Herbicide Incorporation by Irrigation and Tillage Impact on Runoff Loss

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Runoff from farm fields is a common source of herbicide residues in surface waters. Incorporation by irrigation has the potential to reduce herbicide runoff risks. To assess impacts, rainfall was simulated on plots located in a peanut (*Arachis hypogaea* L.) field in Georgia's Atlantic Coastal Plain region after pre-emergence application of metolachlor (2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-[(1*S*)-2-methoxy-1-methylethyl]-acetamide) and pendimethalin (*N*-(1-ethylpropyl)-3,4-dimethyl-2,6-dinitro-benzenamine). Runoff, sediment, and herbicide loss as function of strip tillage (ST) versus conventional tillage (CT) were compared with and without irrigation (12.5 mm) after application of an herbicide tank mixture. For the CT system, metolachlor runoff was reduced 2× and pendimethalin 1.2× when compared with the non-irrigated treatment. The difference in irrigated and non-irrigated metolachlor means was significant (P = 0.05). Irrigation reduced metolachlor runoff by 1.3× in the ST system, but there was a 1.4× increase for pendimethalin. Overall results indicated that irrigation incorporation reduces herbicide runoff with the greatest impact when CT is practiced and products like metolachlor, which have relatively low K_{oc} and high water solubility, are used. The lower ST system response was likely due to a combination of spray interception and retention by the ST system cover crop mulch and higher ST soil organic carbon content and less total runoff. During the study, the measured K_{oc} of both herbicides on runoff sediment was found to vary with tillage and irrigation after herbicide application. Generally, K_{oc} was higher for ST sediment and when irrigation incorporation was used with the CT system. These results have significant implications for simulation model parametization.

Runoff is a common route of pesticide transport to surface waters (Wauchope, 1978; Leonard, 1990; Capel et al., 2001; Gilliom et al., 2006). Numerous reports have indicated that conservation tillage (CsT) may effectively reduce runoff and erosion, thereby reducing the potential for negative water quality impacts (Fawcett et al., 1994). This was found to be the case in studies that compared pre-emergence herbicide runoff under strip tillage (ST) and conventional tillage (CT) during cotton (*Gossypium hirsutum* L.) production in Georgia's Atlantic Coastal Plain region (Potter et al., 2004; Potter et al., 2006). Strip tillage is a CsT practice in which crops are planted in narrow strips tilled into killed cover crop mulch. Typically, CT involves turning crop residue into soil and planting into bare soil on prepared seed beds. The ST system had consistently lower edge-of-field losses of pendimethalin and fluometuron when compared with the CT system in studies of runoff from 0.15-ha fields under natural rainfall.

In companion investigations, pendimethalin runoff loss was reduced by ST during rainfall simulations conducted 1 d after herbicide treatment (DAT) on 6-m^2 plots; however, loss of fluometuron was increased (Potter et al., 2004; Potter et al., 2006). Pendimethalin sorbs strongly to soil and crop residue, whereas fluometuron sorption is relatively weak (Gaston et al., 2001; Gaston et al., 2003). The difference in reported soil sediment organic carbon water partition coefficient (K_{oc}) values is >100-fold. In addition, fluometuron's water solubility is nearly 300 times greater than pendimethalin's (Footprint, 2006). These differences and the timing of runoff relative to herbicide application seemed to explain the observed tillage-related runoff responses.

Sorption parameters and water solubility of two other widely used herbicides, atrazine and metolachlor, are similar to fluometuron (Footprint, 2006). Greater runoff of these two compounds was also observed with CsT compared with CT management when natural or simulated events generated runoff and the time between runoff and herbicide application was a week or less (Kenimer et al., 1987; Sauer and Daniel, 1987; Fawcett et al., 1994).

These data indicate that when CsT is practiced, additional measures may be required to control runoff loss of active ingredients whose physical-chemical properties make them susceptible to runoff and when runoff occurs close to the time of applica-

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Abbreviations: AWC, antecedent soil water content; CsT, conservation tillage; CT, conventional tillage; DAT, days after treatment; K_{oc}, sediment organic carbon water partition coefficient; RZWQM, Root Zone Water Quality Model; SOC, soil organic carbon; ST, strip tillage; VWC, volume-weighted concentration.

tion. A practice often recommended on pesticide labels and in extension literature is incorporation by irrigation. Increased weed control efficacy may also be observed as the herbicides are moved below the soil surface into the zone where weed seeds are germinating (Prostko et al., 2001; Smith et al., 2002).

Although herbicide runoff reduction is anticipated by post-application irrigation, there are few published studies quantifying the effects of the practice, and study results are mixed. During an investigation conducted in a citrus orchard in California's central valley, Liu and O'Connell (2002) found that 5 to 18 mm of irrigation about 1 h after simazine application reduced its runoff by 50% or more during subsequent rainfall simulations. Smith et al. (2002) reported a similar response with atrazine when it was applied to soil trays, "watered in" with 4 to 8 mm of irrigation, and runoff was produced by rainfall simulation 1 DAT. However, "watering in" increased atrazine runoff when simulations were conducted 8 and 15 DAT. In another study, irrigation after diazinon application to tall fescue (*Festuca arundinacea*) increased runoff loss of this insecticide (Evans et al., 1998). The increased loss was attributed to an increase in antecedent soil water content (AWC) due to the irrigation. Typically higher AWC shortens the time to runoff and increases runoff volume (Hillel, 1982).

These uncertainties motivated our investigations. Runoff of two widely used herbicides, metolachlor and pendimethalin, as a function of tillage (ST and CT), with and without post-application irrigation were compared during rainfall simulations in a field in a cotton–peanut rotation in south-central Georgia. Cotton and peanut dominate row-crop production in the region, and increasingly growers are converting to ST and other forms of CsT management (Sullivan et al., 2006). Quantitative assessment of management practices designed to minimize the potential for adverse water quality impacts from use of herbicides and other crop protections chemicals is needed.

Materials and Methods

Study Site, Management, and Rainfall Simulations

Simulations were conducted in a gently sloping (3–4%) field in Tift County, Georgia. The field was equally divided across the slope by ST and CT. The practices were established in 1999. The soil is Tifton loamy sand (fine-loamy, siliceous, thermic, Plinthic Kaniudult). Soil properties, site conditions and management, and techniques and equipment used for rainfall simulations are described elsewhere (Potter et al., 2003; Potter et al., 2004; Potter et al., 2006; Franklin et al., 2007; Truman et al., 2007). Cotton was produced in 1999, 2000, 2001, 2003, and 2005 and peanut (*Arachis hypogaea* L.) in 2002, 2004, and 2006. In the fall of each year, rye (*Secale cearale* L.) was planted. The rye was terminated by glyphosate application about 1 mo before planting cotton or peanut in the following spring. Where ST was practiced, crops were planted in 15-cm strips tilled into the cover crop residue surface mulch. At planting, the average (SD) mulch coverage in the ST area was 52% (11%) (Dana Sullivan, personal communication). In the CT area, crops were planted into beds of freshly tilled soil that was free of surface residue. Extension service recommendations guided planting date and crop management (Prostko et al., 2007; Jost et al., 2005).

After peanuts were planted in May 2006, four steel frames (2 × 3 m × 0.15 m in depth) were installed in ST and CT portions of the field. The frames, which were pushed 5 cm into the soil, were oriented so that they spanned two peanut rows and a wheel track with the longer dimension parallel to the rows. Prowl 3.3 EC (BASF, Research Triangle Park, NC) and Dual II Magnum (Syngenta Crop Protection Inc., Greensboro, NC) active ingredients pendimethalin and metolachlor, respectively, were tank-mixed with water and applied with a backpack sprayer at 180 L ha^{-1} and 275 kPa. Target active ingredient rates were 1 kg ha^{-1} pendimethalin and 1.5 kg ha^{-1} metolachlor. The application rates were measured by analyzing spray-targets made of 7-cm diameter cellulose filter paper (n = 4) placed on plots before spraying. Two to three hours after herbicide application on two plots in each tillage area, 12.5 mm of water at 0.28 mm min^{-1} was applied using the rainfall simulator. This was the amount recommended for herbicide "activation" (Prostko et al., 2007). The water source for irrigation and simulations was a nearby well drawing from the Floridian aquifer (Potter et al., 2003). In the text that follows, the four treatment groups are referred to as CT irrigated (CT-I), CT not-irrigated (CT-NI), ST-irrigated (ST-I), and ST not-irrigated (ST-NI).

Twenty-four hours after herbicide application, simulated rainfall was applied for 70 min to each plot. The simulated intensity pattern was based on characteristics of convective thunderstorms that occur with high frequency in the region (Frauenfeld and Truman, 2004; Potter et al., 2006; Truman et al., 2007). During simulations, rainfall rates and amounts were measured using a tipping bucket rain gage (Texas Electronics Inc., Dallas, TX) and 15-cm-diameter collection cans (n = 3).

All runoff was collected from an aluminum trough installed at the down-slope end of each frame. Runoff was composited in 5-min intervals in 12-L stainless steel buckets. Bucket contents were mixed before collection of two subsamples: one by filling a 1-L glass bottle and the second by filling a 500-mL glass bottle. Bottles were sealed with Teflon-lined screw caps and placed in a laboratory refrigerator at 4°C after each simulation was completed. Any water remaining in the buckets was poured into 1-L polyethylene bottles. All bottles were weighed, and weights were summed to determine the total runoff volume for each time increment.

Composite soil samples were collected at four depths (0–2 cm, 2–8 cm, 8–15 cm, and 15–30 cm) 1 h before and after each simulation. The "before" samples were collected in herbicide-treated areas adjacent to each plot, and the "after" samples were collected within plot boundaries. The water content was determined on a portion of each sample by drying overnight at 105°C in a laboratory oven. All soil samples were stored in a freezer at −20°C.

Mulch for washoff studies was obtained from a sprayed area about 20 m from the simulator plots. The mulch from an area where soil was completely covered by mulch was cut using a 20-cm-diameter aluminum pie plate as a template. The mulch was carefully wrapped in a pre-weighed sheet of aluminum foil to avoid disturbance of the cover crop residue arrangement. The foil was weighed to determine mulch weight and stored in a laboratory refrigerator overnight. Just before beginning simulations, the

mulch was transferred, sprayed surface up, to a second plate that was perforated with 0.3-cm-diameter holes. This plate was placed in a 25-cm-diameter glass funnel mounted on a wooden stand positioned under the simulator. Leachate was collected from the funnel directly into 250-mL glass bottles in step with runoff samples.

Sample Preparation, Analysis, and Quality Control

The 1-L runoff samples were glass fiber filtered (Whatman GFF filters; 0.7-μm nominal pore size). Filters and sediment were weighed and frozen. Duplicate portions (1 g) of the filtrate were placed in 2-mL autosampler vials for herbicide analysis and stored in the refrigerator at 4°C. The washoff samples were handled similarly; bottles were weighed to determine washoff volume, and all bottles were combined per corresponding 5-min interval.

Filters and sediment from runoff samples and 50-g subsamples of sieved (2-mm) field-moist soil were sequentially extracted with methanol (3 by 50 mL). After the extractions were complete, sediment was air-dried and then dried in an oven at 105°C and weighed to determine "filtered" sediment dry weight. Combined soil and sediment extracts were concentrated to 10 mL under a direct stream of N_2 gas. Filter paper spray targets were shaken with 25 mL methanol. Aliquots (1 mL) of spray target, soil and sediment extracts, and runoff and mulch washoff filtrate were fortified with 5 μg of 2-chlorolepidine (internal standard) and analyzed by HPLL-APCI-MS (Potter et al., 2006). Standards for runoff sample analysis were prepared by spiking well water used in simulations. Ions used for quantitation were base peaks in full-scan spectra, $m/z^+ = 282$ for pendimethalin and $m/z^+ = 284$ for metolachlor. Method detection limits based on the low concentration standard in each calibration were 10 μg L^{-1} for runoff, 5.0 μg kg^{-1} for soil, and 50 to 100 μg kg^{-1} for sediment, depending on the mass recovered by filtration.

Sediment recovered after drying the 500-mL subsample (referred to as "suspended- sediment") in a laboratory oven at 105°C was sieved (1 mm) and pulverized before organic carbon analysis with a Carlo-Erba Model NA1500 II CN-analyzer (CE Elantech, Inc., Lakewood, NJ). The combined sediment recovered from the polyethylene bottles after acid flocculation and oven drying was handled and analyzed in the same way. This material was termed the "bulk sediment."

Before each simulation, two 1-L water samples were collected from the simulator water tank. One was retained as a "blank." The second was used as matrix-spike by fortifying it with the target analytes at 50 μg L^{-1}. Their concentration was below the method detection limit of 10 μg L^{-1} in all blanks. In matrix spikes, average (SD; $n = 8$) metolachlor recovery was 108% (22%), and average pendimethalin recovery was 101% (21%), indicating relatively high measurement precision and accuracy. Quality control samples (blanks, spikes, and duplicates) for soil and sediment were not prepared or analyzed. Prior work with these compounds in fortified soil and sediment indicated that recoveries were quantitative and reproducible (Potter et al., 2006).

Data Analysis

In a prior investigation using the same equipment and sample handing techniques, total sediment concentration measured in runoff samples collected for herbicide analysis was 40 to 60% less than corresponding bulk-sample values (Potter et al., 2006). To address the potential for bias in computations for total sediment-bound concentration of each herbicide in runoff in the current study, measured herbicide concentrations in filtered sediment were multiplied by the ratio of the organic carbon concentration measured in corresponding bulk- and suspended-sediment samples. Linear equilibrium partitioning of the herbicides between sediment organic carbon and water was assumed. Metolachlor and pendimethalin K_{oc} values were determined for each sample by dividing the ratio of their measured concentrations in sediment and filtrate by the suspended-sediment fraction organic carbon. Tests for differences in K_{oc} medians were made by Kruskal-Wallis one-way ANOVA on ranks (Systat, 2004). Herbicide runoff data were evaluated by multiplying the concentration (dissolved and sediment bound) by the volume of runoff measured in each time step and summing over the duration of each simulation to determine total mass loss. Values were divided by the computed mass applied to simulator plots (average of spray target measurements) or total runoff volume. Results were termed "% loss" and "volume-weighted concentration" (VWC), respectively. Runoff rates were assessed by linear regression through the origin of cumulative runoff (% of rainfall) and % loss data by treatment group and compound. Slopes of regression lines were termed the "loss rate." Differences in rainfall, runoff, sediment loss, AWC, % loss, and VWC means were evaluated with unpaired *t* tests assuming unequal variances. Computations were made with Excel 2003 (Microsoft, 2003). Comparisons of loss rates (regression line slopes) were made using GraphPad Prism 5.0 (GraphPad, 2007). All test statistics were evaluated at $P = 0.05$ unless otherwise noted.

Results and Discussion

Runoff and Sediment Loss

Peak runoff and sediment loss occurred soon after maximum rainfall intensity was reached (Fig. 1 and 2). Rates were highest for the CT system and when plots were irrigated (I) before simulations. CT-I were significantly greater when compared with CT-NI and ST-I means. Total runoff and sediment loss followed the same trends, with CT-I > CT-NI > ST-I > ST-NI with CT system runoff (about 1.5×) and sediment loss (about 2×) greater than for the ST system (Table 1). For runoff means, significant differences were indicated but only when the acceptance level was increased to $P = 0.10$. Significant differences between sediment loss means were not indicated even when evaluated at this level. As observed in prior investigations, sediment loss was more variable than runoff results (Potter et al., 2004; Potter et al., 2006; Truman et al., 2007). With only two replications, the power of the statistical test was also very low.

Generally, runoff and sediment loss results when compared by tillage were consistent with other studies conducted at the research site (Potter et al., 2004; Potter et al., 2006; Truman et al., 2007). Runoff results were also consistent; a large number of studies reported that higher soil AWC yielded more runoff more quickly and in greater amounts (Knisel, 1980; Hillel, 1982; Smith et al., 2002). The AWC impact on runoff was greatest for

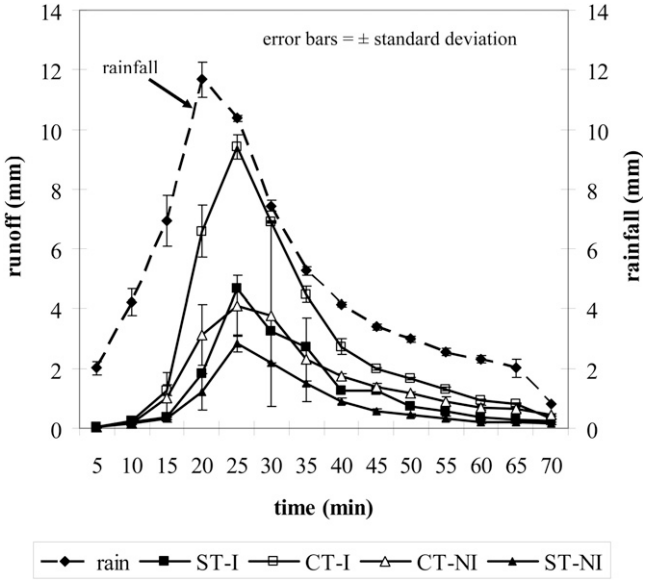

Fig. 1. Rainfall and mean runoff from plots. I, irrigated; NI, non-irrigated; ST, strip tillage; CT, conventional tillage.

the CT-I treatment, with runoff nearly two thirds of all simulated rainfall applied. This was about 1.7 times greater than for the CT-NI treatment. The mean AWC for ST-I treatment group was nearly equal to the CT-I value, but ST-I runoff was 2-fold less. This was another indication of the large impact that ST had in reducing runoff and increasing infiltration.

Sediment loss also trended higher for the irrigated treatments (CT-I and ST-I) for both tillages (Table 1 and Fig. 2). This was likely due to surface processes that occurred during wetting of dry soil, including aggregate breakdown, soil crusting, and surface sealing. Often this results in increased runoff velocity, soil detachment due to raindrop impact, and erosion (Hairsine et al., 1992; Römkens et al., 2001). With the ST system, sediment loss

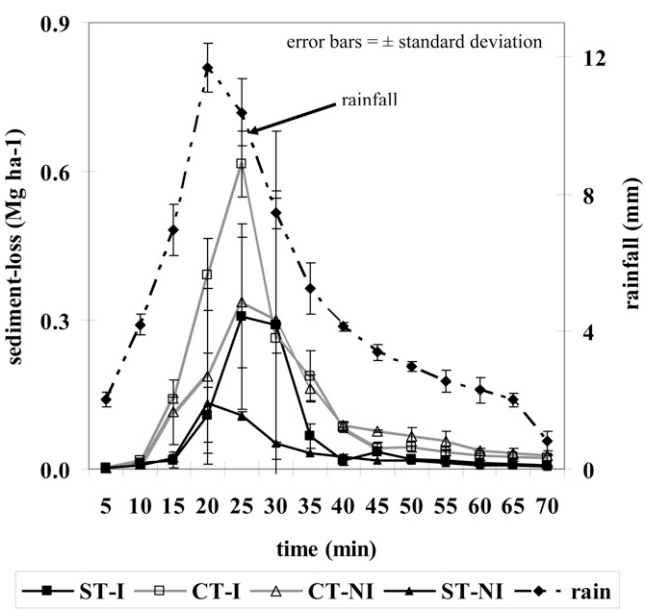

Fig. 2. Rainfall and mean sediment loss from plots. I, irrigated; NI, non-irrigated; ST, strip tillage; CT, conventional tillage.

Table 1. Mean (SD) antecedent soil water content and event-based summary of rainfall, runoff, and sediment loss by tillage treatment with and without irrigation for herbicide incorporation.

	Rainfall	% Runoff†	Sediment loss	% AWC‡
	mm		Mg ha^{-1}	
ST-I§	66 (0.5)	32 (5.8)	0.93 (0.5)	12 (0.4)¶
ST-NI	68 (4.5)	21 (1.0)	0.44 (0.1)	7.8 (0.2)¶
CT-I	66 (0.8)	65 (0.4)	1.9 (0.6)	11 (0.4)
CT-NI	65 (2.7)	39 (5.1)	1.5 (0.4)	8.6 (0.1)#

† % of rainfall.

‡ % antecedent soil water content (depth integrated [0–30 cm]; gravimetric). Unpaired *t* test assuming unequal variances was used to test differences between means.

§ CT-I, conventional-till plots irrigated; CT-NI, conventional-till plots not irrigated; ST-I, strip-till plots irrigated; ST-NI, strip-till plots not irrigated.

¶ Significant difference between ST-I and ST-NI means.

Significant difference between ST-NI and CT-NI means.

was lower, presumably due to mulch intercepting irrigation and rainfall and reducing the rate at which soil surface properties that influence runoff and erosion changed during simulations. The process was reported to change erosion dynamics from detachment- to transport-limiting conditions of when ST systems were used on a Tifton soil (Truman et al., 2007).

Herbicide Washoff from Cover Crop Mulch

The mulch also intercepted the broadcast herbicide spray, thereby reducing soil deposition. Mulch coverage was estimated to be 52 ± 11%. It was assumed that this provided a reasonable interception estimate (Linders et al., 2000). During irrigation and rainfall simulations, a portion of the intercepted pendimethalin and metolachlor was washed off. Foliage washoff studies have indicated that when washoff occurs soon after application, pesticide runoff concentrations may be substantially increased (Reddy and Locke, 1996; Wauchope et al., 2004). Thus, washoff from mulch particularly during simulations likely increased the amounts of pendimethalin and metolachlor available for runoff. During irrigation, there was no runoff; thus, this process likely increased contact with and infiltration of herbicides washed off. A reduction in runoff potential was anticipated.

Potential metolachlor and pendimethalin washoff by irrigation and during simulations was assessed by measuring washoff of these compounds from sprayed mulch during each simulation (n = 8) and fitting the data to Eq. [1].

$$C_f = C_{fi} F_{wo} e^{-(P_{wo} I \Delta t)} \quad [1]$$

where P_{wo} and F_{wo} are fitted parameters termed the "washoff coefficient" and "available washoff fraction," respectively; I is the rainfall rate; C_{fi} is the initial herbicide concentration; C_f is herbicide concentration; and Δt is the time increment. The equation, which was originally developed to describe pesticide washoff from foliage, is used to describe washoff from foliage and mulch in the Root Zone Water Quality Model (RZWQM) and in other simulation models (Willis et al., 1980; Wauchope et al., 2004).

Nonlinear regression R^2 values were 0.61 for metolachlor and 0.70 for pendimethalin, indicating a reasonable data fit with available washoff fractions (93 and 99%, respectively) and washoff coefficients (0.005 and 0.0004 mm^{-1}, respectively) (Fig. 3). In

insecticide washoff studies from cotton foliage, washoff coefficients increased 2- to 3-fold, with a 10-fold increase in water solubility (Willis et al., 1980). Mulch washoff results for metolachlor and pendimethalin followed the same trend. Water solubility was reported to be 500 mg L^{-1} for metolachlor and 0.3 mg L^{-1} for pendimethalin (Footprint, 2006). To our knowledge, our results are a first report of metolachlor and pendimethalin washoff parameters from mulch. Wauchope et al. (2004) observed that there are few published washoff measurements and little reported data that almost exclusively examined washoff from foliage.

Using irrigation amounts (12.5 mm) and fitted parameters in Eq. [1], irrigation delivered 13% of metolachlor and 0.6% of pendimethalin intercepted to the soil surface (Table 2). For metolachlor, this amounted to an increase of about 7% of applied. Given the potential for metolachlor sorption and/or infiltration after soil contact, a small decrease in runoff potential was suggested. The very small amount of pendimethalin washoff (0.3% of applied) indicated little or no impact on runoff dynamics.

Overall, results were consistent with fluometuron and pendimethalin washoff data obtained in laboratory investigations (Gaston et al., 2001; Gaston et al., 2003). Extrapolation to a leaching model indicated that 20 mm of rainfall would deliver between 0.1 and 0.5% of the pendimethalin and 15 to 21% of fluometuron from treated cover crop mulch to soil. Fluometuron, like metolachlor, has relatively high water solubility and low K_{oc} (Footprint, 2006); thus, similar washoff behavior is expected.

Washoff during simulations estimated using Eq. [1] and fitted parameters indicated that the process contributed an additional 16% (I) to 19% (NI) of metolachlor and 1.3% (I) to 1.6% (NI) of pendimethalin to the soil. The bulk of the material was delivered at a time when infiltration and runoff were increasing. Studies with foliar applied compounds have shown that washoff can substantially increase herbicide runoff concentrations (Reddy and Locke, 1996; Wauchope et al., 2004). It follows that the process may have substantially increased the amount of metolachlor, but not pendimethalin, available for runoff.

A final set of washoff computations compared estimates made using fitted parameters with Eq. [1] and default values proposed in the RZWQM model (Wauchope et al., 2004). For irrigation, results showed that pendimethalin washoff using the default values was about four times greater than with fitted values. There was little difference between the two metolachlor values. Using simulated rainfall amounts, which were about five times greater than irrigation, differences in computed values for both herbicides increased (Table 2). Given the magnitude of uncertainties, especially with simulated rainfall amounts and pendimethalin, further experimental work examining washoff from mulch is necessary to determine the suitability of use of default values in assessing washoff potential. Our data suggest that washoff may be overestimated by greater than fourfold. This could introduce substantial error into simulation model outputs.

Metolachlor and Pendimethalin Runoff

Differences in computed runoff metrics, % loss, VWC, and loss rate indicated that irrigation after application substantially reduced the total amount and rate of metolachlor runoff. Volume-weighted concentration means were 3- to 5-fold, loss rate means were 2- to 3-fold, and % loss means were 1.2- to 2-fold less for the ST and CT systems, respectively (Table 3; Figure 4). This was observed even though irrigation increased the total volume of ST system runoff by 1.5-fold and CT system runoff by 1.7-fold (Table 1). Differences in loss rate and VWC means were significantly lower when CT-I and CT-NI and ST-I and ST-NI runoff responses were compared. The CT-I % loss mean was also significantly lower than the CT-NI value. This was not the case for the ST-I and ST-NI treatments. One possible explanation was washoff of metolachlor from mulch during simulations (Table 2). It was likely available for runoff and contributed substantially to the amount detected in runoff.

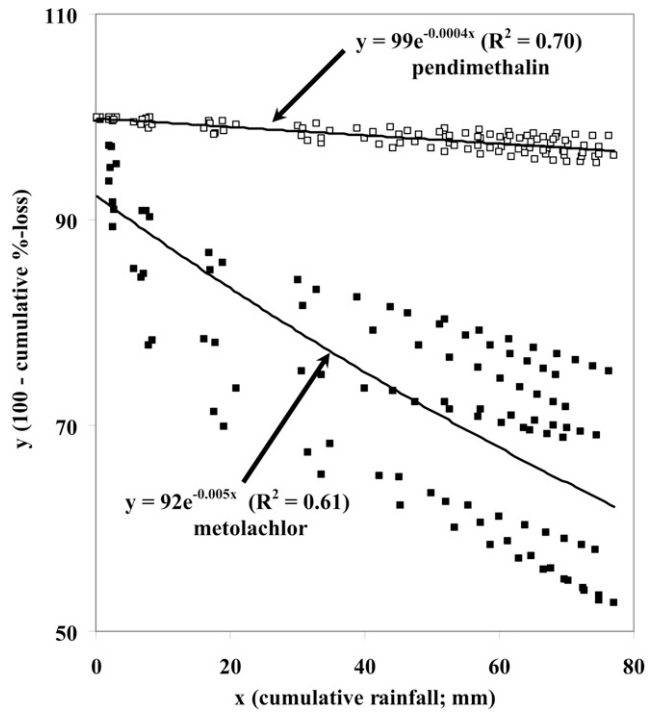

Fig. 3. Metolachlor and pendimethalin washoff from cover crop mulch expressed as the cumulative percent retained on mulch versus cumulative runoff.

Table 2. Estimated metolachlor and pendimethalin washoff (% of intercepted) by irrigation and during simulations using Eq. [1] and fitted and default values of the "available washoff fraction" and "washoff coefficient" parameters.

Treatment	Metolachlor	Pendimethalin
Irrigation		
Fitted†	13	0.6
Default‡	15	2.5
Rainfall simulation		
Irrigated		
Fitted	31	2.5
Default	52	12
Not irrigated		
Fitted	36	3
Default	61	14

† For fitted values, see Fig. 3.

‡ For default values, see Wauchope et al. (2004).

Table 3. Mean (SD) metolachlor and pendimethalin applied and volume-weighted concentration (VWC), % loss, and loss rate (see Fig. 4 and 5).

	ST-I†	ST-NI	CT-I	CT-NI
Metolachlor				
Applied, μg cm^{-2}	13 (1.5)	15 (2)	12 (0.1)	18 (1.5)
VWC,‡ μg L^{-1}	200 (31)§	430 (51)§¶	140 (27)#	750 (70)¶#
% Loss, % of applied	3.4 (1.7)	4.1 (0.4)	5.0 (1)#	10 (1.7)#
Loss rate, % mm^{-1}	0.16¶§	0.30¶§	0.12#††	0.45¶#
Pendimethalin				
Applied, μg cm^{-2}	11 (0.7)	12 (1.8)	9.5 (0.1)#	14 (1.2)#
VWC, μg L^{-1}	92 (40)	97 (31)	51 (2)#	170 (28)#
% Loss, % applied	1.7 (0.5)	1.2 (0.4)¶	2.3 (0.1)	3.0 (0.3)¶
Loss rate, % mm^{-1}	0.08††	0.08¶	0.06#††	0.13¶#

† CT-I, conventional-till plots irrigated; CT-NI, conventional-till plots not irrigated; ST-I, strip-till plots irrigated; ST-NI, strip-till plots not irrigated.

‡ VWC = dissolved plus computed sediment-bound. Loss rate = slope of linear regression lines (Fig. 4 and 5). Unpaired *t* test assuming unequal variances was used to test differences between means.

§ Significant difference between ST-I and ST-NI means.

¶ Significant difference between ST-NI and CT-NI means.

Significant difference between CT-I and CT-NI means.

†† Significant difference between ST-I and CT-I means.

Our results also indicated that irrigation of the CT system contributed to lower pendimethalin runoff. Both VWC means and loss rate were significantly lower for the CT-I treatment and the CT-I % loss, although they were not significantly different from the CT-NI mean, which was about 25% lower (Table 3; Fig. 5). With the ST system, irrigation had no impact on VWC means and or loss rate. The ST-I and ST-NI values were nearly equal. Comparison of ST-I and ST-NI means indicated that irrigation may have increased % loss (about 30%), but the difference was not significant.

Irrigation impact on metolachlor runoff can be attributed at least in part to leaching by infiltrating irrigation water and a reduction in the amount available for runoff. Leaching was facilitated by metolachlor's relatively high water solubility and low K_{oc} and by the low soil organic carbon (SOC) content in the study area. In

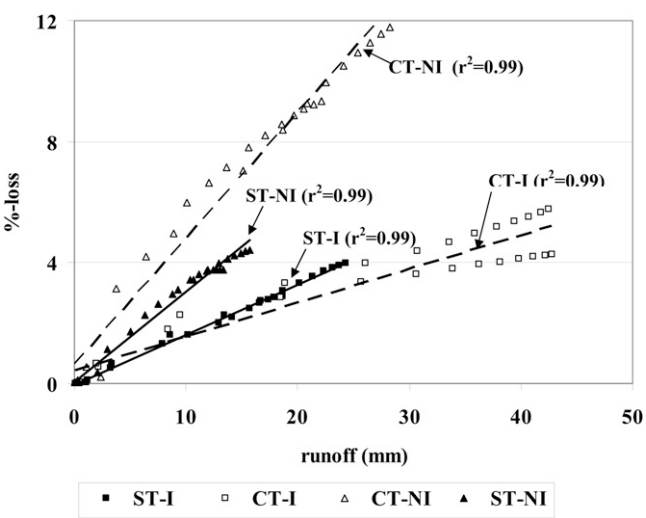

Fig. 4. Cumulative metolachlor loss expressed as percent of applied versus cumulative runoff during simulations. I, irrigated; NI, non-irrigated; ST, strip tillage; CT, conventional tillage.

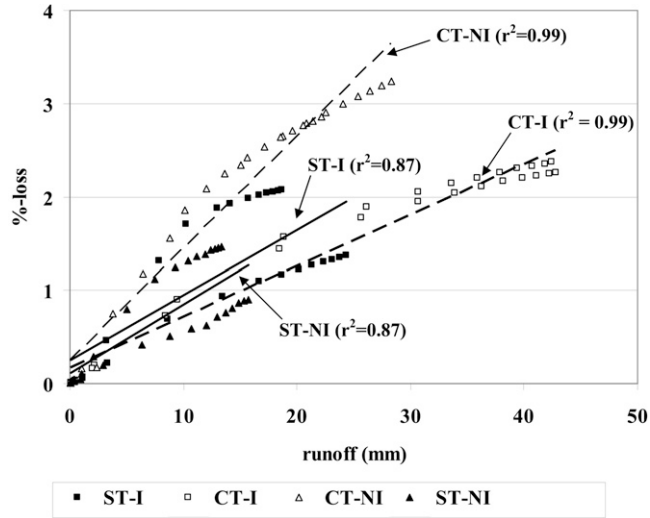

Fig. 5. Cumulative pendimethalin loss expressed as percent of applied versus cumulative runoff during simulations. I, irrigated; NI, non-irrigated; ST, strip tillage; CT, conventional tillage.

the CT portion of the field, the average (SD) organic carbon concentration in eight surface (0–2 cm) soil samples collected before simulations was 7.7 (1.0) g kg^{-1}. Values for samples collected in the ST area—12.4 (3.4) g kg^{-1}—were significantly greater.

Spreadsheet solution of a one-dimensional plug flow leaching model followed by application of results to the non-uniform mixing model described by Smith et al. (1993) provided support for this conclusion. The leaching model was based on spreadsheet simulation of a chromatographic separation (Freiser, 1992). Measured SOC and bulk density values were used with the assumption of linear sorption on SOC and metolachlor K_{oc} = 200 (Footprint, 2006) in the solution. The "availability for runoff" of the computed mass of metolachlor at each depth increment was determined using Eq. [2].

$$\text{Fraction available for runoff} = M \times e^{-bz} \quad [2]$$

where M is the mass or metolachlor, z is the soil depth (mm), and b is a constant reflecting "extractability" into runoff. In solutions, b was set to 0.8, which is the default used in the RZWQM (Wauchope et al., 2004). Fractions were summed and expressed as % of applied. Results indicated a 63% reduction in metolachlor availability for runoff for the CT system and a 26% reduction in metolachlor availability for the ST system. Values were in reasonable agreement with corresponding metolachlor % loss values that indicated runoff reductions of 50 and 17% (Table 3).

Although it seems that there was some metolachlor leaching during irrigation, transport distances were likely small. Based on the plug-flow model, >99% of the metolachlor was retained in the top 1.0 cm of soil. This observation helped to explain why results of analysis of surface soil samples collected over the depth interval 0 to 2 cm before simulations did not indicate a difference between ST-I and ST-NI and CT-I and CT-NI treatments.

During simulations, about five times more water was applied. As a result, leaching was greater. Comparison of metolachlor data for soil samples collected before and after simulations confirmed this (Fig. 6 and 7). Results for CT and ST

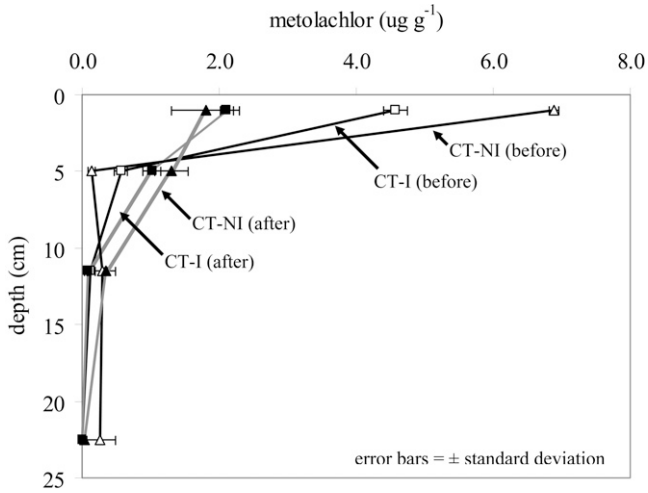

Fig. 6. Average metolachlor concentration in CT soil samples collected before and after rainfall simulations. I, irrigated; NI, non-irrigated; CT, conventional tillage.

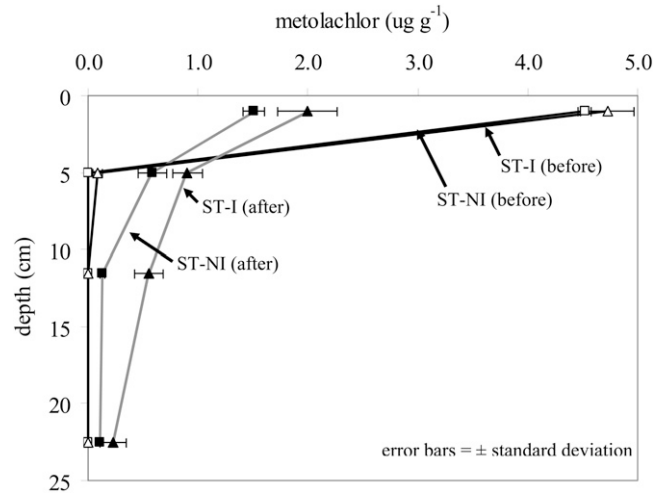

Fig. 7. Average metolachlor concentration in ST soil samples collected before and after rainfall simulations. I, irrigated; NI, non-irrigated; ST, strip tillage.

system sample sets showed that peak concentrations in the ST and CT system samples were found in the 2- to 8-cm depth increment. This was consistent with leaching model estimates.

For pendimethalin, the computed reduction in the availability for runoff due to leaching was <4% for the ST and CT systems. Thus, leaching likely had little impact on pendimethalin runoff. In spite of this, irrigation reduced CT system pendimethalin runoff (Table 4). A possible explanation is the impact of irrigation on soil surface processes, such as the destruction of aggregates. As aggregates were broken down, internal surfaces enriched in organic carbon would likely have been exposed. Pendimethalin has a very high K_{oc} value; thus, it would bind strongly to these surfaces, reducing the amount that would dissolve in runoff.

The hypothesis was supported by computed pendimethalin K_{oc} values for sediment entrained in runoff (Table 4). The median pendimethalin K_{oc} for sediment recovered in CT-I when compared with CT-NI runoff samples was about 2-fold greater. The same trend was observed in computed metolachlor K_{oc} values, with the difference in medians being greater than 4-fold and significant (Table 4). Thus, it seems that irrigation impact on soil surface properties had the potential to effectively increase binding to soil and sediment and to contribute to reduced runoff.

In the case of the ST system, computed metolachlor K_{oc} values did not indicate an irrigation impact on metolachlor binding to soil and sediment. The ST-I and ST-NI medians were nearly equal, and the difference was not significant. For pendimethalin, the median ST-NI K_{oc} was about 4-fold greater than the ST-I value, but ST-NI results were more variable; thus, a significant difference was not indicated (Table 3). A likely explanation of why an irrigation impact on sediment K_{oc} was not observed for both compounds with the ST system was the interception of irrigation water by cover crop mulch. Interception decreased irrigation droplet energy before impact with the soil surface; thus, the potential for change in soil surface properties was less.

Large and significant differences between ST-I and CT-I and ST-NI and CT-NI sediment metolachlor and pendimethalin K_{oc} medians also suggested that there were qualitative differences in the nature of the organic matter retained at the soil surface in the two tillage systems. The ST system sediment K_{oc} medians were in all cases greater than the corresponding CT system values (Table 3). Greater binding combined with lower runoff volumes had the potential to reduce irrigation effects on ST system for both herbicides.

Together, the K_{oc} measurements suggested that tillage and irrigation may influence forms and availability of soil and sediment organic carbon for binding herbicides like metolachlor and pendimethalin. There are significant implications for simulation modeling because most models assume that pesticide K_{oc} values are constants with no adjustments made for management practices such as tillage or irrigation.

Summary and Conclusions

This study found that in the southern Atlantic Coastal Plain, where surface soils are often sandy and have low organic carbon content, irrigation after herbicide application can substantially reduce runoff losses of these products. During rainfall simulations, total runoff of metolachlor, an herbicide with a relatively high water solubility and low K_{oc}, was reduced by 2-fold from irrigated

Table 4. Reported metolachlor and pendimethalin sediment organic carbon water partition coefficient (K_{oc}) values and median (25th to 75th percentile) of values computed for suspended sediment in runoff samples from strip-tilled and conventionally tilled plots with and without irrigation incorporation.

	Metolachlor	Pendimethalin
ST-I†	520 (290–670)‡	18,000 (16,000–24,000)‡
ST-NI	610 (150–1700)§	71,000 (19,000–130,000)§
CT-I	170 (140–220)‡¶	3100 (2600–4800)‡
CT-NI	41 (32–58)§¶	1700 (1300–2700)§
Reported value#	200	16,000

† CT-I, conventional-till plots irrigated; CT-NI, conventional-till plots not irrigated; ST-I, strip-till plots irrigated; ST-NI, strip-till plots not irrigated.

‡ Significant difference between ST-I and CT-I means.

§ Significant difference between ST-NI and CT-NI means.

¶ Significant difference between CT-I and CT-NI means.

Footprint (2006). Tests for differences in Koc medians were made by Kruskal–Wallis one way analysis of variance on ranks.

versus non-irrigated plots in CT management. Computations indicated that metolachlor leaching during irrigation reduced the compound's availability for runoff. A reduction in pendimethalin runoff due to irrigation on CT plots was also indicated, but differences between irrigated and non-irrigated treatments were less and not significant. Pendimethalin has much lower water solubility and higher K_{oc}; thus, leaching into the soil matrix with infiltrating irrigation was likely less. For plots in ST, irrigation reduced metolachlor runoff, but no impact was observed on pendimethalin.

The overall impact of irrigation on herbicide runoff with ST was lower. This was attributed to higher SOC in ST surface soil, lower runoff volume, and, in the case of metolachlor, a relatively high washoff rate from mulch during simulations. Data collected for herbicides indicated that tillage and irrigation may strongly affect computed runoff sediment K_{oc} values. Sediment organic carbon water partition coefficients of the herbicides were found to be about 10 times greater on ST when compared with CT sediment, and there was a trend to higher K_{oc} values on sediment after irrigation with the CT system. Further study is needed to confirm this and to develop a K_{oc} database appropriate for various modeling scenarios. Finally, comparison of computed washoff amounts using fitted and default model parameters showed that the use of default values may result in large washoff overestimates. Improvement in the accuracy of simulation model outputs is anticipated by the development of a database of mulch washoff parameters.

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