Interactions of Tillage and Cover Crop on Water, Sediment, and Pre-emergence Herbicide Loss in Glyphosate-Resistant Cotton: Implications for the Control of Glyphosate-Resistant Weed Biotypes

L. Jason Krutz,* Martin A. Locke, and R. Wade Steinriede, Jr. USDA

The need to control glyphosate [*N*-(phosphonomethyl) glycine]-resistant weed biotypes with tillage and preemergence herbicides in glyphosate-resistant crops (GRCs) is causing a reduction in no-tillage hectarage thereby threatening the advances made in water quality over the past decade. Consequently, if environmental gains afforded by GRCs are to be maintained, then an in-field best management practice (BMP) compatible with tillage is required for hectarage infested with glyphosate-resistant weed biotypes. Thus, 1 d after a preemergent application of fluometuron [*N*,*N*-dimethyl-*N*'-(3-(trifluoromethyl)phenyl) urea] (1.02 kg ha^{-1}) and metolachlor [2-chloro-N-(2-ethyl-6-methylphenyl)-N-(2-methoxy-1-methylethyl)acetamide] (1.18 kg ha^{-1}) to a Dundee silt loam (fine-silty, mixed, active, thermic Typic Endoaqualf), simulated rainfall (60 mm h^{-1}) was applied to 0.0002-ha microplots for approximately 1.25 h to elucidate tillage (no tillage [NT] and reduced tillage [RT])and cover crop (no cover [NC] and rye cover [RC]) effects on water, sediment, and herbicide loss in surface runoff. Regardless of tillage, RC delayed time-to-runoff 1.3-fold, reduced cumulative runoff volume 1.4-fold, and decreased cumulative sediment loss 4.7-fold. Cumulative fluometuron loss was not affected by tillage or cover crop. Conversely, total metolachlor loss was 1.3-fold lower in NT than RT and 1.4-fold lower in RC than NC. These data indicate that RC can be established in hectarage requiring tillage and potentially curtail water, sediment, and preemergence herbicide losses in the spring to levels equivalent to or better than that of NT, thereby protecting environmental gains provided by GRCs.

Published in J. Environ. Qual. 38:1240–1247 (2009).
doi:10.2134/jeq2008.0342
Received 28 July 2008.
*Corresponding author (jason.krutz@ars.usda.gov).
© ASA, CSSA, SSSA
677 S. Segoe Rd., Madison, WI 53711 USA

Glyphosate-resistant crops facilitated the widespread adoption of NT cropping systems (Cedeira and Duke, 2006; Holland, 2004; Kleter et al., 2007). No tillage, that is, omitting all tillage, disking, or harrowing operations, promotes crop residue accumulation on the soil surface (Locke and Bryson, 1997). These crop residues protect the soil surface from rainfall impact, impede surface crust formation, and reduce soil erosion (Foster and Meyer, 1977; McGregor et al., 1990; Alberts and Neibling, 1994). Consequently, relative to systems that receive tillage, NT reduces erosion and the loss of pesticides transported primarily by sediment (Afyuni et al., 1997; Basta et al., 1997; Baughman et al., 2001; Benhan et al., 2007; Locke et al., 2008b; Mamo et al., 2006; Meyer et al., 1999; Mutchler and McDowell, 1990; Pantone et al., 1996; Reddy et al., 1994; Yoo et al., 1987; Zeimen et al., 2006; Zhu et al., 1989). Additionally, NT typically improves soil structure, often enhances infiltration rates and amounts, and purportedly reduces the loss of moderately sorbed pesticides (Locke and Bryson, 1997). Accordingly, GRCs are accredited with improving U.S. soil and water quality (Cedeira and Duke, 2006; Holland, 2004; Kleter et al., 2007; Locke et al., 2008a).

However, glyphosate-resistant weed biotypes threaten the environmental gains afforded by GRCs. The number of glyphosate-resistant weed biotypes and the hectarage they infest is increasing (Gustafson, 2008; Powles, 2008). The current recommendation for the control of glyphosate-resistant weed biotypes in GRCs is integrated weed management, that is, tillage coupled with pre- and postemergence herbicides (Gustafson, 2008; Werth et al., 2008). This recommendation could drastically reduce NT hectarage across the United States. For example, Tennessee no-tillage cotton (*Gossypium hirsutum* L.) hectarage decreased fourfold from 2005 to 2008 because tillage was needed to control glyphosate-resistant horse weed (*Conyza canadensis* L.) (L. Stickel, personal communication, 2008). Thus, if environmental gains afforded by GRCs are to be maintained, then a viable alternative to NT is required for hectarage that will be cultivated and treated with traditional pre- and postemergence herbicides.

L.J. Krutz, United States Department of Agriculture, Agriculture Research Service, Southern Weed Science Research Unit, P.O. Box 350, Stoneville, MS 38776; M.A. Locke and R.W. Steinriede, Jr., United States Department of Agriculture, Agriculture Research Service, National Sedimentation Laboratory, Water Quality and Ecology Research Unit, P.O. Box 1157, Oxford, MS 38655.

Abbreviations: BMPs, best management practices; GRCs, glyphosate-resistant crops; K_{oc}, organic carbon partitioning coefficient; MDL, method detection limit; NC, no cover; NT, no tillage; RC, rye cover; RT, reduced tillage.

A potential alternative to NT for reducing water, sediment, and herbicide loss in GRCs is the establishment of annual grass (i.e., wheat [*Triticum aestivum* L.], oat [*Avena sativa* L.], rye [*Secale cereal* L.], and ryegrass [*Lolium multiflorum* Lam.]) or annual legume [i.e., vetch (*Vicia* sp.) and clover (*Trifolium* sp.)] cover crops during fallow periods. However, there is limited data on the effects of fallow cover crops on pesticide transport. The objective of this simulated rainfall experiment was to elucidate the interactions of tillage (RT and NT) and cover crop (NC and RC) on water, sediment, and preemergent herbicide loss in glyphosate-resistant cotton.

Materials and Methods

Site Description

A split-plot experiment arranged as a randomized complete block with four replications of each treatment was established on a Dundee silt loam near Stoneville, MS in the fall of 2000. Tillage (RT or NT) was the whole plot and cover crop (RC or NC) was the subplot. The RT consisted of disking and rowing into beds in the fall. For RT-NC the tops of the seedbeds were smoothed before planting by removing a thin layer of soil from the top of the seedbed with a do-all harrow. The NT and RT-RC involved planting directly into the row beds from the previous year's crop. The RC was planted in the fall each year and killed with paraquat or glyphosate 2 wk before planting cotton the following spring.

Soil and Residue Properties

Soil properties were determined on samples (0- to 2-cm, 2- to 5-cm, and 5- to 15-cm depths) collected from 0.0260-ha field plots before rainfall simulations. Soil samples were collected at random within respective plots, bulked as a composite by depth within each plot, and stored moist at 4°C until use. Texture was determined following methods described by Gee and Bauder (1986), and total C was determined on air-dried, ground soil using a Vari Max CNS (Elementar, Hanau, Germany). Bulk density and antecedent moisture content were determined on samples collected from the 0- to 10-cm depth at two randomly selected locations within each plot before initiating simulated rainfall. These soils were dried at 55°C for ≥3d, and bulk density was calculated from the total dry weight of soil and volume of coring device. Percent residue coverage at the time of 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).

Rainfall Simulations

Fluometuron [*N*,*N*-dimethyl-*N'*-(3-(trifluoromethyl)phenyl) urea] and metolachlor [2-chloro-N-(2-ethyl-6-methylphenyl)-N-(2-methoxy-1-methylethyl)acetamide] were tank-mixed and applied by block on 30 Apr. and 7, 8, and 14 May 2007 with a tractor-mounted sprayer delivering 140 L ha^{-1} at 206 KPa to 0.0260-ha field plots. Fluometuron [1.02 kg ha^{-1}; standard error (SE) 0.06] and metolachlor (1.18 kg ha^{-1}; SE 0.07) application rates were confirmed by analysis of four 7-cm diam. filter paper spray targets (Whatman no.2, Whatman Inc., Clifton, NJ). Following herbicide application, 0.0002-ha microplots were established within each 0.0260-ha field plot. Microplots, 1-m wide by 2.43-m long, were centered over the bed, delineated with aluminum frames pressed approximately 10 cm into the soil surface. All microplots contained one wheel track and had an average slope of 1%. An oscillating nozzle rainfall simulator was calibrated to deliver a nominal rainfall intensity of 60 mm h^{-1} (Meyer and Harmon, 1979). Rainfall simulations were initiated 1 d after herbicide application and continued until 60 min of runoff was generated per plot. Rainfall intensity-duration-frequency curves for this region of Mississippi indicate that the return frequency for this storm is 10 to 25 yr. All runoff generated during the simulation was captured in a holding tank positioned on the downslope end of the plot. Runoff rate was determined by manually recording the water height in the holding tank at 60-s intervals. Runoff samples were collected for herbicide and sediment analysis at 5, 10, 15, 20, 30, 40, 50, and 60 min in 1-L glass bottles. All glass bottles were sealed with Teflon-lined screw caps, placed on ice, and transferred to the laboratory refrigerator within 1 h of completing the simulation.

Sample Preparation and Analysis

Sediment runoff concentrations were determined by transferring a 200-mL aliquot of well-shaken runoff sample into a tared beaker and recording the weight of the residue after oven drying. Spray-targets were extracted 1 h after collection by shaking 24 h with 25-mL methanol, and a 1-mL aliquot was removed for analysis. Runoff samples were fortified with terbuthazine at 5 μg mL^{-1} and filtered (Whatman GFF; 0.7-μ nominal pore size). Runoff subsamples (10 mL) were then extracted using a 3-mL C_{18} solid phase extraction column (Bakerbond, JT Baker Phillipsburg, PA) preconditioned with 4 mL methanol followed by 4 mL distilled water. The column was eluted with 2 mL methanol under negative pressure, and the extract was dried to 1 mL under a stream of N. Analytes were identified and quantified using a Waters 2695 HPLC separations module (Waters Corp., Milford, MA) equipped with a Waters 996 photodiode array detector (Waters Corp., Milford, MA). The HPLC was fitted with a 2.1-mm-diam. by 150-mm-length Waters Symmetry C_{18} column (Waters Corp., Milford, MA). The mobile phase solvents were HPLC-grade and consisted of A [acetonitrile and water (30:70 v/v)] and B [acetonitrile and water (90:10 v/v)]. Initial conditions, 100% A, were held for 1 min, increased linearly to 100% B over 20 min, and then held isocratic for 1 min. Mobile phase flow rate was constant at 1.0 mL min^{-1}. Based on the lowest standard, 0.1 μg mL^{-1}, the method detection limit (MDL) for both herbicides was 10.0 μg L^{-1}.

Quality Control

Recovery of fluometuron and metolachlor from fortified spray targets was 94 ± 0.4% (n = 8) and 103 ± 0.4% (n = 8), respectively. Field application rates were adjusted based on these recovery values. Herbicide concentrations were below the MDL in all field and laboratory blank water samples. Matrix fortified runoff samples were prepared by adding 0.4 mL of 50 μg mL^{-1} metolachlor and fluometuron to 10 mL of field blank sample. Extraction efficiency was 98 ± 7% for fluometuron and 105 ± 14% for metolachlor (n = 8). Herbicide runoff concentrations were not corrected for extraction efficiency.

Data Calculations

Herbicide and sediment concentrations were multiplied by the volume of runoff represented by the samples taken for analysis, and the results were summed to give total loads. Estimates for cumulative mass loss were obtained by multiplying the average concentration for each time step by the corresponding runoff volume. Average concentrations in the portion of the runoff that were not analyzed were estimated by linear interpolation between adjacent data points on chemographs (Potter et al., 2006).

Statistical Analysis

Analysis of variance and mean separation was performed using Proc Mixed (SAS version 9.1, SAS Institute Inc., Cary, NC). All results were considered significantly different at $P < 0.10$. Regression analysis was used to determine the relationships between independent and dependent variables (SAS version 9.1, SAS Institute Inc., Cary, NC).

Results and Discussion

Soil and Residue Conditions at Time of Simulated Rainfall

There were no statistical differences in the sand, silt, or clay fractions among the tillage, cover crop, and depth intervals evaluated (Table 1). When pooled over tillage, cover crop and depth, the percent sand, silt, and clay for all plots averaged 21.6, 49.5 and 28.9%, respectively. These data indicate that soil texture was homogenous throughout the 0- to 15-cm depth profiles, and that blocking adequately controlled for a known textural gradient in the experimental area. Consequently, runoff differences observed among treatments were not attributed to inherent variability in soil texture among plots.

For percent residue coverage, a significant tillage by cover crop interaction (P = 0.0007) was noted. In the absence of RC, surface residue coverage was 30-fold higher in NT (60%) than RT (2%). Establishing RC increased residue coverage 1.5-fold in NT systems and 44-fold in RT systems. Moreover, there were no statistical differences in residue coverage between NT-RC (91%) and RT-RC (88%). For soil organic C content, a significant tillage by cover crop by depth interaction was observed (P = 0.0007), and several trends were noted (Table 1). First, within a given tillage and cover crop treatment, the organic C content was negatively correlated with soil depth. Second, within the 0- to 2-cm depth, soil organic C was at least 1.6-fold higher in NT-RC than all other tillage by cover crop combinations. Third, within the 2- to 5-cm depth, soil organic C was at least 1.2-fold lower in NT-NC than all other treatments. Finally, within the 5- to 15-cm depth, soil organic C content was treatment independent. Despite some differences in organic matter content and distribution among treatments, bulk density did not differ among tillage or cover crop combinations and averaged 1150 kg m^{-3}. Conversely, antecedent moisture content was affected by main effects, tillage (P = 0.0100) and cover crop (P = 0.0010). For example, volumetric moisture content was 1.1-fold higher in NT (0.25 m^3 m^{-3}) than RT (0.22 m^3 m^{-3}) and 1.4-fold higher in RC (0.27 m^3 m^{-3}) than NC (0.20 m^3 m^{-3}). These noted effects of tillage and cover crop on soil properties are consistent with other reports in the literature (Reddy et al., 2003).

Hydrology

Cropping systems that delay time-to-runoff allow more rainfall to infiltrate before runoff inception thereby promoting leaching of pesticides beneath the mixing zone, that is, the 2- to 3-mm zone of surface soil where pesticides are entrained in runoff through a mixing-extraction process (Ahuja, 1986; Leonard, 1990). Cumulative pesticide loss in runoff is positively correlated with mixing zone concentrations (Leonard et al., 1979). Consequently, time-to-runoff is a critical contaminant transport parameter that indicates potential for a cropping system to concomitantly reduce runoff volumes and pesticide mixing zone concentrations.

In this experiment, only the cover crop main effect significantly altered time-to-runoff (P = 0.0983). The RC in both NT and RT delayed time-to-runoff 1.3-fold and allowed approximately 3.3 mm more rainfall to infiltrate before runoff inception (Table 2). Similarly, an Italian ryegrass (*Lolium multiflorum* Lam.) and crimson clover (*Trifolium incarnatum* L.) cover crop mixture increased time-to-runoff fivefold and allowed approximately 9.7 mm more rainfall to infiltrate when compared to a conventional tillage system (Reddy et al., 1994).

The cover crop main effect on time-to-runoff was attributed to higher residue levels and altered soil subsurface properties arising from establishing RC in either NT or RT systems. For example, residue coverage is positively correlated with time-to-runoff (Alberts and Neibling, 1994), and residue levels were 2.9-fold higher in RC than NC. Additionally, cropping systems that delay time-to-runoff infer enhanced infiltration rates and amounts. This is typical for cover crop systems because they reduce surface sealing while concurrently increasing water storage capacity, soil macroporosity, and hydrologic resistance (Dabney, 1998). Thus, the time-to-runoff data indicate potential for RC established in either NT or RT to increase infiltration rates and amounts in the spring thereby reducing pesticide transport by decreasing concentrations in the mixing zone before runoff inception and reducing cumulative runoff volume.

In contrast to the cover crop main effect, time-to-runoff was not different between tillage systems (P = 0.6066; Table 3). This observation is surprising in that surface crop residues and improved soil structure are generally credited with improving infiltration rates and amounts in NT compared to RT (Wilson et al., 2004). A plausible explanation for an insignificant tillage main effect is that RT beds were "knocked down" 1 d before rainfall simulations in accordance with standard practices established for this treatment. Disturbing RT beds destroyed a surface crust and increased surface roughness, two mechanisms that transiently increase infiltration rates and amounts (Steiner, 1994). However, as RT beds consolidated, differences in runoff rates between tillage systems became evident.

For runoff rate, the tillage by time ($P = 0.0289$) and cover crop by time ($P < 0.0001$) interactions were significant. Pooled over cover crop, the runoff rate from 10 to 30 min after runoff inception was at least 1.2-fold lower in NT than RT (Fig. 1A). Thus, NT did not alter the steady-state runoff rate; rather, NT only delayed its onset. Conversely, from 10 min after runoff inception until rainfall termination, the runoff rate pooled over tillage was at least 1.3-fold lower in RC than NC (Fig. 1B). These data indicate that independent of tillage, RC both delayed and reduced the steady-state runoff rate.

The effect of tillage and cover crop on runoff rate was attributed primarily to residue coverage at the time of simulated rainfall. Generally, as residue coverage increases, the time required to achieve steady-state runoff is delayed, and the maximum runoff rate is reduced. This arises from the absorption of runoff water by plant residues and the formation of small reservoirs that physically block flow (Alberts and Neibling, 1994; Locke and Bryson, 1997; Wilson et al., 2004). Our data support this assertion in that residue levels were 1.7-fold higher in NT than RT and 2.9-fold higher in RC than NC. Since NT and RC increase plant residue levels relative to RT-NC, both BMPs have potential to decrease cumulative runoff volume. However, only RC both delayed and reduced the steady-state runoff rate; therefore, RC, regardless of tillage, is likely a better in-field BMP for reducing water, sediment, and pesticide loss in surface runoff. The cumulative runoff data support this assertion.

For cumulative runoff, the tillage × cover crop × time interaction was significant ($P = 0.0574$), and several trends were noteworthy. First, from 30 min after runoff inception until study termination, cumulative runoff volume was at least 1.3-fold higher in RT-NC than all other treatments. Second, RC reduced cumulative runoff volume at least 1.6-fold relative to NC, regardless of tillage. Moreover, at no point during the rainfall simulation was cumulative runoff volume statistically different between NT-RC and RT-RC. Thus, since pesticide transport potential is positively correlated with cumulative runoff volume, these data signify that pesticide transport potential in the spring decreases in the order of RT-NC > NT-NC > RT-RC = NT-RC.

The NT-NC and RT-NC data are in agreement with conventional wisdom, that is, NT reduces cumulative runoff volume relative to systems that receive tillage. However, this observation is in contrast with the majority of current pesticide transport studies that indicate cumulative runoff volume under NT is equal to or greater than that observed in systems that receive tillage (Afyuni et al., 1997; Baughman et al., 2001; Locke et al., 2008b; Logan et al., 1994; Mamo et al., 2006; Myers et al., 1995; Olson et al., 1998; Rector et al., 2003; Shipitalo and Owens, 2006; Webster and Shaw, 1996; Zeimen et al., 2006). Others have noted the inconsistent effect of NT on surface runoff volume, and explanations for the apparent contradiction have been offered. Foremost, many NT runoff studies are conducted shortly after establishment, and the benefits of eliminating tillage may not have been fully realized, for example, improved infiltration rates and amounts associated with increased organic matter, greater porosity, enhanced aggregate stability, and reduced bulk density (Locke and Bryson, 1997; Rhoton et al., 2002; Wilson et al., 2004). Second, tillage can break up the surface crust and increase surface roughness thereby reducing cumulative runoff amounts relative to NT (Dabney, 1998; Wilson et al., 2004). In this experiment, NT had been established for 7 yr and RT did not receive an intensive tillage operation before simulated rainfall. Thus, there is likely some validity to the effects of time since NT establishment and tillage on the inconsistent behavior of NT reported in the literature.

Moreover, it is critical to note that runoff volume was 1.3-fold lower in RT-RC than NT-NC (Fig. 2). These data indicate that increased residue coverage associated with RC reduces cumulative runoff volume and subsequent pesticide transport potential to a greater extent than eliminating tillage. This assertion is further supported by the observation that cumulative runoff volume was not different between NT-RC and RT-RC. Thus, our data indicate that if NT systems must be tilled to control glyphosate-resistant weed biotypes, then cumulative runoff volume and subsequent pesticide transport potential can be reduced in the spring by establishing RC.

Table 1. Selected soil physical and chemical properties for all tillage (no tillage [NT] and reduced tillage [RT]) and cover crop (rye cover [RC] and no cover [NC]) treatments at three different depth intervals. Values are the mean of four replicates.

Tillage	Cover	Depth	Sand	Silt	Clay	OC
		cm	%			
NT	NC	0 to 2	21.8	51.6	26.5	1.4
NT	RC	0 to 2	22.4	51.1	26.6	2.4
RT	NC	0 to 2	19.9	50.7	29.4	1.5
RT	RC	0 to 2	18.8	51.7	29.5	1.5
NT	NC	2 to 5	19.2	44.9	35.9	1.0
NT	RC	2 to 5	24.5	47.6	27.9	1.2
RT	NC	2 to 5	24.0	46.7	29.4	1.2
RT	RC	2 to 5	22.3	47.9	29.8	1.2
NT	NC	5 to 15	20.3	51.2	28.5	0.7
NT	RC	5 to 15	20.9	51.5	27.6	0.9
RT	NC	5 to 15	20.6	49.5	29.9	0.9
RT	RC	5 to 15	22.0	49.9	28.1	0.8
LSD (0.05) (tillage × cover × depth)			NS†	NS	NS	0.1730

† Not significantly different at $P \le 0.10$.

Table 2. Main effects of cover crop and tillage on sediment concentration in runoff.

Tillage	Rye cover	No cover	Tillage mean
	g L^{-1}		
Reduced tillage	1.91	5.84	3.88 a†
No tillage	1.48	3.96	2.72 b
Cover crop mean	1.69 a	4.90 b	

† Treatment means followed by same letter are not significantly different at $P \le 0.05$.

Table 3. Main effects of tillage and cover crop on time-to-runoff.

Tillage	Rye cover	No cover	Tillage mean
	min		
Reduced tillage	17.5	12.7	15.7 a†
No tillage	14.4	12.5	13.4 a
Cover crop mean	15.9 a	12.6 b	

† Treatment means followed by same letter are not significantly different at $P \le 0.05$.

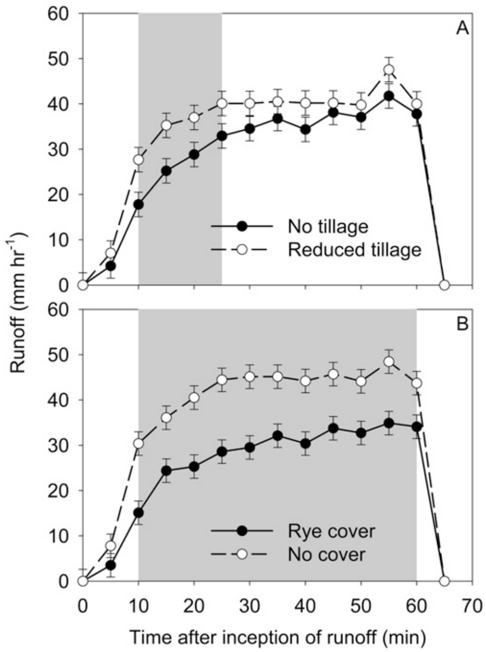

Fig. 1. Runoff rate (mm h^{-1}) pooled over (A) cover crop and (B) tillage, respectively. Symbols represent the mean of eight replicates. Error bars denote one standard error. Shaded areas indicate differences in runoff rate between systems at discrete time intervals: LSD (0.05) (tillage × time) for Fig. 1A = 6.1 and LSD (0.05) (cover × time) for Fig. 1B is 6.3.

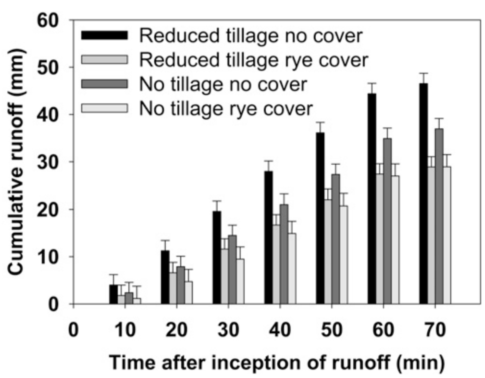

Fig. 2. Cumulative runoff (mm) for reduced tillage no cover (RT-NC), reduced tillage rye cover (RT-RC), no tillage no cover (NT-NC) and no tillage rye cover (NT-RC). Shaded bars represent the mean of four replicates. Error bars denote one standard error. LSD (0.05) (tillage × cover × time) = 5.7.

Sediment Transport

Sediment concentrations within treatments did not vary over time (P = 0.7327). Yet, sediment concentrations differed within tillage (P = 0.0634) and cover crop (P = 0.0044) systems. Specifically, runoff sediment concentrations were 1.4-fold lower in NT than RT and 2.9-fold lower in RC than NC (Table 3). In general, sediment concentrations in runoff were inversely correlated with percent residue coverage at time of rainfall application. These data imply potential for increased residue levels in both NT and RC to reduce erosion and the subsequent loss of pesticides transported primarily by mobilized sediment. The cumulative sediment loss data support this conclusion.

For cumulative sediment loss, a significant tillage by cover crop by time interaction was detected (P = 0.0677). Several trends were noteworthy. First, from approximately 30 min after runoff inception until study termination, cumulative sediment loss was at least 1.9-fold greater in RT-NC than all other treatments (Fig. 3). Second, from approximately 50 min after runoff inception until study termination, cumulative sediment loss was at least 2.8-fold higher in NT-NC than NT-RC and RT-RC. Additionally, at no point during the rainfall simulation was sediment loss statistically different between NT-RC and RT-RC. These data indicate that the potential loss of pesticides transported primarily by sediment decreases in the order of RT-NC > NT-NC > RT-RC = NT-RC.

The cumulative sediment loss data have implications for regions in the United States that will implement integrated weed management strategies on NT soils. Primarily, our data indicate that increased residue coverage associated with RC reduces cumulative sediment loss to a greater extent than eliminating tillage. Since controlling erosion reduces the potential for sediment-sorbed pesticide transport, pesticide runoff could be minimized by coupling RC with the application of herbicides that are transported primarily by sediment, that is, pesticides with average organic C partitioning coefficient (K_{oc}) values ≥ 10^4. Candidate preplant, foliar herbicides include paraquat and glyphosate, while preemergence compounds include the dinitroaniline herbicides, pendimethalin and trifluralin. Pendimethalin would be preferred over the latter in that it does not require incorporation after application.

Herbicide Transport

The effect of tillage, cover crop, and time on runoff concentration and cumulative runoff loss was herbicide dependent. For metolachlor, the tillage by time (P = 0.0524) and cover crop by time (P = 0.0183) interactions were significant for both runoff concentration and cumulative loss. Conversely, only the cover crop (P = 0.0748) and time (P = 0.0001) main effects were significant for fluometuron runoff concentration, and only the time (P < 0.0001) main effect was significant for cumulative fluometuron loss. Thus, tillage and cover crop effects on runoff concentration and cumulative loss are discussed separately to highlight transport differences between herbicides within tillage and cover crop systems.

Tillage had no effect on fluometuron runoff concentration or cumulative fluometuron loss (Fig. 4A; Fig. 5A). Conversely, metolachlor runoff concentrations were transiently higher in NT than RT (Fig. 6A), with cumulative losses 1.3-fold lower in the former (Fig. 7A). Within cover crop, average fluometuron runoff concentrations were 2.1-fold higher in RC than NC (Fig. 4B), but at no point during the simulation was cumulative fluometuron loss statistically different between systems (Fig. 5B). In contrast, the average metolachlor concentrations was 1.1-fold higher in RC than NC (Fig. 6B), with cumulative loss 1.4-fold lower in the former (Fig. 7B). These data reveal several significant trends: (i) herbicide runoff concentrations are positively correlated with residue coverage; (ii) increased infiltration rates and amounts are required in residue managed systems if cumulative pesticide losses are to be reduced; and

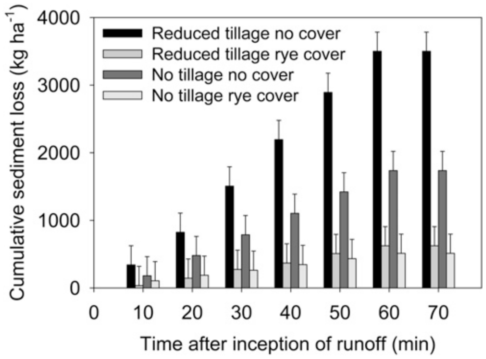

Fig. 3. Cumulative sediment loss (kg ha^{-1}) for reduced tillage no cover (RT-NC), reduced tillage rye cover (RT-RC), no tillage no cover (NT-NC), and no tillage rye cover (NT-RC). Shaded bars represent the mean of four replicates. Error bars denote one standard error. LSD (0.05) (tillage × cover × time) = 711.

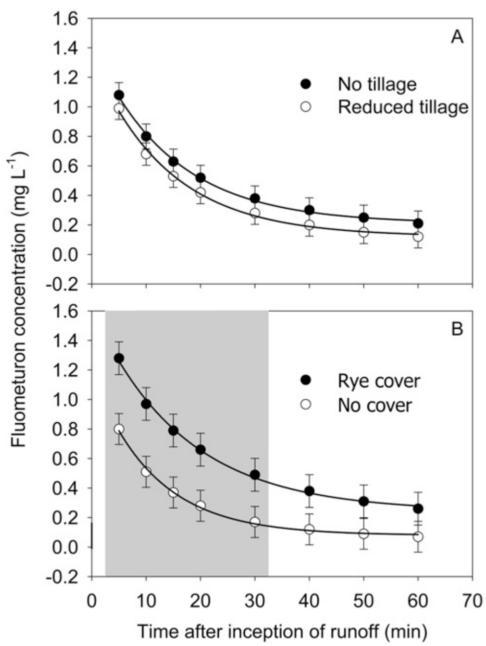

Fig. 4. Fluometuron runoff concentration (mg L^{-1}) pooled over (A) cover crop and (B) tillage, respectively. Symbols represent the mean of eight replicates. Error bars denote one standard error but do not appear when smaller than the symbol for the mean. Shaded areas indicate differences in metolachlor runoff concentration between systems at discrete time intervals: LSD (0.05) (tillage × time) for Fig. 1A is not significant and LSD (0.05) (cover × time) for Fig. 1B = 0.30. Solid lines represent the best fit of the first order kinetics model generated by SAS NLIN: No tillage = 0.2099 + 1.2094exp(–0.0688*t); Reduced tillage = 0.1210 + 1.2200exp(-0.0722*t); No cover = 0.0799 + 1.1027 exp(–0.0885*t); Rye cover = 0.2417 + 1.3765exp(–0.0600*t).

(iii) there is a differential response between moderately sorbed herbicides within tillage and cover crop systems.

Others have noted higher runoff concentrations in residue managed systems, particularly for moderately sorbed pesticides (Potter et al., 2006; Pantone et al., 1996; Afyuni et al., 1997; Mickelson et al., 2001; Olson et al., 1998). In the present study, higher runoff concentrations in NT and RC were attributed to herbicide interception and subsequent rainfall washoff from plant residues. A similar mechanism was proposed by Potter et al. (2006) to describe higher fluometuron runoff concentrations in strip tilled relative to conventional tilled systems. This point highlights a critical limitation of residue management systems: owing to higher runoff concentrations of moderately sorbed pesticides in residue management systems, cumulative runoff must be reduced to mitigate transport. If not, residue management systems will only be effective for reducing erosion and the loss of pesticides transported primarily by sediment.

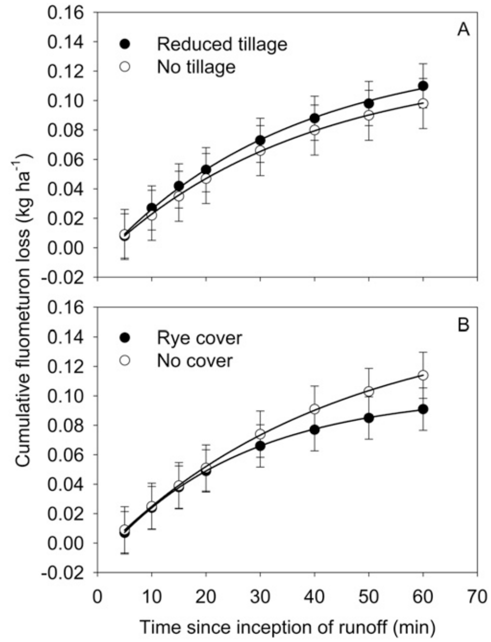

Fig. 5. Cumulative fluometuron loss in surface runoff (kg ha^{-1}) pooled over (A) cover crop and (B) tillage, respectively. Symbols represent the mean of eight replicates. Error bars denote one standard error. Lack of shaded areas indicates no significant difference in cumulative fluometuron loss between systems at discrete time intervals: LSD (0.05) (tillage × time) and LSD (0.05) (cover × time) for Fig. 1A and 1B, respectively, is not significant. Solid lines represent the best fit of the first order kinetics model generated by SAS NLIN: No tillage = –0.0088 + 0.1334[1 – exp(–0.0271*t)]; Reduced tillage = –0.01010 + 0.1434[1 – exp(–0.0291*t)]; No cover = 0.0094 + 0.1629[1 – exp(–0.0237*t)]; Rye cover = –0.0131 + 0.1147[1 – exp(–0.0389*t)].

Relative to NT, cover crops may be more effective at reducing cumulative runoff volume and the ensuing transport of moderately sorbed pesticides. For example, studies indicate that cumulative runoff volume and the subsequent transport of moderately sorbed pesticides from NT is often equal to or greater than that from systems that receive tillage (Afyuni et al., 1997; Logan et al., 1994; Rector et al., 2003; Shipitalo and Owens, 2006; Zeimen et al., 2006). However, our data indicate that increased residue coverage associated with RC reduces cumulative runoff volume to a greater extent than eliminating tillage. Thus, owing to higher infiltration rates and amounts in RC relative to NT, RC may be a better in-field BMP for reducing the transport of moderately sorbed pesticides, particularly when K_{oc} value exceeds 200 mg L^{-1}.

Transport differences between pesticides within tillage and cover crop systems were correlated with their K_{oc} values. The average metolachlor K_{oc} value (200 mL g^{-1}) is twofold higher than

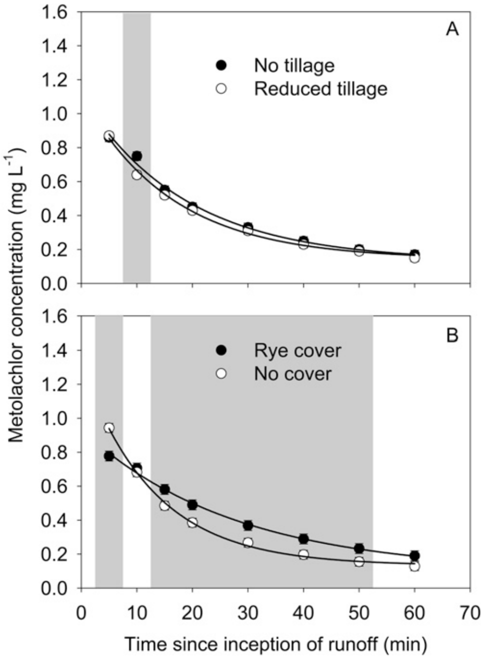

Fig. 6. Metolachlor runoff concentration (mg L^{-1}) pooled over (A) cover crop and (B) tillage, respectively. Symbols represent the mean of eight replicates. Error bars denote one standard error but do not appear when smaller than the symbol for the mean. Shaded areas indicate differences in metolachlor runoff concentration between systems at discrete time intervals: LSD (0.05) (tillage × time) for Fig. 1A = 0.06 and LSD (0.05) (cover × time) for Fig. 1B = 0.07. Solid lines represent the best fit of the first order kinetics model generated by SAS NLIN: No tillage = 0.1313 + 0.9767exp(−0.0535*t); Reduced tillage = 0.1421 + 0.9701exp(−0.0618*t); No cover = 0.1343 + 1.1734 exp(−0.0764*t); Rye cover = 0.0928 + 0.8447exp(−0.0365*t).

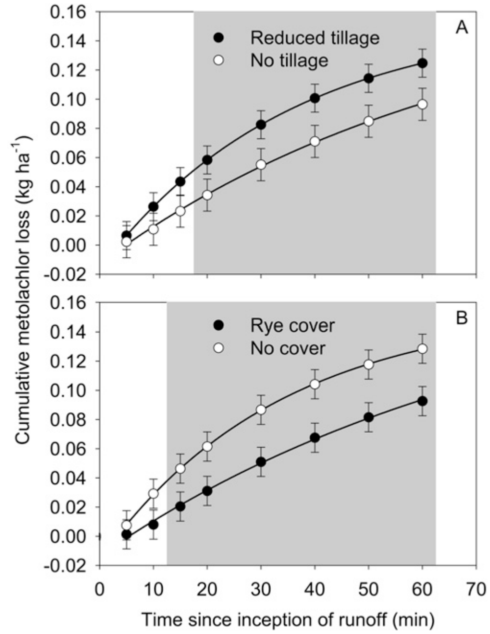

Fig. 7. Cumulative metolachlor loss in surface runoff (kg ha^{-1}) pooled over (A) cover crop and (B) tillage, respectively. Symbols represent the mean of eight replicates. Error bars denote one standard error but do not appear when smaller than the symbol for the mean. Shaded areas indicate differences in cumulative metolachlor runoff between systems at discrete time intervals: LSD (0.05) (tillage × time) for Fig. 1A = 0.02 and LSD (0.05) (cover × time) for Fig. 1B = 0.02. Solid lines represent the best fit of the first order kinetics model generated by SAS NLIN: No tillage = −0.0128 + 0.1899[1 − exp(−0.0144*t)]; Reduced tillage = −0.0163 + 0.1724[1 − exp(−0.0284*t)]; No cover = 0.0161 + 0.1730[1 − exp(−0.0299*t)]; Rye cover = −0.0135 + 0.2007[1 − exp(−0.0127*t)].

that of fluometuron (100 mL g^{-1}), thereby indicating greater affinity for plant residue sorption and reduced rainfall washoff by the former (Vencill, 2002). If greater sorption and reduced rainfall washoff is the primary mechanism responsible for transport differences between herbicides within tillage and cover crop systems, then runoff concentration ratios should be greater for fluometuron than metolachlor, for example, $[NT_F]/[RT_F] > [NT_M]/[RT_M]$ and $[RC_F]/[NC_F] > [RC_M]/[NC_M]$ where $[NT_F]$ is the average fluometuron runoff concentration in no-tillage systems pooled over cover crop and time; $[RT_F]$ is the average fluometuron runoff concentration in reduced tillage systems pooled over cover crop and time; where $[NT_M]$ is the average metolachlor runoff concentration in no-tillage systems pooled over cover crop and time; $[RT_M]$ is the average metolachlor runoff concentration in reduced tillage systems pooled over cover crop and time; where $[RC_F]$ is the average fluometuron runoff concentration in rye cover systems pooled over tillage and time; $[NC_F]$ is the average fluometuron runoff concentration in no cover systems pooled over tillage and time; where $[RC_M]$ is the average metolachlor runoff concentration in rye cover systems pooled over tillage and time; and $[NC_M]$ is the average metolachlor runoff concentration in no cover systems pooled over tillage and time. The runoff ratio for $(NT_F)/(RT_F) > (NT_M)/(RT_M)$ was 1.23 > 1.07, and the runoff ratio for $(RC_F)/(NC_F) > (RC_M)/(NC_M)$ was 2.15 > 1.10. These ratios suggest that transport differences between herbicides arose primarily from differential partitioning and rainfall washoff from plant residues.

Linking the differential response of herbicides with their K_{oc} values may have significant implications for pesticide transport in residue management systems. Foremost, runoff concentrations in residue management systems may be reduced by selecting moderately sorbed post- and preemergent pesticides with K_{oc} values greater than or equal to that of metolachlor, that is, approximately 200 mg L^{-1}. Preemergent cotton herbicides meeting these criteria include clomazone, diuron, and norflurazon, while potential postemergence herbicides include MSMA, lactofen, linuron, oxyfluorfen, and fluazifop. Second, many of these pre- and postemergence herbicides have activity on glyphosate resistant weed biotypes; consequently, they should be considered for use in RC established on tilled soils with glyphosate resistant weed pressure.

In conclusion, results from this study have immediate implications for one of the most pressing issues in modern agriculture, management of glyphosate-resistant weed biotypes. The current recommendation for managing glyphosate-resistant weed biotypes in GRCs is tillage coupled with conventional pre- and postemergent herbicides. This recommendation has significant environmental ramifications in that the adoption of GRCs reduced the use of conventional pre- and postemergence herbicides and fostered NT adoption by producers, two factors contributing to improvements in U.S. soil and water quality. Thus, the data presented herein are relevant in that they demonstrate that RC can be established in hectarage requiring tillage and likely curtail water, sediment, and preemergence herbicide losses in the spring to levels equivalent to or greater than that of NT, thereby preserving environmental gains afforded by GRCs.

References

Afyuni, M.M., M.G. Wagger, and R.B. Leidy. 1997. Runoff of two sulfonylurea herbicides in relation to tillage system and rainfall intensity. J. Environ. Qual. 26:1318–1326.

Ahuja, L.R. 1986. Characterization and modeling of chemical transfer to runoff. Adv. Soil Sci. 4:149–188.

Alberts, E.E., and W.H. Neibling. 1994. Influence of crop residues on water erosion. p. 19–39. *In* P.W. Unger (ed.) Managing agricultural residues. Lewis Publ., Ann Arbor, MI.

Basta, N.T., R.L. Huhnke, and J.H. Stiegler. 1997. Atrazine runoff from conservation tillage systems: A simulated rainfall study. J. Soil Water Conserv. 52:44–48.

Baughman, T.A., D.R. Shaw, E.P. Webster, and M. Boyette. 2001. Effect of cotton (*Gossypium hirsutum*) tillage systems on off-site movement of fluometuron, norflurazon, and sediment in runoff. Weed Technol. 15:184–189.

Benhan, B.L., D.H. Vaughan, M.K. Laird, B.B. Ross, and D.R. Peek. 2007. Surface water quality impacts of conservation tillage practices on burley tobacco production systems in southwest Virginia. Water Air Soil Pollut. 179:159–166.

Cedeira, A.L., and S.O. Duke. 2006. The current status and environmental impacts of glyphosate-resistant crops: A review. J. Environ. Qual. 35:1633–1658.

Dabney, S.M. 1998. Cover crop impacts on watershed hydrology. J. Soil Water Conserv. 53:207–213.

Foster, G.R., and D. Meyer. 1977. Soil erosion and sedimentation by water: An overview. p.1–13. *In* Proc. Natl. Symp. on Soil Erosion and Sedimentation by Water, Chicago, IL. American Soc. Agric. Eng., St. Joseph, MI.

Gee, G.W., and J.W. Bauder. 1986. Particle-size analysis. p. 383–411. *In* A. Klute (ed.) Methods of soil analysis. Part I. Physical and mineralogical methods. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Gustafson, D.I. 2008. Sustainable use of glyphosate in North American cropping systems. Pest. Manage. Sci. 64:409–416.

Holland, J.M. 2004. The environmental consequences of adopting conservation tillage in Europe: Reviewing the evidence. Agric. Ecosyst. Environ. 103:1–25.

Kleter, G.A., R. Bhula, K. Bodnaruk, E. Carazo, A.S. Felsot, C.A. Harris, A. Katayama, H.A. Kuiper, K.D. Racke, B. Rubin, Y. Shevah, G.R. Stephenso, K. Tanaka, J. Unsworth, R.D. Wauchope, and S. Wong. 2007. Altered pesticide use on transgenic crops and the associated general impact from an environmental perspective. Pest. Manage. Sci. 63:1107–1115.

Leonard, R.A. 1990. Movement of pesticides into surface waters. p. 303–350. *In* H.H. Cheng (ed.) Pesticides in the soil environment: Process, impacts, and modeling. SSSA Book Ser. 2. SSSA, Madison, WI.

Leonard, R.A., G.W. Langdale, and W.G. Fleming. 1979. Herbicide runoff from upland piedmont watersheds–Data and implications for modeling pesticide runoff. J. Environ. Qual. 8:223–229.

Locke, M.A., and C.T. Bryson. 1997. Herbicide-soil interactions in reduced tillage and plant residue management systems. Weed Sci. 45:307–320.

Locke, M.A., R.M. Zablotowicz, and K.N. Reddy. 2008a. Integrating soil conservation practices and glyphosate-resistant crops: Impacts on soil. Pest. Manage. Sci. 64:457–469.

Locke, M.A., R.M. Zablotowicz, K.N. Reddy, and R.W. Steinriede. 2008b. Tillage management to mitigate herbicide loss in runoff under simulated rainfall conditions. Chemosphere 70:1422–1428.

Logan, T.J., D.J. Eckert, and D.G. Beak. 1994. Tillage, crop and climatic effects on runoff and tile drainage losses of nitrate and four herbicides. Soil Tillage Res. 30:75–103.

Mamo, M., W.L. Kranz, E.R. Douskey, S. Kamble, and J.F. Witkowski. 2006. Impact of tillage and placement methods on terbufos insecticide runoff. Appl. Eng. Agric. 22:555–560.

McGregor, K.C., R.L. Bengston, and C.K. Mutchler. 1990. Effects of tillage with different crop residues on runoff and soil loss. Trans. ASAE 33:1551–1556.

Meyer, L.D., S.M. Dabney, C.E. Murphree, W.C. Harmon, and E.H. Grissinger. 1999. Crop production systems to control erosion and reduce runoff from upland silty soils. Trans. ASAE 42:1645–1652.

Mickelson, S.K., P. Boyd, J.L. Baker, and S.I. Ahmed. 2001. Tillage and herbicide incorporation effects on residue cover, runoff, erosion, and herbicide loss. Soil Tillage Res. 60:55–66.

Meyer, L.D., and W.C. Harmon. 1979. Multiple-intensity rainfall simulator for erosion research on row sideslopes. Trans. Am. Soc. Agric. Eng. 22:100–103.

Mutchler, C.K., and L.L. McDowell. 1990. Soil loss from cotton with winter cover crops. Trans. ASAE 33:432–436.

Myers, J.L., M.G. Wagger, and R.B. Leidy. 1995. Chemical movement in relation to tillage system and simulated rainfall intensity. J. Environ. Qual. 24:1183–1192.

Olson, B.L.S., D.L. Regehr, K.A. Jansse, and P.L. Barnes. 1998. Tillage system effects on atrazine loss in surface water runoff. Weed Technol. 12:646–651.

Pantone, D.J., K.N. Potter, H.A. Torbert, and J.E. Morrison, Jr. 1996. Atrazine loss in runoff from no-tillage and chisel-tillage systems on a Houston Black clay soil. J. Environ. Qual. 25:572–577.

Potter, T.L., C.C. Truman, T.C. Strickland, D.D. Bosch, T.M. Webster, D.H. Franklin, and C.W. Bednarz. 2006. Combined effects of constant versus variable intensity simulated rainfall and reduced tillage management on cotton preemergence herbicide runoff. J. Environ. Qual. 35:1894–1902.

Powles, S.B. 2008. Evolved glyphosate-resistant weeds around the world: Lessons to be learnt. Pest. Manage. Sci. 64:377–387.

Rector, R.J., D.L. Regehr, P.L. Barnes, and T.M. Loughin. 2003. Atrazine, S-metolachlor, and isoxaflutole loss in runoff as affected by rainfall and management. Weed Sci. 51:810–816.

Reddy, K.N., M.A. Locke, and C.T. Bryson. 1994. Foliar washoff and runoff losses of lactofen, norflurazon, and fluometuron under simulated rainfall. J. Agric. Food Chem. 42:2338–2343.

Reddy, K.N., R.M. Zablotowicz, M.A. Locke, and C.H. Koger. 2003. Cover crop, tillage, and herbicide effects on weeds, soil properties, microbial populations, and soybean yield. Weed Sci. 51:987–994.

Rhoton, F.E., M.J. Shipitalo, and D.L. Lindbo. 2002. Runoff and soil loss from Midwestern and southeastern US silt loam soils as affected by tillage practice and soil organic matter content. Soil Tillage Res. 66:1–11.

Shipitalo, M., and L.B. Owens. 2006. Tillage system, application rate, and extreme event effects on herbicide losses in surface runoff. J. Environ. Qual. 35:2186–2194.

Steiner, J.L. 1994. Crop residue effects on water conservation. *In* P.W. Unger (ed.) Managing agricultural residues. Lewis Publ., Ann Arbor, MI.

Vencill, W.K. (ed.). 2002. Herbicide handbook. 8th ed. Weed Sci. Soc. of Am., Lawrence, KS.

Webster, E.P., and D.R. Shaw. 1996. Off-site runoff losses of metolachlor and metribuzin applied to different soybean (*Glycine max*) production systems. Weed Technol. 10:556–564.

Werth, J.A., C. Preston, I.N. Taylor, G.W. Charles, G.N. Roberts, and J. Baker. 2008. Managing the risk of glyphosate resistance in Australian glyphosate-resistant cotton production systems. Pest. Manage. Sci. 64:417–421.

Wilson, G.V., S.M. Dabney, K.C. McGregor, and B.D. Barkoll. 2004. Tillage and residue effects on runoff and erosion dynamics. Trans. ASAE 47:119–128.

Yoo, K.H., J.T. Touchton, and R.H. Walker. 1987. Effects of tillage on surface runoff and soil loss from cotton. Trans. ASAE 30:166–168.

Zeimen, M.B., K.A. Janssen, D.W. Sweeney, G.M. Pierzynski, K.R. Mankin, D.L. Devlin, D.L. Regehr, M.R. Langemeier, and K.A. McVay. 2006. Combining management practices to reduce sediment, nutrients, and herbicides in runoff. J. Soil Water Conserv. 61:258–267.

Zhu, J.C., C.J. Gantzer, S.H. Anderson, E.E. Alberts, and P.R. Beuselinck. 1989. Runoff, soil, and dissolved nutrient losses from no-till soybean with winter cover crops. Soil Sci. Soc. Am. J. 53:1210–1214.