, it is difficult in this case to ascertain the source of N contributing to this loss. In the warm, moist spring season, microbial activity is enhanced, and decomposing plant residues provide a source of N and C from immobilized soil reserves. Similar to P, runoff losses of TKN were strongly correlated with TS and SS ($r = 0.82$, $P < 0.001$ for both) and turbidity ($r = 0.61$, $P < 0.013$) but only in the fall. These correlations were similar to the strong relationships between N and soil loss in runoff observed by others that contributed to lower N lost in runoff (Laflen and Tabatabai, 1984; McDowell and McGregor, 1984; Tiessen et al., 2010). The enhanced DOC observed in the spring runoff from NT soils may be indicative of this activity. Dissolved organic C was correlated with DS in both spring and fall ($r = 0.46$, $P < 0.084$; and 0.67, $P < 0.0048$, respectively) but not with any other solids fraction. The TKN lost in runoff was also strongly associated with DS in both spring and fall ($r = 0.68$, $P < 0.0057$; and 0.58, $P < 0.018$, respectively). Neither NH_4 nor NO_3 were correlated with any solids in the spring runoff but were correlated with DS in the fall. The correlation of TKN, NH_4, and NO_3 with SS ($r = 0.82$, $P < 0.001$; $r = 0.88$, $P < 0.001$; and $r = 0.44$, $P < 0.086$, respectively) in the fall rainfall simulation was probably linked to the recent soil tillage in MT plots. The most important observation from this study is that conservation practices mitigated N runoff loss. Proximity of a tillage operation to a rainfall event also was a major factor contributing to N loss.

Implications for these results with regard to GMC systems relate to the extent that the use of an herbicide-resistant GMC provides the flexibility to minimize herbicide use and eliminate tillage. The NT option in this study consistently reduced the loss of nutrients associated with the solid phase of runoff (TKN and particulate P). Either combining NT or MT with cover crops or the use of a cover crop alone also reduced the runoff loss of nutrients associated with the solid phase.

SUMMARY AND CONCLUSIONS

Although substantial research has addressed the impacts of conservation practices on soil health and erosion, considerably more work is needed to assess nutrient runoff losses in conservation systems. Studies have suggested that coincidental adoption of both GMCs and conservation management may be mutually complementary, but relatively little work has been done to assess the environmental impacts of glyphosate-resistant GMC systems despite their widespread use. This study did not compare GMC and non-GMC systems but rather addressed conservation management options within the context of a glyphosate-resistant GMC system. Patterns observed for erosion and nutrient runoff were similar to those observed in previous studies for non-GMC systems. For most tillage and cover crop treatment combinations, enhanced plant residue coverage on the soil surface reduced runoff and erosion loss. Recent tillage in the fall (1 d before rainfall simulation) was the largest contributor to runoff and erosion loss. Although the MT plots had not been tilled for 7 mo, the effects of fall tillage on runoff, erosion, and particulate N and P loss were still apparent during spring rainfall simulations if cover crops were not included. The highest loss of dissolved organic C in runoff occurred in the spring with NT at a time when winter plant residues had been recently desiccated with herbicide and were decomposing. The lowest DOC loss in runoff was associated with NT soil in the fall.

This study demonstrates the effectiveness of a cover crop and conservation tillage in reducing runoff and nutrient losses within a glyphosate-resistant GMC system. Overall, NT and CC tended to reduce nutrient and sediment losses. The dilemma for responsible managers is to determine which option is acceptable to them in terms of sustainability: avoid or minimize tilling the soil while adopting a program of limited use of herbicides by using an herbicide-resistant GMC; use a non-GMC and potentially use more herbicide with or without tillage; or avoid using either an herbicide-resistant GMC or herbicides and control weeds by tilling or other cultural methods (such as cover crops or crop rotation). In the current study, adopting a GMC system provided the option to judiciously apply herbicides and limit or eliminate tillage. The lack of tillage reduced runoff losses and the use of a cover crop provided an added environmental benefit.

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