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RESEARCH PAPER

Impacts of tillage and application methods on atrazine and alachlor losses from upland fields

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The effects of tillage practises and the methods of chemical application on atrazine and alachlor losses through run-off were evaluated for five treatments: conservation (untilled) and surface (US), disk and surface, plow and surface, disk and preplant-incorporated, and plow and preplant-incorporated treatments. A rainfall simulator was used to create 63.5 mm h^{-1} of rainfall for 60 min and 127 mm h^{-1} for 15 min. Rainfall simulation occurred 24–36 h after chemical application. There was no significant difference in the run-off volume among the treatments but the untilled treatment significantly reduced erosion loss. The untilled treatments had the highest herbicide concentration and the disk treatments were higher than the plow treatments. The surface treatments showed a higher concentration than the incorporated treatments. The concentration of herbicides in the water decreased with time. Among the experimental sites, the one with sandy loam soil produced the greatest losses, both in terms of the run-off volume and herbicide loss. The US treatments had the highest loss and the herbicide incorporation treatments had smaller losses through run-off as the residue cover was effective in preventing herbicide losses. Incorporation might be a favorable method of herbicide application to reduce the herbicide losses by run-off.

Keywords: erosion, herbicide, residue, run-off.

INTRODUCTION

Atrazine and alachlor have been used widely for weed control as they are relatively inexpensive and provide a wide range of weed control. Despite this good aspect of their usage, the detection of these herbicides in public water from stream water in Australia (Popov & Cornish 2006) to the USA (Rebich *et al.* 2004), sometimes with concentrations well above the standard limits (Popov & Cornish 2006), has raised concerns about the long-term effects of these herbicides to human and animal health. Both atrazine and alachlor were reported among the most frequently detected pesticides in public waters (Rebich *et al.* 2004). In Kansas, concentrations of alachlor and atrazine are detectable throughout the year. The maximum concentration was 3.1 μg L^{-1} for alachlor and 22.0 μg L^{-1} for atrazine, which occurred in early June, coinciding with the time when maximum run-off and erosion occurs (Kansas Department of Health and Environment 1989). These concentrations were greater than the maximum contaminant level of drinking water for alachlor (2.0 μg L^{-1}) and for atrazine (3.0 μg L^{-1}).

Baker and Johnson (1979) reported that herbicide losses from run-off following an intense rainstorm of 49 mm that occurred within 24 h after herbicide application could be 10% and 15% for alachlor and atrazine, respectively. Sauer and Daniel (1988) found that early run-off events contained as much as 80% of the total annual herbicide loss. Run-off events occurring shortly after herbicide application pose the greatest off-site movement risk and losses can only be reduced with management practises that reduce run-off volume, as

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well as sediment loss (Wauchope 1978). Therefore, the continued use of atrazine and alachlor requires management techniques that prevent their off-site movement.

While studies evaluating the herbicide loss in surface run-off from different tillage practises have had mixed results (Hansen *et al.* 2001), another approach to control run-off is to consider the application method. Incorporation is thought to reduce the exposure of pesticides to rainfall and run-off water, thus possibly reducing pesticide losses through run-off. Baker and Laflen (1979) found that losses of pesticide from pesticide-incorporated plots was smallest followed by surface application and wheel-track compaction plots. Mickelson *et al.* (2001) also reported that herbicide incorporation by disking reduced herbicide losses. It is thus important to investigate the combined effect of both the application method and tillage on pesticide losses caused by run-off.

The objectives of this study are to measure the losses of alachlor and atrazine from cropland run-off water (dissolved pesticide) and from sediment (pesticide carried by soil) and determine the relationship of pesticide loss to tillage practises and the herbicide application method.

MATERIALS AND METHODS

Field experiment

Field experiments were conducted on four sites in May and June of 1991. Sites A and B were located in Gage County near Pickrell in south-eastern Nebraska, USA, and sites C and D were located in Marshall County near Vermillion in north-eastern Kansas. The slope, soil properties, and plant residue covers of the sites are listed in Table 1.

The experimental design was a combined analysis of four randomized, complete block designs with three replications for each treatment. The tillage systems included plowing (P) and disking (D) tillage, and untilled (U). The chemical application methods included surface application (S) and preplant-incorporated application (I). The studied treatments were plow and surface (PS), disk and surface (DS), untilled and surface (US), plow and preplant-incorporated (PI), and disk and preplant-incorporated (DI). There also were control plots without chemical application for the P, D, and U treatments.

The treatments were evaluated up and down the slope and positioned to obtain equivalent slopes within each replication. The P plots were moldboard plowed once, going up and down the hill, in the fall of 1990. The P and D plots had the first disking performed in April 1991. These plots were sprayed with cyanazine and 2,4-D to prevent weed growth. The final disking and chemical applications were conducted the day before the rainfall simulation. The tillage depths were 10 cm for D and 20 cm for P.

Atrazine was applied at a rate of 1.49 kg ha^{-1} and alachlor was applied at a rate of 2.24 kg ha^{-1}. The plots specified for the surface chemical application method were disked before the application of pesticides. The I plots were sprayed, then disked, in order to incorporate the chemicals into the soil. The plots were covered with plastic to protect them from natural rainfall and to reduce the volatilization of the chemicals.

Standard production implements were used for all field operations. A straw shredder attachment behind the combine was used to leave residues at each plot before tilling the soil. The average percentages of residue cover on the

Table 1. Soil type, slope, soil fractions, and organic matter at the sites

Characteristic	Site			
	A	B	C	D
Soil type	Clay loam	Silt loam	Sandy loam	Clay
Slope (%)	6.0	5.0	12.0	7.0
Sand (%)	27.0	23.0	58.0	21.0
Silt (%)	42.0	55.0	23.0	42.0
Clay (%)	31.0	23.0	19.0	37.0
Organic matter (%)	2.3	4.2	1.4	2.4
Plant residue cover (plow) percentage†	1.3	0.7	0.0	0.2
Plant residue cover (disk) percentage†	9.1	10.6	3.2	4.3
Plant residue cover (untilled) percentage†	39.4	51.3	17.5	28.4

† Data from Watermeier *et al.* (1992).

soil surface on the P, D, and U plots were 0.6, 6.7, and 31.8%, respectively (Table 1). The plots were planted up and down the hill with a surface planter with row spacing of 76 cm. The planting depth was 3.8 cm in all plots.

The size of the plots was 3.0 m × 9.1 m. Prior to the rainfall simulation, sheet metal borders were used to define the plot's size and contain the run-off. The borders were driven ≈ 10 cm into the soil. On the downhill end of the plots, PVC pipes, with a slot cut the full width of the subplot, were used to collect the surface run-off for sampling. The percentage of the soil surface covered with residue was measured using the photographic grid method described by Laflen *et al.* (1978). The slope and plot size measurements also were taken at each individual plot before the rainfall simulation occurred.

A rotating-boom rainfall simulator (Swanson *et al.* 1965) was used for providing simulated rains of 63.5 mm h^{-1} for 60 min and 127 mm h^{-1} for 15 min. The simulated rainfall was applied to the plots within 24–36 h after the chemicals' application. During the simulation, run-off samples were taken 1 min after run-off began, every 3 min for the first 10 min, and every 5 min until 50 min for 63.5 mm h^{-1} rainfall intensity. After a 15 min rest interval, 127 mm h^{-1} rainfall was started and samples were taken every 3 min for the first 10 min and one sample was taken at 15 min. Also, discharges at the outlet were recorded at the same time schedule as that of the sampling (Watermeier *et al.* 1992). One liter of water was sampled for herbicide analysis and another 0.5 L for erosion analysis. The collected samples were stored at a constant temperature of 2.8°C in a refrigerated truck at the site and transferred to refrigerated laboratory storage until they were analyzed.

Laboratory procedure

Each run-off water sample for herbicide analysis consisted of run-off water and sediment. Four consecutive samples in the first rainfall simulation were evenly mixed to make a time-averaged composite sample. The composites were made from these groups: 1, 4, 7, and 10 min; 15, 20, 25, and 30 min; 35, 40, 45, and 50 min. All five samples of the second rainfall event were composited. After the composition, the samples were filtered using filter paper (no. 2; Whatman International, Maidstone, UK) to separate the water and sediment samples before extraction. All sediment samples of the first and the second simulations from each plot were combined to give one composite sample for herbicide analysis. Meanwhile, the separate sediment samples corresponding to the run-off water samples of selected plots were analyzed to evaluate the concentration changes over time.

Alachlor and atrazine were solid phase-extracted by using the C18-SepPak cartridge (Milford, MA, USA). A 100 mL sample of the water was spiked with 5 μL of terbuthylazine (TBT) as an internal standard, then gravity-dripped through a C18-SepPak cartridge. The cartridges were conditioned with 2 mL of methanol, 6 mL of ethyl acetate, 2 mL of methanol again, and 2 mL of distilled water prior to use. Then, the cartridge was eluted with 2.5 mL of ethyl acetate. The ethyl acetate layer was separated from the water layer, then dried with sodium sulfate and kept in 2 mL capped glass vials for gas chromatograph (GC) analysis.

Approximately 2 g of sediment was placed into 20 mL glass scintillation vials with 10 mL of methanol. The samples were capped and shaken vigorously by a wrist-action shaker for 60 min. The methanol extract was filtered through the filter paper into a 100 mL glass jar. The glass vial was rinsed with 2 mL of methanol and the rinsed solution also was filtered and combined with the extract. After that, 90 mL of distilled water and 5 μL of TBT, as an internal standard, were added to the methanol extract. The solutions then were extracted by the same procedure as for water, as described above.

The final samples were analyzed by a GC (5890; Hewlett-Packard, Palo Alto, CA, USA) equipped with a column (30 m × 0.25 mm × 0.25 μm; DB-5; J & W, Folsom, CA, USA) and a nitrogen-phosphorus detector. The carrier gas was helium, with a flow rate of 27 mL min^{-1}, air flow of 103 mL min^{-1}, and hydrogen flow of 2.7 mL min^{-1}. The injector temperature and the detector temperature were 170°C and 220°C, respectively. The initial column oven temperature was 50°C, which was raised to 210°C with a rate of 50°C min^{-1}. Then, it was raised to 240°C with a rate of 5°C min^{-1} before being maintained at 240°C for 5 min. The injection volume was 1.0 μL. The limits of detection in the water were 1.1 μg L^{-1} for atrazine and 1.6 μg L^{-1} for alachlor. The limits of detection in the sediment were 91 μg kg^{-1} and 134 μg kg^{-1} for atrazine and alachlor, respectively.

Data analysis

The SAS general linear model analysis of variance for treatment means comparison procedure (SAS Institute 1982) was used to evaluate the difference in the herbicide concentrations, as well as the losses through run-off and erosion among the treatments. The linear contrast procedure for P versus D tillage systems, S versus I application methods, and tilled versus conservation treatment was used. This method evaluated the difference in the response of tillage systems, chemical application methods, and the interaction between the tillage system and the chemical application methods. In the primary statistical evaluation of the herbicide concentrations and herbicide losses, data from site C were separately analyzed as the site produced an extremely high amount of erosion that might not be representative of the cultivated soil conditions of this region.

RESULTS AND DISCUSSION

Run-off volume and erosion

During the first simulation, the average value of the total run-off depth (Fig. 1) ranged from 27.4 mm (DS) to 28.0 mm (US), corresponding to 43% and 44% of the applied rainfall, respectively. In this simulation, no significant difference in the run-off depth between the three tillage systems was observed. Mamo *et al.* (2006) reported similar results for water run-off under simulated rainfall from the U, D, and P treatments. In some cases, the U system even increased the surface run-off because of less water-holding capacity as compared to the plowed soil (Gaynor *et al.* 1995). In this study, it might also be related to the relatively low percentages of plant residue cover on the soil surface for the U treatment and D tillage for all sites compared with other studies. For the second simulation, the average value of the total run-off depth (Fig. 1) ranged from 17.2 mm (US) to 24.0 mm (PI), which were equal to 54% and 76% of the applied rainfall, respectively. The U treatment significantly reduced the run-off volume compared to the other treatments. In the second simulation, the flow channels on the surface that developed from the previous simulation were supposed to increase the run-off. Therefore, it was possible that the conservation tillage treatment had higher infiltration because the higher residue coverage had reduced the development of these flow channels.

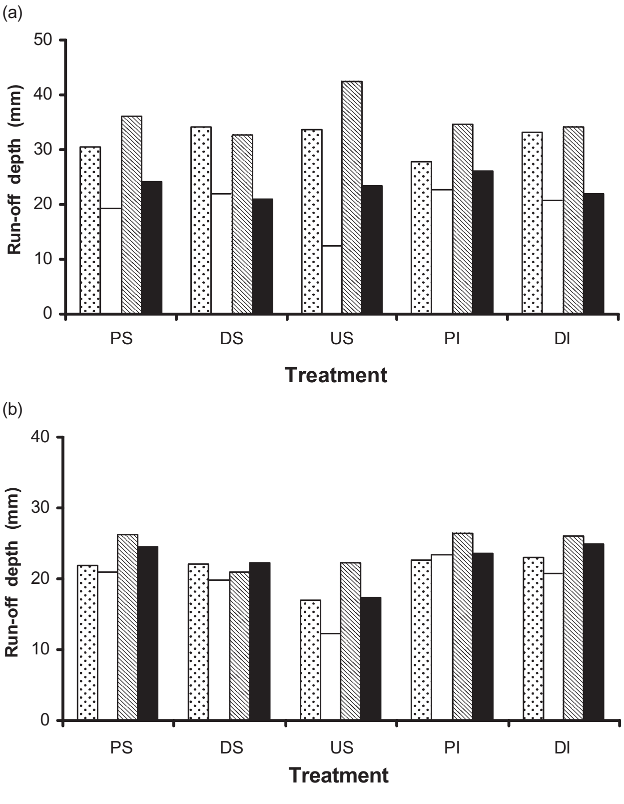

Fig. 1. Depth of water run-off in (a) the first rainfall simulation and (b) the second rainfall simulation. (░), site A; (□), site B; (▨), site C; (■), site D. DI, disk and preplant-incorporated treatment; DS, disk and surface treatment; PI, plow and preplant-incorporated treatment; PS, plow and surface treatment; US, conservation (untilled) and surface treatment.

The erosion rate was significantly different from one tillage system to another, with the average values ranging from 4.9 t ha^{-1} (US) to 26.7 t ha^{-1} (PS) for the first simulation and from 4.3 t ha^{-1} (US) to 26.8 t ha^{-1} (PI) in the second simulation (Fig. 2). Site C had extremely high erosion because of sandy loam soil on a 12% slope with the least plant residue cover among the four sites (Table 1). The P tillage was the most erosive of the three and the D tillage was more erosive than the conservation tillage. The conservation tillage reduced 82% and 84% of erosion losses from the P tillage for the first and the second simulation, respectively. The average erosion from the D tillage was 46% and 44% less than the P tillage for the first and the second simulations, respectively. A simulation study conducted by Dickey *et al.* (1984) also showed that D tillage reduced 30% of the soil loss compared with that of moldboard plowing, while the U treatment reduced 75% of the erosion compared with the P tillage.

In this research, the residue cover was shown to have a great effect on preventing erosion. Although the average residue cover of the conservation tillage was only 35%, it helped reduce erosion significantly, by ≈ 90% for both simulations. The D tillage had only ≈ 8.1% residue cover but it reduced erosion by ≈ 40%. These results indicate that conservation tillage systems were very effective for reducing erosion. In a study on a hillside vineyard, Battany and Grismer (2000) also reported that, for the rainfall run-off erosion process, the dominant limiting factor limiting soil loss was the soil cover by residue or vegetation. More detailed discussion on the run-off and erosion with respect to tillage practises

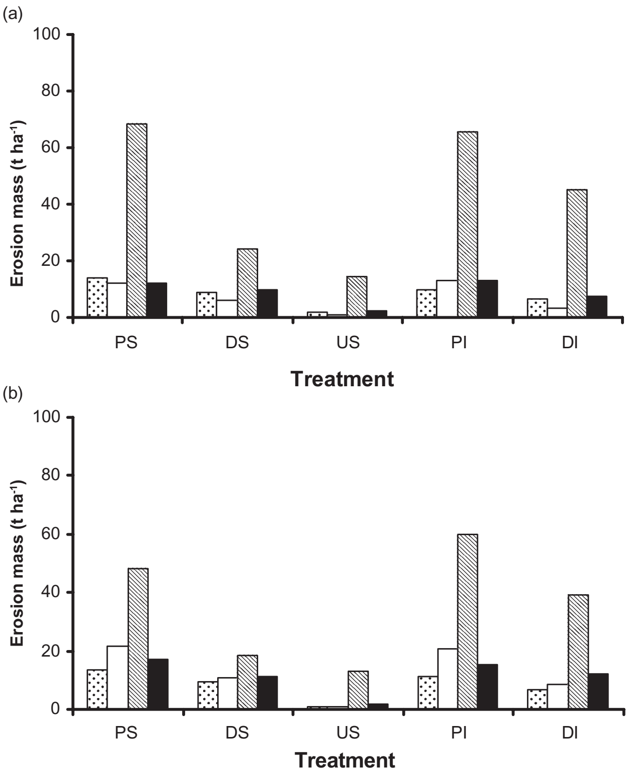

Fig. 2. Erosion rates in (a) the first rainfall simulation and (b) the second rainfall simulation. (⊡), site A; (□), site B; (▨), site C; (■), site D. DI, disk and preplant-incorporated treatment; DS, disk and surface treatment; PI, plow and preplant-incorporated treatment; PS, plow and surface treatment; US, conservation (untilled) and surface treatment.

on this experiment was presented by Watermeier *et al.* (1992).

Herbicide concentrations

In order to correct the effects of the previous herbicide residues and the spray drifts from adjacent plots, the mean concentrations of both herbicides from the non-chemical treatments of each tillage were subtracted from the concentrations of the corresponding tillage treatments. The highest herbicide concentration in the run-off water was 16.2 μg L^{-1} for atrazine and 22.0 μg L^{-1} for alachlor. The highest herbicide concentrations in the sediment were 187.0 μg kg^{-1} for atrazine and 149.2 μg kg^{-1} for alachlor, which occurred in the U treatments. In the source water used for the rainfall simulations, alachlor and atrazine were detected in five and two samples out of 21 samples, respectively. The highest detected concentrations of alachlor and atrazine were 2.5 and 1.3 μg L^{-1}, respectively. Also note that the time-weighted concentration presented in this paper might have some error from the true value as the flow-weighted composite sampling procedure was not taken. Therefore, we focused on the comparison of temporal trends and responses between treatments and readers should note that the absolute values of the herbicide concentrations and losses might differ from the real values in the corresponding treatments.

For sites A, B, and D combined, the time-weighted concentrations of atrazine and alachlor in the run-off water for the first 10 min, 15–30 min, and 35–50 min of the first rainfall simulation and the time-weighted concentrations in the sediment for the entire simulations are listed in Table 2.

The herbicide concentrations in the run-off water reduced with time in a similar way to other studies (Baker & Laflen 1979; Hansen *et al.* 2001). The US treatment produced the highest concentrations of herbicide in the run-off water, with 805 μg L^{-1} for atrazine and 1564 μg L^{-1} for alachlor, respectively. For the US treatment, the high initial concentration can be explained with a wash-off effect from the residue cover (Martin *et al.* 1978). If the residue adsorbs the herbicide less tightly than the soil, the water washing over the residue would extract the herbicides (Baker *et al.* 1982). The average concentrations of the five chemical-applied treatments ranged from high to low in the order of US, DS, PS, DI, and PI. A similar trend was reported by Mickelson *et al.* (2001), who concluded that the lack of incorporation and/or more interception with greater crop residue with the U treatment were believed to be responsible for the higher herbicide concentrations. The S application treatments resulted in higher herbicide concentrations than the I treatments and the D treatments were higher than that of the P plots, as shown in Fig. 3. From the results of the linear contrast for sites A, B, and D combined, the significant difference, at greater than the 95% level, was detected for the S application versus the I application and the tilled (D and P) versus the U treatments for both atrazine and alachlor in all run-off and sediment samples. Meanwhile, the differences between the D versus the P treatments depended on the samples and they were not obvious (Table 3).

The effects of chemical incorporation were similar to those observed by others (Baker & Laflen 1979; Mickelson *et al.* 2001). The results in Table 2 indicated that the concentrations of atrazine and alachlor for the I plots decreased more gradually compared to those in the S application plots. The S application enhanced the high

Table 2. Average herbicide concentration in the water and sediment for sites A, B, and D

Treatment	Time (min)	Method				
		PS	DS	US	PI	DI
Atrazine†						
1st simulation	0–10	234	318	805	71	132
	10–30	122	222	337	35	139
	30–50	76	121	205	20	83
2nd simulation	0–15	73	88	118	21	47
Sediment	–	462	664	1428	109	385
Alachlor†						
1st simulation	0–10	319	449	1564	90	160
	10–30	159	300	617	43	155
	30–50	93	157	335	24	88
2nd simulation	0–15	87	109	176	23	45
Sediment	–	673	762	1415	258	439

† $\mu g\ L^{-1}$ for water; $\mu g\ kg^{-1}$ for sediment. DI, disk and preplant-incorporated treatment; DS, disk and surface treatment; PI, plow and preplant-incorporated treatment; PS, plow and surface treatment; US, conservation (untilled) and surface treatment.

Table 3. Linear contrast for herbicide concentration in run-off and total herbicide losses of sites A, B, and D

Treatment	Method			
	Disk vs plow	Surface vs PI	Tilled vs untilled	Interaction between tillage and application
Atrazine concentration				
1st simulation (min)				
0–10	★	★★★	★★★	–
10–30	★★★	★★	★★★	–
30–50	★★★	★★	★★★	–
2nd simulation (min)				
0–15	★	★★★	★★★	–
Sediment	–	★★	★★★	–
Atrazine loss in 1st simulation	★	–	★★	–
Atrazine loss in 2nd simulation	★	★★★	–	–
Alachlor concentration				
1st simulation (min)				
0–10	–	★★	★★★	–
10–30	★★	★★	★★★	–
30–50	★★	★★	★★★	–
2nd simulation (min)				
0–15	–	★★★	★★★	–
Sediment	–	★★★	★★★	–
Alachlor loss in 1st simulation	–	–	★★★	–
Alachlor loss in 2nd simulation	–	★★★	–	–

Significance of difference: ★$P = 90\%$; ★★$P = 95\%$; ★★★$P = 99\%$. –, no interaction between tillage and application.

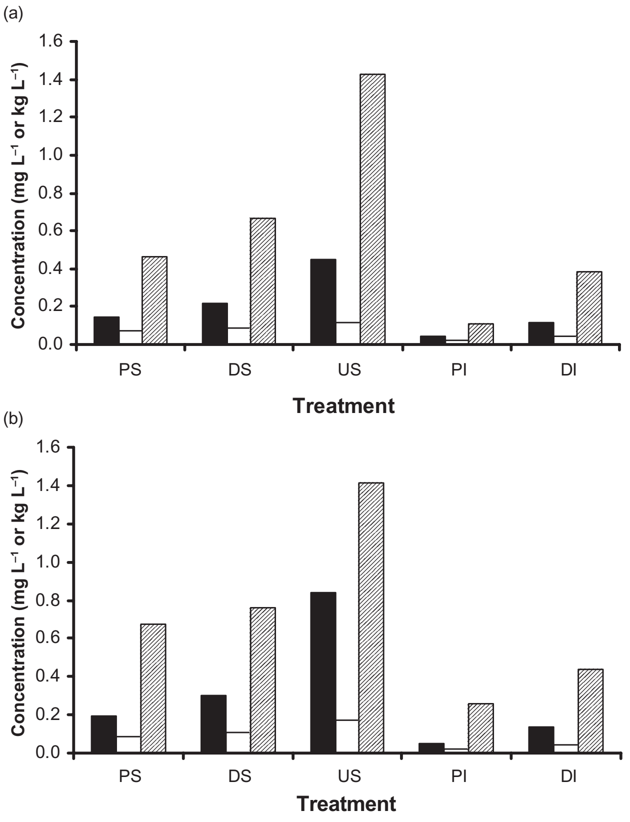

Fig. 3. Time-weighted average concentrations of (a) atrazine and (b) alachlor in the run-off water and sediment. (■), first simulation; (☐), second simulation; (▨), sediment. DI, disk and preplant-incorporated treatment; DS, disk and surface treatment; PI, plow and preplant-incorporated treatment; PS, plow and surface treatment; US, conservation (untilled) and surface treatment.

initial herbicide concentrations as compared to the I plots, which had chemicals mixed into the soil. The atrazine concentrations in the run-off water from the S application plots averaged 1.8-fold and 3.5-fold greater for the D and P tillage, respectively, than for those in the I plots. The corresponding results for alachlor were 2.2-fold and 3.7-fold greater, respectively. Baker and Laflen (1979) also reported that herbicide concentrations in the water from S application plots averaged 3.5-fold more than those of the I plots. For the herbicide concentration in the run-off water among the three sites, site A had the highest for both alachlor and atrazine.

For the average herbicide concentrations in the sediment for the entire simulations, the US treatment indicated the highest concentrations, with 1428 μg kg^{-1} for atrazine and 1415 μg kg^{-1} for alachlor, respectively. For both herbicides, the significant differences between the tilled versus the U treatments and the S application versus the I treatments were > 95%, while there was no significant difference between the D versus the P treatments (Table 3). The S application contributed to increasing the herbicide concentrations. A large amount of herbicide adsorbed on the soil surface, while incorporation prevented it by the mixing of chemicals on the soil surface into the soil. Site B had the highest concentration for both atrazine and alachlor among the three sites. As soil organic matter is the primary soil constituent responsible for the adsorption of non-ionic organic compounds, the highest organic matter content, which was found at site B, probably contributed to this result.

Herbicide losses

Herbicide losses in the first simulation of atrazine and alachlor ranged from 0.009 (PI) to 0.078 kg ha^{-1} (US) and from 0.013 (PI) to 0.137 kg ha^{-1} (US), respectively (Table 4). For both the atrazine and alachlor losses, the US treatment had the greatest losses among the five treatments. When comparing the four treatments, except US, the S application lost more than the I treatment, while the D treatment had a greater loss than the P treatment. The linear contract for sites A, B, and D combined indicated that the differences between the US and the tilled (P or D) surface were significant, while neither the losses between the S and I treatments, nor between the D and P tillage, were significantly different (Table 3).

The losses in the second simulation ranged from 0.007 (PI) to 0.025 kg ha^{-1} (PS) for atrazine and from 0.009 (DI) to 0.032 kg ha^{-1} (DS) for alachlor (Table 4). In contrast to the first simulation rainfall, the highest means of both herbicides losses in the second simulation rainfall were not those of the US treatment. In this case, the only significant difference that was detected was between the S application and I treatments (Table 3).

The total losses of the two herbicides also are shown in Table 4. The atrazine losses ranged from 0.016 kg ha^{-1} (PI) to 0.097 kg ha^{-1} (US) and those of alachlor ranged from 0.022 kg ha^{-1} (PI) to 0.166 kg ha^{-1} (US). They correspond to a decrease in losses from 7.4% (US) to 1.0% (PI) and from 4.4% (US) to 0.7% (PI) for the amounts of atrazine and alachlor applied to the experimental plots, respectively. As the herbicide losses through the sediment are minor and the run-off volume did not differ significantly among the treatments, the overall trend was similar to that of the herbicide concentrations.

Mickelson *et al.* (2001) and Heatwole *et al.* (1991) reported that the conservation tillage reduced herbicide losses by reducing run-off and erosion. However,

Table 4. Average herbicide losses in rainfall simulations for sites A, B, and D

Treatment	Method				
	PS	DS	US	PI	DI
Atrazine					
Loss in 1st simulation (kg ha^{-1})	0.033	0.051	0.078	0.009	0.033
Loss in 2nd simulation (kg ha^{-1})	0.025	0.025	0.019	0.007	0.014
Loss in 1st simulation (%)	1.460	2.300	3.490	0.410	1.480
Loss in 2nd simulation (%)	1.110	1.130	0.860	0.300	0.620
Total losses (kg ha^{-1})	0.057	0.077	0.097	0.016	0.047
Loss by run-off water (%)	75.400	82.000	94.600	79.300	83.300
Alachlor					
Loss in 1st simulation (kg ha^{-1})	0.045	0.072	0.137	0.013	0.038
Loss in 2nd simulation (kg ha^{-1})	0.031	0.032	0.029	0.009	0.014
Loss in 1st simulation (%)	2.000	3.220	6.130	0.570	1.690
Loss in 2nd simulation (%)	1.400	1.410	1.290	0.420	0.620
Total losses (kg ha^{-1})	0.076	0.104	0.166	0.022	0.052
Loss by run-off water (%)	70.800	82.000	96.200	66.700	80.400

DI, disk and preplant-incorporated treatment; DS, disk and surface treatment; PI, plow and preplant-incorporated treatment; PS, plow and surface treatment; US, conservation (untilled) and surface treatment.

the present study indicated that the conservation tillage had significantly greater herbicide losses compared with the other tillage systems. The highest herbicide concentrations in the run-off and sediment in the U treatment were responsible for the greatest herbicide losses. In addition, the run-off was not reduced in our conservation tillage as discussed above; this also was not the case for most of the other studies (Sauer & Daniel 1988; Heatwole *et al.* 1991; Mickelson *et al.* 2001). As a result, the total herbicide losses followed the trends of the herbicide concentrations in the run-off.

By reducing erosion, and often the run-off volume, conservation tillage reduces the losses of pesticides in run-off relative to other tillage, particularly for more strongly adsorbed pesticides that are transported by sediment. In the case of terbufos, which possesses a distribution coefficient based on organic carbon (K_{oc}) ≈ 10-fold greater than atrazine (Baskaran *et al.* 1996), 90% of the total transport accounted for in the sediment-adsorbed phase and the U treatment had the least loss, as compared to other tillage systems (Mamo *et al.* 2006). In general, the U treatment seems to be applicable for pesticides that are highly adsorptive and less effective for weakly adsorptive compounds. Also, in order to have effective pesticide run-off control, the U system should be maintained for reducing the run-off of both water and sediment.

The effect of herbicide incorporation was discussed by Baker and Laflen (1979). They reported that surface-applied herbicides with wheel-track plots had ≈ 3.5-fold the total herbicide losses compared to those of the I plots. Meanwhile, in this study, the total losses of atrazine and alachlor from the S treatments with D tillage were, respectively, 1.5-fold and 1.9-fold higher than those from the I treatments. The corresponding numbers for the P treatment was 3.5-fold for both atrazine and alachlor. The herbicide concentrations in the run-off water and in the sediment for the S treatments also were ≈ 2-fold greater than the I treatment for D tillage and 3-fold greater for P tillage. Hall *et al.* (1983) also reported that the preplant-incorporation of atrazine reduced losses from external drainage compared to the S treatment.

The percentages of herbicide losses through the run-off water in total losses are shown in Table 4. These percentages indicate that major losses occurred through the water phase, as other studies indicated (Sauer & Daniel 1988; Hansen *et al.* 2001). The percentages varied according to the tillage systems but not by different incorporation methods. Statistically, conservation tillage was significantly different from the others and the P and D tillage also were different from each other (Watanabe 1993). The results suggest that the more erosive the tillage system, the greater the percentage of herbicide loss through the sediment.

Table 5. Average herbicide concentration in the water and sediment for site C

Treatment	Time (min)	Method				
		PS	DS	US	PI	DI
Atrazine†						
1st simulation	0–10	343	600	1096	178	286
	10–30	221	245	389	217	156
	30–50	145	124	202	203	114
2nd simulation	0–15	117	84	119	189	80
Sediment		317	453	642	262	230
Alachlor†						
1st simulation	0–10	599	1075	2189	227	389
	10–30	332	325	535	329	159
	30–50	185	138	238	302	97
2nd simulation	0–15	132	83	103	193	66
Sediment		329	371	398	198	213

† μg L^{-1} for water; μg kg^{-1} for sediment. DI, disk and preplant-incorporated treatment; DS, disk and surface treatment; PI, plow and preplant-incorporated treatment; PS, plow and surface treatment; US, conservation (untilled) and surface treatment.

Herbicide concentrations and losses with extreme soil losses in site C

As explained in the methods and procedure section, site C was separately analyzed as the site might not be representative of the characteristics of the farmland in the Blue River Basin. Site C had an average slope of 12%, ranging from 7.5–15.8%, and a sandy loam soil, with the sand fraction being 58%, which is more than twice as much as the other three sites. However, the soil survey conducted by the Natural Resources Conservation Service indicated that the area was Shelby clay loam with a slope of 6–10%. The critical problem on site C was that there were extremely large erosion losses.

The average value of the run-off depth in site C (Fig. 1) was 35.9 mm and 24.4 mm for the first and the second simulations, respectively. For both the first and second simulations, the run-off was not significantly different among the five treatments (Watanabe 1993). Site C had average erosion losses of 43.5 t ha^{-1} and 35.8 t ha^{-1} during the first and the second simulations, respectively. These values were more than five-fold and three-fold the corresponding average of the other three sites. However, significant differences in erosion were detected between the U and tilled treatments and between the D and P treatments for the first simulation and between the D and P treatments for the second simulation (Watanabe 1993).

For the herbicide concentrations in the run-off water during the initial period of 10 min, the order was similar to that of the other three sites (Table 5). However, the concentrations of each treatment were higher than the corresponding average concentrations of the other three sites. The herbicide concentrations of the U treatment were ≈ 1.4-fold greater than those of the other three sites. The concentrations for the other treatments were about double the level of the other three sites. As time progressed, the concentrations decreased for both herbicides, except in the PI treatment.

For the herbicide concentrations in the sediment, the averages of the herbicide concentrations in the sediment for the five treatments were ≈ 0.6-fold and 0.4-fold the average concentrations of the other three sites for atrazine and alachlor, respectively. The lower level of organic matter at site C probably contributed to the low herbicide concentrations in the sediment compared to the other sites.

In site C, the amount of erosion tended to increase the herbicide concentration in the run-off water. Pesticides can be extracted in water by desorption from soil particles into the moving liquid boundary and scouring of the pesticide particulate and its subsequent dissolution in the moving water (Bailey *et al.* 1974). During the initial period, herbicides were extracted from stationary soil particles and, later, during the simulation, more herbicides were dissolved from the flowing sediment into the run-off water. This might be a possible explanation why the herbicide concentration did not

Table 6. Average herbicide losses in rainfall simulations for site C

Treatment	Method				
	PS	DS	US	PI	DI
Atrazine					
Loss in 1st simulation (kg ha^{-1})	0.091	0.081	0.161	0.099	0.061
Loss in 2nd simulation (kg ha^{-1})	0.046	0.025	0.034	0.070	0.030
Loss in 1st simulation (%)	6.080	5.420	10.820	6.620	4.070
Loss in 2nd simulation (%)	3.080	1.700	2.290	4.680	2.000
Total loss by run-off water (%)	72.300	77.400	85.000	76.900	76.900
Alachlor					
Loss in 1st simulation (kg ha^{-1})	0.127	0.103	0.248	0.135	0.061
Loss in 2nd simulation (kg ha^{-1})	0.051	0.024	0.026	0.069	0.026
Loss in 1st simulation (%)	8.530	6.890	16.610	9.030	4.110
Loss in 2nd simulation (%)	3.400	1.600	1.770	4.630	1.720
Loss by run-off water (%)	75.200	81.500	87.700	88.400	75.400

DI, disk and preplant-incorporated treatment; DS, disk and surface treatment; PI, plow and preplant-incorporated treatment; PS, plow and surface treatment; US, conservation (untilled) and surface treatment.

decrease significantly in the seriously eroded plots (Table 5).

The total herbicide losses for the first and the second simulations in site C are presented in Table 6. For the first simulation, the U system was significantly greater than the other tillage systems with S application. The total herbicide losses, as the applied mass, ranged from 4.1% (DI) to 10.8% (US) for atrazine and from 4.1% (DI) to 16.6% (US) for alachlor. For the second simulation, PI had the greatest losses among the five treatments, and this difference was significant (Watanabe 1993). The corresponding maximum and minimum losses, equivalent to the percentages of applied mass, were 4.7% (PI) and 1.7% (DS) for atrazine and 4.6% (PI) and 1.6% (DS) for alachlor.

Comparing the trend of total herbicide losses, P tillage had greater losses than D tillage at site C, while sites A, B, and D indicated an opposite trend. For both herbicides, the PS and PI treatments in site C gave ≈ 3-fold and 10-fold the losses from the corresponding treatments from the other three sites, respectively. The losses from the U treatment and D tillage at site C were 1.6–2-fold greater than the corresponding losses for the other three sites. The herbicide losses in the second simulation also indicated great losses from the P tillage. The herbicides were lost mostly through the run-off water for the first simulation. As the herbicide concentrations in the sediment were low, the herbicide losses though erosion were less than those through the run-off water in the second simulation.

Extremely large erosion losses, high herbicide concentrations in the run-off water, and low herbicide concentrations in the sediment were the characteristics of site C. Consequently, greater amounts of herbicide were lost. These characteristics were especially pronounced with the PI treatment, where the greatest amount of erosion was produced. As a result of these altered trends by erosion failure, incorporation was not effective for controlling the herbicide losses.

In conclusion, conservation tillage, especially the U system, has an advantage in reducing soil erosion, but it also has the disadvantage of increasing herbicide loss from the cropland. Unless the U system reduces the amount of run-off significantly, this system tends to lose more herbicide compared with the other treatments. The incorporation of herbicide showed a significant potential for reducing the herbicide loss. Herbicide losses tended to increase in areas more susceptible to severe erosion. Considering soil erosion problems, the D and I treatments were most successful in controlling both problems. The herbicide run-off simulation at the steep and extremely erosive site revealed that herbicide loss is increased as compared to less steep and erosive sites and that herbicide incorporation cannot be effective for controlling herbicide loss.

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REFERENCES

Bailey G.W., Swank R.R. and Nicholson H.P. 1974. Predicting pesticide runoff from agricultural land: a conceptual model. *J. Environ. Qual.* **3**, 95–102.

Baker J.L. and Johnson H.P. 1979. The effect of tillage systems on pesticides in runoff from small watersheds. *Trans. ASAE* **22**, 554–558.

Baker J.L. and Laflen J.M. 1979. Runoff losses of surface-applied herbicides as affected by wheel tracks and incorporation. *J. Environ. Qual.* **8**, 602–607.

Baker J.L., Laflen J.M. and Hartwig R.O. 1982. Effect of corn residue and herbicide placement on herbicide runoff losses. *Trans. ASAE* **25**, 340–343.

Baskaran S., Bolan N.S., Rahman A. and Tillman R.W. 1996. Pesticide sorption by allophanic and non-allophanic soils of New Zealand. *N. Z. J. Agric. Res.* **39**, 297–310.

Battany M.C. and Grismer M.E. 2000. Development of a portable eld rainfall simulator for use in hillside vineyard runoff and erosion studies. *Hydrol. Process.* **14**, 1119–1129.

Dickey E.C., Shelton D.P., Jasa P.J. and Peterson T.R. 1984. Tillage, residue and erosion on moderately sloping soils. *Trans. ASAE* **27**, 1093–1099.

Gaynor J.D., MacTavish D.C. and Findlay W.I. 1995. Atrazine and metolachlor loss in surface and subsurface runoff from three tillage treatments in corn. *J. Environ. Qual.* **24**, 246–256.

Hall J.K., Hartwing N.L. and Hoffman L.D. 1983. Application mode and alternate cropping effects on atrazine losses from a hillside. *J. Environ. Qual.* **12**, 336–340.

Hansen N.C., Moncrief J.F., Gupta S.C., Capel P.D. and Olness A.E. 2001. Herbicide banding and tillage system interactions on runoff losses of alachlor and cyanazine. *J. Environ. Qual.* **30**, 2120–2126.

Heatwole C.D., Zacharias S., Dillaha T.A. and Mostaghimi S. 1991. Tillage effects on fate and transport of pesticides in a coastal plain soil: I. Surface runoff. In: *1991 International Winter Meeting*. No. 912543 (Chicago, IL, USA, 17–20 December 1991). ASAE, St Joseph, MI.

Kansas Department of Health and Environment. 1989. *Atrazine in Kansas*. Water Quality Assessment Section, Bureau of Water Protection, Kansas Department of Health and Environment, Manhattan, KS.

Laflen J.M., Baker J.L., Hartwig R.O., Buchele W.F. and Johnson H.P. 1978. Soil and water loss from conservation tillage system. *Trans. ASAE* **21**, 881–885.

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

Martin C.D., Baker J.L., Erbach D.C. and Johnson H.P. 1978. Washoff of herbicide applied corn residue. *Trans. ASAE* **21**, 1164–1168.

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

Popov V. and Cornish P. 2006. Atrazine tolerance of grass species with potential for use in vegetated filters in Australia. *Plant Soil* **280**, 115–126.

Rebich R.A., Coupe R.H. and Thurman E.M. 2004. Herbicide concentrations in Mississippi River Basin – the importance of chloroacetanilide herbicide degradates. *Sci. Total Environ.* **321**, 189–199.

SAS Institute. 1982. *SAS User's Guide Statistics*. SAS Institute, Cary, NC.

Sauer T.J. and Daniel T.C. 1988. Effect of tillage system on runoff losses of surface-applied pesticides. *J. Soil Sci. Soc. Am.* **51**, 410–415.

Swanson N.P., Dedrick A.R. and Weakly H.E. 1965. Soil particles and aggregates transported in runoff from simulated rainfall. *Trans. ASAE* **8**, 437–440.

Watanabe H. 1993. Alachlor and atrazine losses from runoff and erosion in the Blue River basin (Masters thesis). Kansas State University, Manhattan, KS.

Watermeier N.L., Jasa P.J., Shelton D.S., Dickey E.C., Barnes P. and Steichen J. 1992. Quality aspects of tillage, soil type and slope – part I: Runoff and erosion. In: *1992 International Summer Meeting*. No. 922009 (Charlotte, NC, USA, 21–24 June 1992). ASAE, St Joseph, MI.

Wauchope R.D. 1978. The pesticide content of surface water draining from agricultural fields – A review. *J. Environ. Qual.* **7**, 459–472.