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Tillage and herbicide incorporation effects on residue cover, runoff, erosion, and herbicide loss☆

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Abstract

A natural rainfall study was conducted to evaluate the effect of tillage and herbicide application methods on crop residue cover, surface runoff volume, erosion, and herbicide losses with sediment and runoff water. Sediment, water, and three herbicides (atrazine [(6-chloro-*N*-ethyl)-*N*-(1-methylethyl-1,3,5 triazine)-2-4-diamine], metolachlor [2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl)], and cyanazine [2-{{4-chloro-6-(ethylamino)-1,3,4-triazin-2-yl}amino}-2-methylpropionitrile]) losses were measured from continuous corn runoff plots (1.7×12.0 m long) in 1993 and 1994. Four tillage/herbicide application treatments were studied: no-till/herbicide broadcast sprayed (NT), fall chisel plow-spring disk/herbicide broadcast sprayed after disking (DS), fall chisel plow-spring disk/herbicide broadcast sprayed before disking (SD) and fall chisel plow-spring "mulch master"/herbicide applied with John Deere's Mulch Master (MM). Results showed that herbicide incorporation with the MM and SD treatments reduced herbicide losses. Residue measurements after any tillage and planting showed that percent residue cover was greatest on NT plots, second on MM plots, and least and similar on SD and DS plots. By runoff event, NT plots generally had the least erosion and often the lowest runoff volumes. Herbicides concentrations in both sediment and runoff water were generally in the order NT > DS > MM > SD, with herbicide concentrations 2–10 times higher in sediment than in the runoff water. Since the herbicides used were not strongly adsorbed, more than 95% of the runoff loss in each case was in the dissolved phase. Lack of incorporation and/or more interception with the greater crop residue with NT were believed to be responsible for the higher herbicide concentrations with that treatment. Total losses for all three herbicides each year were less than 2% of that applied, and ranged from 1.5% for atrazine in 1993 to 0.07% for metolachlor in 1994, both for the NT treatment. Relative herbicide losses with NT by event were variable, sometimes being the greatest, sometimes the least; depending primarily on runoff volumes, which in turn were dependent on the storm volume and intensity, and the time of year; however, for the other three treatments, losses were usually in the order DS > MM > SD.

Keywords: Herbicide application methods; Mulch Master; Cultivation; Rainfall; Herbicide losses with runoff

1. Introduction

Use of pesticides and fertilizers in current agricultural systems has significantly contributed to the increase in crop production. However, losses of these chemicals from treated fields to water resources create human health concerns by potentially affecting

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the quality of drinking water. Aquatic ecosystems also can be affected by the presence of pesticides. Pesticide loss in runoff contaminates surface water quality and also increases the potential of groundwater pollution due to transport of pesticides through macropores as determined by pesticide concentrations in ponded surface water (Steenhuis et al., 1994).

Drinking water standards, in the form of regulatory maximum contaminant levels (MCLs), have been established in US for a limited number of pesticides, e.g., 3 $\mu g\, l^{-1}$ for atrazine. However, for most of the remainder of the pesticides at least a non-regulatory health advisory (HA) level has been established, e.g., 1 $\mu g\, l^{-1}$ for cyanazine and 70 $\mu g\, l^{-1}$ for metolachlor. These three herbicides make up a major portion of pesticide use in the Corn Belt (NASS, 1995). Studies have shown that concentrations of these products in surface runoff water from treated fields at times can exceed 1000 $\mu g\, l^{-1}$, although usually only for runoff event(s) occurring shortly after application (Baker and Johnson, 1979; Johnson and Baker, 1984; Wauchope, 1978).

Several studies of pesticides in streams, rivers, and reservoirs in the Midwest (Johnson and Baker, 1982, 1984; USGS, 1993) show that even with attenuation during field-to-stream transport and dilution with drainage from untreated areas, in-stream (and reservoir) concentrations can reach or exceed MCLs or HAs. However, pesticide concentrations known to cause ecosystem concerns are not well established, with wide ranges often cited (SETAC, 1994). Therefore, the USEPA (United States Environmental Protection Agency) has established a new paradigm. If a potential concern is shown to exist, rather than taking time to obtain more data to verify or refute that a pesticide is the cause of the concern, mitigation practices are immediately implemented. A government-industry-academic report (SETAC, 1994) was released describing this new paradigm, with a listing of mitigation practices or best management practices (BMPs) to control surface runoff losses of pesticides, including conservation tillage and mechanical soil incorporation.

Conservation tillage, defined in the US by residue from the previous crop covering at least 30% of the soil surface after planting, can significantly reduce erosion and often reduces the volume of surface runoff, at least on an annual basis relative to that with conventional tillage (Baker, 1987; Chichester and Richardson, 1992). Zhang et al. (1997) reported that decreases in runoff volume also decreased herbicide losses. In contrast, other researchers have found lower losses of herbicides with runoff water under conventional tillage systems than under the no-till system (Gaynor et al., 1995; Smith et al., 1995). With no-till, the extreme in conservation tillage, all crop residue is left on the soil surface. By reducing erosion, and often runoff volume, conservation tillage reduces losses of pesticides in runoff relative to that with the moldboard plow tillage system, particularly for more strongly adsorbed pesticides that are transported mostly by sediment (Baker, 1992; Webster and Shaw, 1996). However, for less strongly adsorbed pesticides, on an individual storm basis, fields that have been recently tilled often have less runoff for the early storm(s) after tillage (Johnson and Baker, 1984), and soil-applied pesticides in the spring are usually applied at the time of or shortly after any tillage is done.

Mechanical soil incorporation of pesticides has been shown to significantly reduce pesticide losses in runoff (Baker and Laflen, 1979; Hall et al., 1983) by reducing the amount in the "surface mixing zone", where the mixing zone is thought to be the top 0.6–1.3 cm of a soil profile with which rainfall and runoff interacts. However, the degree of incorporation is normally directly related to the severity of tillage and inversely related to crop residue remaining after tillage. Incorporation also protects herbicides from volatilization and increases the residence time in soil (Locke and Bryson, 1997). For no-till, incorporation currently is not feasible.

Many studies have documented the effect of surface crop residue on erosion and runoff water quality, where crop residue affects not only the mass of water and sediment carriers, but can also affect concentrations in field carriers (Angle et al., 1984; Chichester and Richardson, 1992; Hatfield and Stewart, 1994). Surface crop residues intercept sprayed pesticides such that a 30% residue cover would result in about 30% of a broadcast-sprayed pesticide being found on the crop residue after application. Washoff studies for commonly used herbicides applied to corn residue show that there is little initial interaction between the herbicide and corn residue with up to 50% of the intercepted herbicide being washed off by the first centimeter of rain coming shortly after application (Baker and Shiers, 1989; Martin et al., 1978). If this washoff water becomes a part of surface runoff, herbicide concentrations can be quite high. This observation has been used to explain why alachlor and cyanazine concentrations increased with residue cover in a rainfall simulation study of runoff losses of recently applied herbicides as affected by conservation tillage (Baker et al., 1978). Olson et al. (1998) reported that soybean residues could not reduce atrazine losses with late spring application when potential of intense rainfall was high.

Others have also found higher concentrations in runoff for conservation tillage, including no-till (Hall et al., 1984). It was concluded that despite higher concentrations, if erosion and runoff volumes are reduced enough, runoff losses can still be less than or equal to those for the moldboard plow or other tillage systems that result in less crop residue being left on the soil surface. In addition, applying atrazine in the fall or early spring rather than in late spring reduced atrazine losses in surface runoff water (Olson, 1997).

Because of the desire to perform secondary tillage in high residue conditions to prepare a seedbed, and to incorporate herbicides in a one-pass operation without incorporating soil-protecting surface crop residue, John Deere[1] designed, tested, and has marketed the 550 MM. This tillage tool has three ranks of 61 cm low-crown sweeps placed at the front of the machine (with a 51 cm spacing), followed by two ranks of incorporation wheels with the first rank moving soil to the right and the second rank moving soil back to the left. In a study by Johnson et al. (1993), with a minimum operating speed of 9.7 km h^{-1} for use of the MM in the spring, the percent cover for corn residue (following fall chisel or disk) on average was not reduced, while soybean residue (no previous tillage) cover was reduced by about 10%.

Because of the potential environmental benefits of this tillage tool, a 2-year natural rainfall study was conducted to quantify soil, water, and herbicide losses with MM incorporation compared with disking, either before or after herbicide application, and also with no-till (all with broadcast spray herbicide applications).

2. Methods and materials

This study was conducted at the Iowa State University's Agronomy and Agricultural Engineering Research Center near Boone, Iowa. Surface runoff monitoring plots (1.7 × 12.2 m long) were established on a Nicollet loam with slopes ranging from 2 to 3%. The plots were hydrologically isolated from their surroundings with 20 cm high metal borders driven about 10 cm into the soil. A 1100-L covered tank at the bottom of the plot collected all the runoff (up to a volume of 5.3 cm). Following a runoff event, runoff water and sediment in the tank were thoroughly mixed and replicate 1-L samples were collected in glass containers. The volume of runoff in the tank was measured either from the depth in the tank or by pumping the water through a flow-meter.

A randomized block design was used to establish four treatments, replicated three times, on 12 plots. All treatments were in continuous corn with one in no-till (NT) and the other three being fall chisel plowed followed either by spring disking before herbicide application (DS), spring disking after herbicide application (SD), and spring tillage with the MM with herbicide applied after the three ranks of sweeps, but before the two ranks of incorporation wheels (MM). Implement wheel spacing relative to plot width was such that the plots received no implement traffic; thus, despite the difference in the sequences of operations, the soil surface conditions for the SD and DS treatments were not different. The NT plots were established 13 years prior to the study. Each year, herbicide application on the 12 plots and the secondary tillage (on the nine fall chisel-plowed plots) took place on the same day (10 June in 1993 and 19 May in 1994).

The herbicides used were atrazine (trade name AAtrex, 4-L formulation), cyanazine (Bladex, 90 DF formulation), and metolachlor (Dual, 8-E formulation), and were broadcast sprayed using 187 l ha^{-1} water at a rate of 2.24, 3.36, and 2.80 kg ha^{-1} active ingredient (a.i.), respectively. The same tractor and spray-boom/pump/flow-meter/control assembly were used for all four treatments.

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[1] Deere and Company Technical Center, 3300 River Drive, Moline, IL 61265, USA.

The samples collected from the runoff events were transported to a storage cooler in the laboratory. Total solids were determined by weighing duplicate 20 ml aliquots of each sample, drying at 105°C for 24 h, and then weighing the dried solids. The method for sediment and herbicide analyses was similar to that previously used (Baker and Laflen, 1979). Atrazine, metolachlor, and cyanazine were extracted and analyzed as follows: Runoff samples from the plots were first centrifuged by using 250 ml stainless steel cups on an IEC B-20A refrigerated centrifuge for 30 min at 8000 rpm. After centrifugation, the water phase was decanted into a 250 ml beaker, and atrazine, metolachlor, and cyanazine were extracted from the remaining sediment by adding 1 ml of distilled deionized water, 5 ml of toluene, and 10 glass beads. The sediment/solvent was shaken for 1 h on a vertical plane rotator at about 60 rpm and for 1 h on a horizontal orbital shaker at approximately 250 rpm. The mixture was allowed to settle for 30 min and then the toluene extracts were decanted into test tubes. The steel centrifuge cups were oven-dried for 24 h at 105°C and the dry weight of the sediment was recorded.

The decanted water portions of the samples were filtered (through 15 cm diameter medium porosity, slow flowrate, and 5 μm pore size filter paper) and the herbicides were extracted from the filtered samples using toluene as follows: a 100 g aliquot was weighed into a 250 ml boiling flask, and about 50 ml of toluene was added by weight (43.3 g). A 150 g sample aliquot and 5 ml of toluene were used for events later in the season when herbicide concentrations were lower. The mixtures were shaken on an orbital shaker at 250 rpm for 1 h and allowed to separate for 30 min, then the toluene extracts were decanted into test tubes.

The toluene extracts from the water and sediment samples were analyzed using a gas–liquid chromatograph equipped with an autosampler and a thermionic detector. The carrier gas was helium with a flow rate of 18 cc min^{-1}, reaction gases were hydrogen with a flow rate of 3.5 cc min^{-1}, and air with a flow rate of 100 cc min^{-1}. Column oven temperature was held constant at 160°C, with an inlet temperature of 246°C. The three herbicides were separated by using a 3% OV-1 and 0.63 cm diameter × 1.8 m packed column.

Runoff losses of sediment by event were calculated from total solids concentrations and runoff volumes. Herbicide losses with sediment and water by event were determined from herbicide concentrations (average of duplicate determinations) and sediment losses and runoff volumes. Total growing season amounts were obtained by summing storm-event data.

Surface residue cover for NT and before and after secondary tillage for the other three treatments was determined using a photographic grid method (Laflen et al., 1981). Slide photographs were taken at the top, middle, and bottom of each plot and projected on a grid to determine percent residue cover. Tests for statistical differences for all parameters on an event and also on a growing season basis were determined at the 10% level of significance (SAS Institute, 1985).

3. Results and discussion

In the spring of 1993, fall chisel plowing had reduced residue cover 20% as compared with NT, while secondary tillage with the disk (DS and SD) reduced it another 30%. Secondary tillage with the MM only caused a 4% reduction, resulting in residue cover significantly higher than for DS or SD (Table 1). The 1992 growing season preceding the spring 1993 measurements was good and the amount of corn residue produced was much greater than during cool, wet 1993. The amount of surface residue with all treatments in 1994 was less than in 1993. For 1994, fall chisel plowing reduced residue cover by 30%. Spring-disk tillage effects on reducing surface residue were not as severe (<12%) as in 1993, and use of the MM slightly increased (3%) the surface residue by lifting some of the covered residue to the surface. After all the runoff events for both years, crop residue cover with the MM treatment was decreased to the level of the disked treatments. This was probably due in part to the loosening action of the MM on the residue, allowing for easier transport some of the residue with surface runoff; as was visually noted after several rainfall events. The NT plot still had more than 60% residue cover after all the runoff events in both years.

There were eight surface runoff events during the growing season in 1993 and six in 1994 (Figs. 1 and 2). Rainfall amounts causing runoff ranged from 1 to 11 cm. For the total growing season, use of NT resulted in the least runoff and erosion, with the differences being significant in some comparisons

Table 1
Average crop residue covers, surface runoff water volumes and sediment losses

Year	Treatment[a]	Surface residue cover (%)			Runoff volume (cm^3)	Sediment loss $(\mathrm{kg\ ha}^{-1})$	Atrazine		Metolachlor		Cyanazine	
		Pre-till	Post-till	After all events			Conc.[b] (μg l^{-1})	Loss[b] (g ha^{-1})	Conc. (μg l^{-1})	Loss (g ha^{-1})	Conc. (μg l^{-1})	Loss (g ha^{-1})
1993	NT	88 a	81 a	63 a	8.99 b	2167 b	33 a	30.2 a	15 ab	14.0 a	46 a	42.8a
	MM	69 b	65 b	27 b	13.40 a	3310 ab	15 b	19.3 a	15 ab	19.0 a	17 b	22.9a
	DS[c]	66 b	35 c	25 bc	14.59 a	5116 a	19 b	28.3 a	19 a	28.5 a	17 b	33.6a
	SD[c]	67 b	38 c	19 c	13.92 a	3261 ab	10 b	14.2 a	10 b	13.9 a	20 b	18.7a
1994	NT	81 a	83 a	66 a	0.25 b	99 b	140 a	3.1 b	70 a	1.7 b	110 a	2.7 b
	MM	50 b	53 b	27 b	2.90 a	870 ab	18 b	5.3 ab	49 bc	14.3 a	14 b	4.2 b
	DS	51 b	39 c	28 b	2.94 a	1193 a	36 b	11.2 a	56 b	16.3 a	38 b	8.9 a
	SD	53 b	44 bc	24 b	3.37 a	1269 a	17 b	5.9 ab	43 c	14.8 a	13 b	4.0 b

[a] NT: no-till herbicide/broadcast spray; MM: fall chisel plow-spring ‘‘Mulch Master’’/herbicide applied with MM; DS: fall chisel plow-spring disk/herbicide broadcast spray after disking; SD: fall chisel plow-spring disk/herbicide broadcast spray before disking.

[b] Differences in concentrations in water, and total losses with both sediment and water (less than 5% of the total loss for all herbicides was with sediment), are indicated by different letters within years and columns and are significant at the 10% level of significance.

[c] SD and DS were considered separate treatments, although for runoff volume and sediment loss they should be identical.

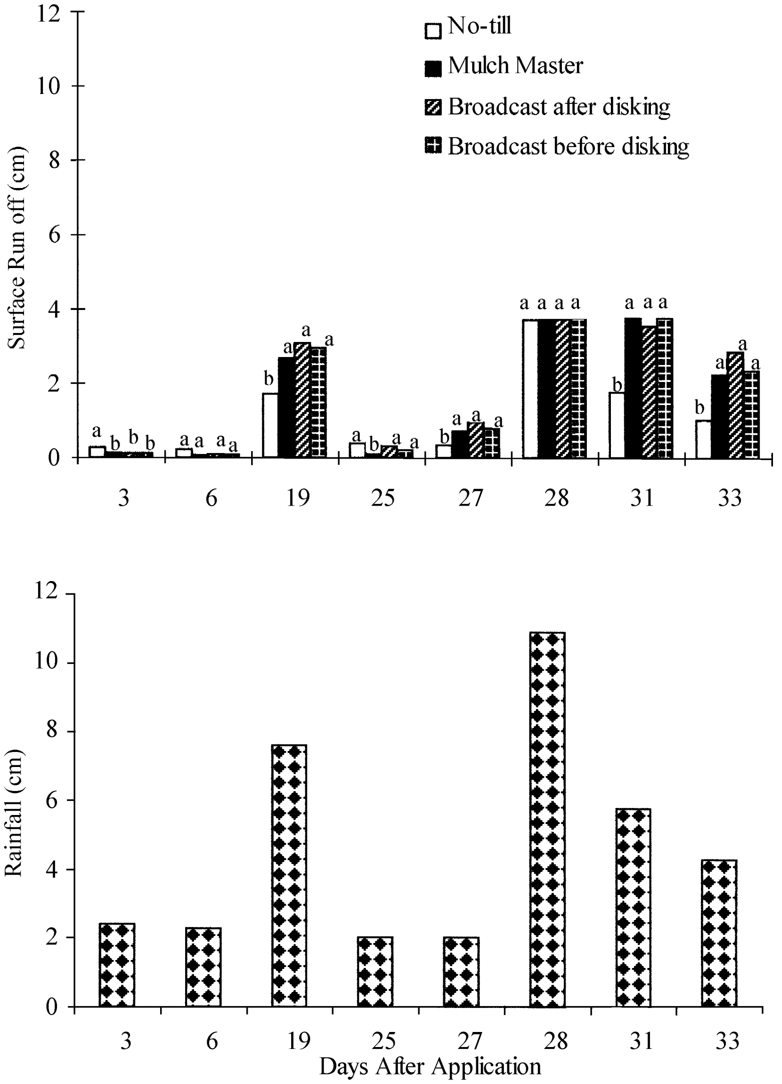

Fig. 1. Eight rainfall events (cm) and surface water runoff (cm) of respective treatments for 1993. Differences among means for each event are indicated at the 10% level of significance.

(Table 1). Treatments DS and SD yielded similar results, as expected. Although the MM treatment resulted in the second lowest runoff and erosion amounts due to less reduction in residue cover, the amounts were not statistically different from those for the SD and DS treatments.

Even though NT had the lowest total runoff volumes, this was not always the case for individual events. In 1993, runoff amounts were highest for NT for three of the first four events, with the difference most significant for the first event (Fig. 1). As shown in Fig. 3, because of the increased runoff for those three events, soil losses for two of those events were highest for NT. For all other events in both years (Fig. 3), soil loss for NT was the least. In 1994, NT had the lowest runoff volumes for all events, with the difference most significant for the fourth event (Fig. 2). On an individual event basis, there were

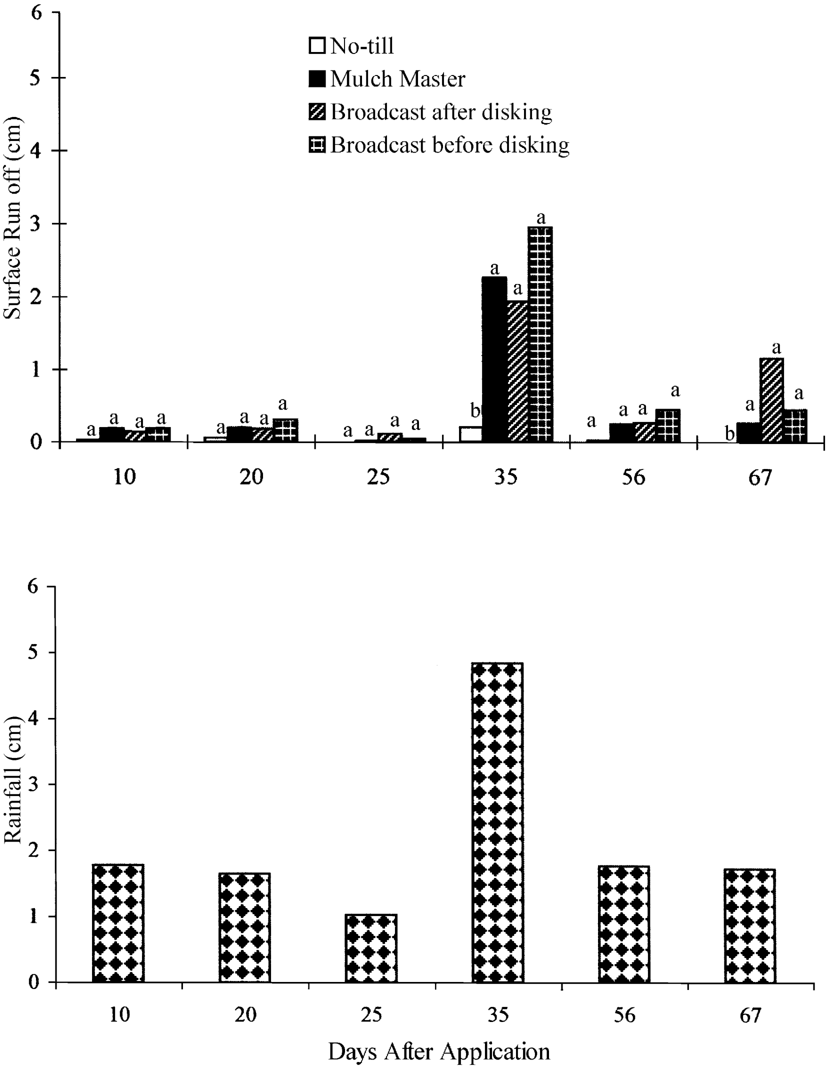

Fig. 2. Six rainfall events (cm) and surface water runoff (cm) of respective treatments for 1994. Differences among means for each event are indicated at the 10% level of significance.

no significant differences in terms of sediment loss among MM, DS, and SD in 1993 or 1994 (Fig. 3).

Herbicide concentrations in runoff water for all three herbicides generally decreased with time (days after application) during both growing seasons (Figs. 4–6). However, in 1994 (Figs. 4 and 5), the highest concentrations for atrazine and cyanazine occurred for the third (rainfall amount, 1.0 cm) event 25 days after application, which was smaller than two larger and previous events 10 and 20 days after application. For atrazine and cyanazine, concentrations for NT were always greater (statistically significant in most cases, particularly for 1994) than for the other treatments. The same was true for metolachlor for the first two events each year, although the results were mixed for later events. Metolachlor has the highest vapor pressure of the three herbicides, and dissipation

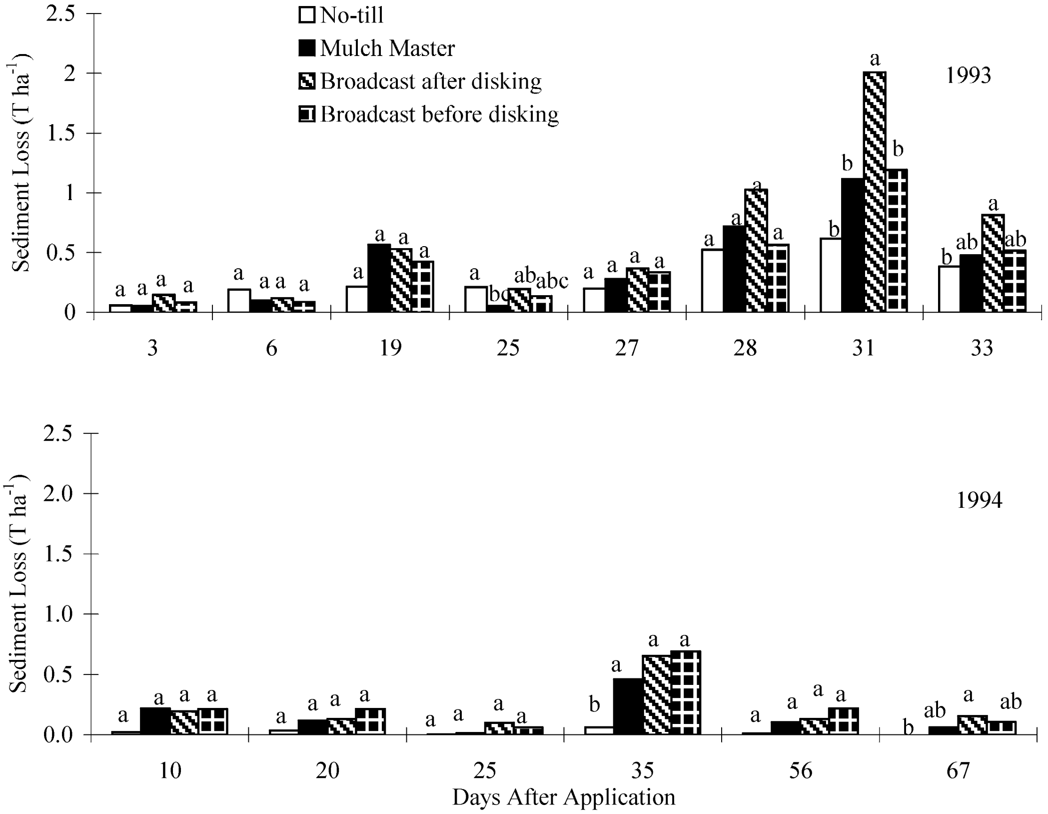

Fig. 3. Sediment loss (t ha^{-1}) for eight rainfall events for 1993, and six rainfall events for 1994 of respective treatments. Differences among means for each event are indicated at the 10% level of significance.

from the corn residue by volatilization, or photodegradation, may have been a factor.

In 1993 (and for 1994), the second highest herbicide concentrations usually occurred for the DS treatment for which the herbicide was not incorporated (Figs. 4–6). The SD treatment generally resulted in the lowest concentrations with concentrations for MM often intermediate between DS and SD. This would seem to be logical if the degree of soil incorporation was SD > MM > DS. Absolute concentrations for atrazine and cyanazine in runoff water were consistently above their MCL or HA (by two orders of magnitude for early events with NT), while for metolachlor, with the exception of NT, concentrations were below its HA.

Trends of herbicide concentrations in sediment (not shown) were similar to those in runoff water (Figs. 4–6 for 1993 and 1994), although herbicide concentrations in sediment were generally 2–10 times higher than those in runoff water. Peak concentrations in sediment generally ranged from 1000 to 4000 μg kg^{-1} (for reference, 2 kg ha^{-1} mixed in 8 cm of soil with a bulk density of 1.25 g cc^{-1}, would give a soil concentration of 2000 μg kg^{-1}). There was no difference in herbicide concentrations in sediment among treatments for individual events for either 1993 or 1994.

Seasonal average flow-weighted herbicide concentrations in runoff water and total losses (with sediment and water) are given in Table 1. Although herbicide concentrations for NT were higher when compared with the other treatments, there was no difference in losses for the three herbicides in 1993. In 1993, high concentrations for NT combined with higher early season runoff amounts caused the largest losses for

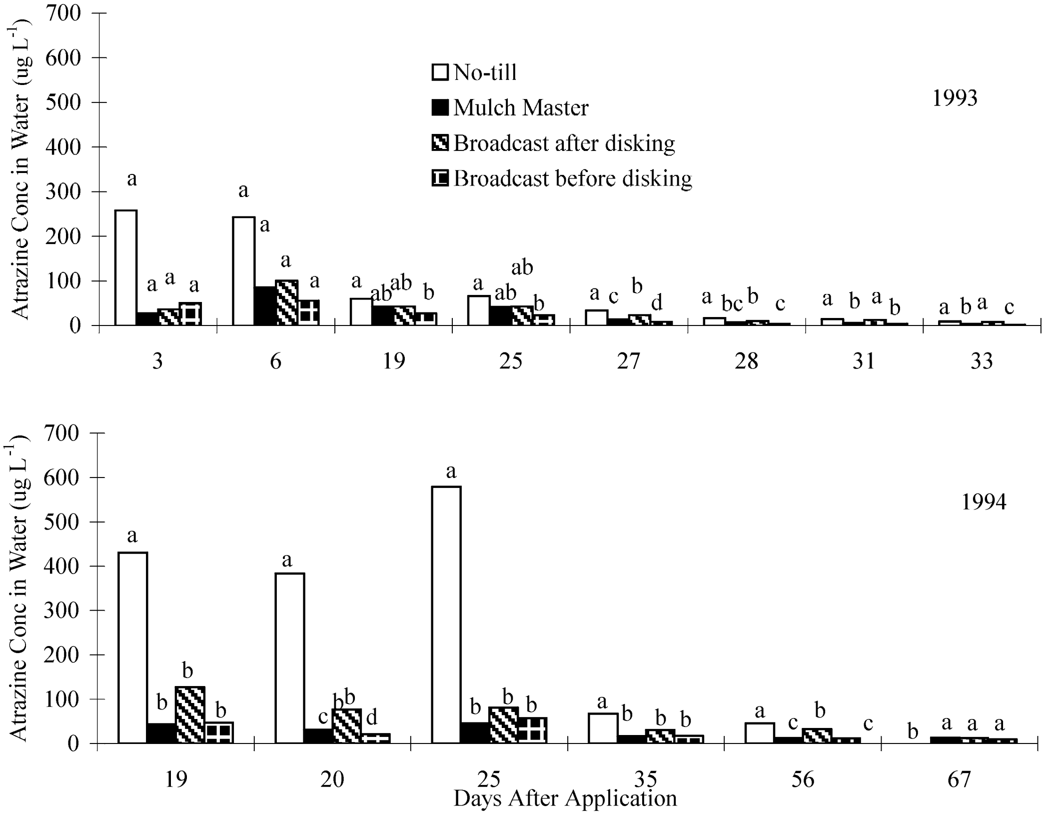

Fig. 4. Atrazine concentration in runoff water samples for eight rainfall events for 1993, and six rainfall events for 1994 of respective treatments. Differences among means for each event are indicated at the 10% level of significance.

individual events. Freese et al. (1993) and Gaynor et al. (1995) have also reported more surface water runoff and atrazine losses under NT.

In 1994, low runoff volumes (and low soil losses) for NT overcame higher herbicide concentrations in runoff water and sediment and resulted in the least herbicide losses. For the sixth event in 1994, no runoff occurred for the NT plots, while runoff occurred for the other three treatments. Losses for the other three treatments were generally in the order DS > MM > SD (Table 1). This order changed in 1994 for atrazine and metolachlor, with the order being DS > SD > MM. Losses, in terms of percent of that applied, ranged from a high of 1.5% for atrazine for NT in 1993 to a low of 0.07% for metolachlor for NT in 1994. The portion of total herbicide lost that was transported with runoff water ranged from 95% to more than 99%.

Overall results from the study show that method of herbicide application plays an important role in herbicide losses with sediment and runoff water. Herbicide application before disking (SD) and incorporation with the Mulch Master (MM) significantly reduced herbicide concentrations and losses in runoff water. Similar results were reported by Olson et al. (1998), when they found less atrazine loss from the chisel-disk system with incorporation compared to NT and ridge-till systems.

Surface residue cover reduced the annual runoff volumes in MM and NT treatments because of more residue cover compared with the SD and DS treatments. These results are consistent with other residue management practices under various tillage systems (Brown et al., 1985; Felsot et al., 1990; Hall and Mumma, 1994; Franti et al., 1998). However, some

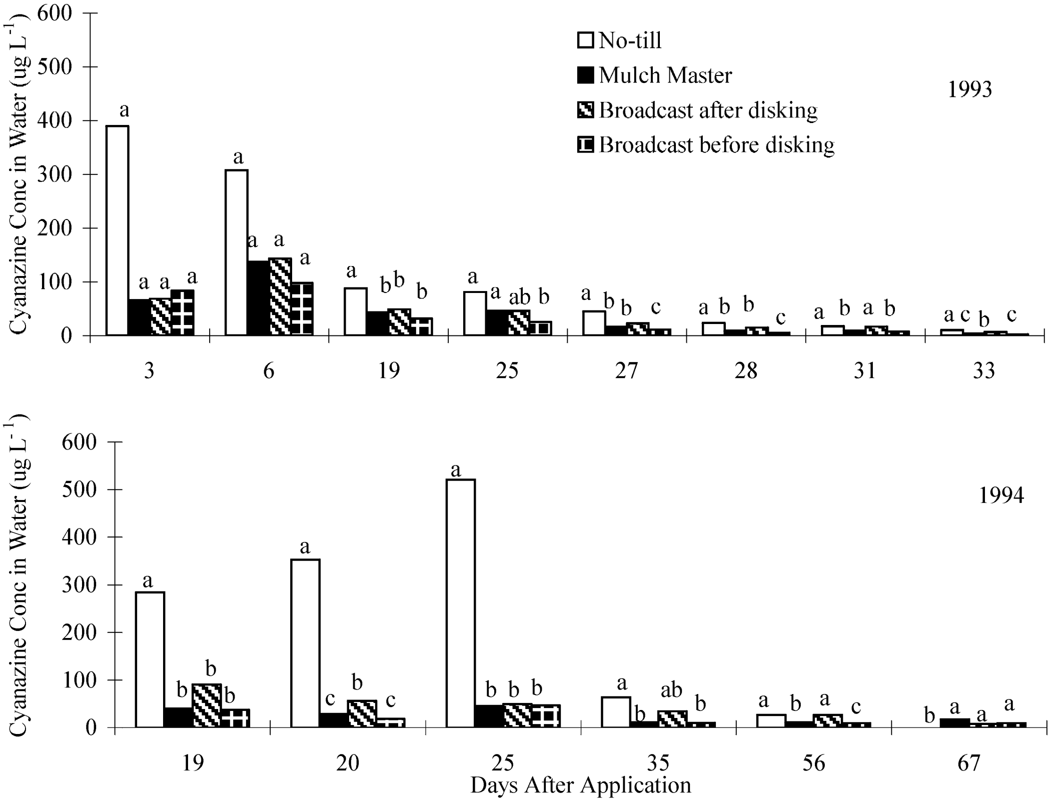

Fig. 5. Cyanazine concentration in runoff water samples for eight rainfall events for 1993, and six rainfall events for 1994 of respective treatments. Differences among means for each event are indicated at the 10% level of significance.

researchers have also reported no difference in herbicide loss under NT and conventional tillage systems (Sauer and Daniel, 1987; Gaynor et al., 1995).

4. Summary and conclusions

A field study was conducted to evaluate the effect of tillage and herbicide application methods on crop residue cover, surface runoff volume, erosion, and herbicide losses with sediment and runoff water during the 1993 and 1994 growing seasons. The losses of the herbicides atrazine, metolachlor, and cyanazine were measured from four tillage/herbicide application treatments (NT, DS, SD, and MM) with runoff water under natural rainfall conditions. Results showed that the herbicide application method plays a significant role in herbicide loss with runoff water. The major findings of this study are summarized as follows:

- MM retained more surface corn residue than SD/DS.
- Total runoff water volumes/soil losses were in the order of NT < MM < SD/DS.
- Herbicide concentrations in runoff were in the order of SD < MM < DS < NT. This shows that although NT had the lowest annual runoff volume and soil loss compared with the other treatments, herbicide concentrations in runoff water were the highest. This was likely due to the herbicide interception by surface residues followed by washoff, that increased the concentrations of herbicides in runoff water.
- Herbicide runoff losses were in the order of SD < MM < DS NT variable for 1993. This order in 1994 was NT < SD < MM < DS for cyanazine,

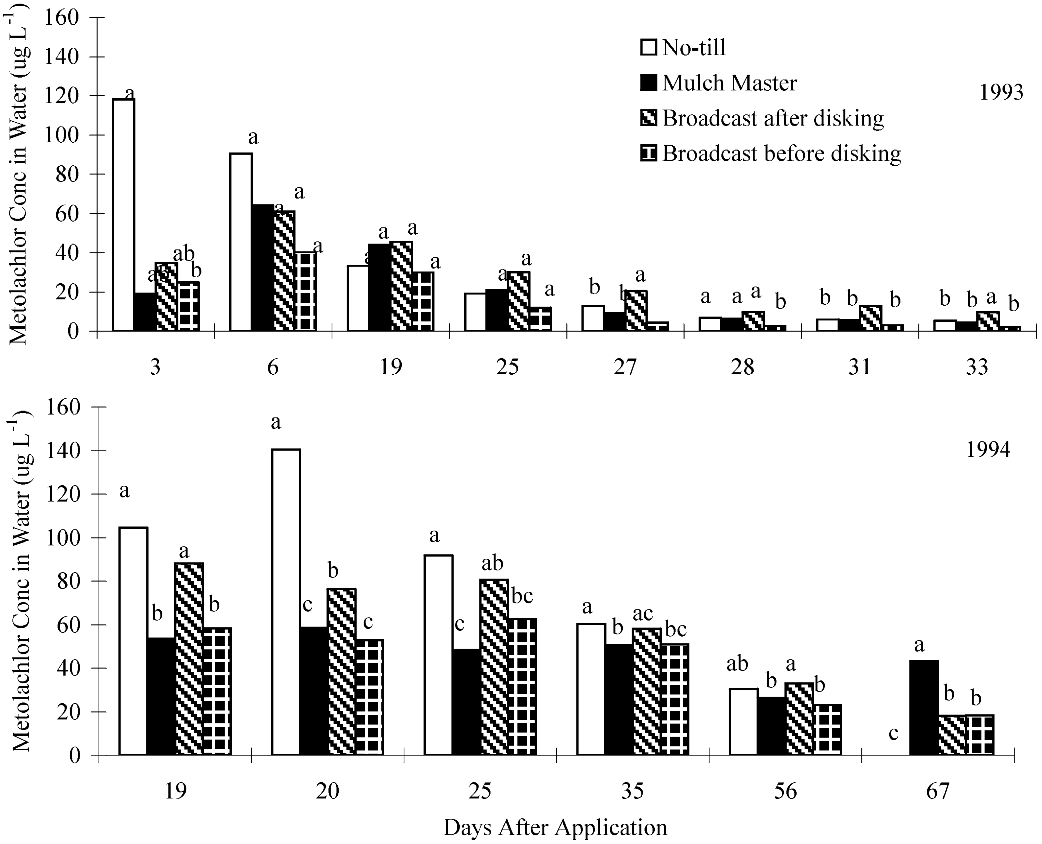

Fig. 6. Metolachlor concentration in runoff water samples for eight rainfall events for 1993, and six rainfall events for 1994 of respective treatments. Differences among means for each event are indicated at the 10% level of significance.

but was NT < MM < SD < DS for atrazine and metolachlor.

- Less than 2% of applied herbicides was lost with runoff water, with at least 95% of the total loss being in solution. The use of Mulch Master, a new tool for herbicide application, showed impressive results in terms of residue cover management and reducing herbicide losses with surface runoff water. In addition, it was found to be an effective tool for incorporating herbicides in the root zone of the soil profile.

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