Herbicide Banding and Tillage System Interactions on Runoff Losses of Alachlor and Cyanazine

N. C. Hansen,* J. F. Moncrief, S. C. Gupta, P. D. Capel, and A. E. Olness

ABSTRACT

Herbicides transported to surface waters by agricultural runoff are partitioned between solution and solid phases. Conservation tillage that reduces upland erosion will also reduce transport of herbicides associated with the solid phase. However, transport of many herbicides occurs predominantly in solution. Conservation tillage practices may or may not reduce transport of solution-phase herbicides, as this depends on the runoff volume. Reducing herbicide application rate is another approach to minimize off-site transport. Herbicide banding can reduce herbicide application rates and costs by one-half or more. Our objective was to compare herbicide losses in runoff from different tillage practices and with band- or broadcast-applied herbicides. The herbicides alachlor [2-chloro-2′,6′-diethyl-*N*-(methoxymethyl)acetanilide] and cyanazine [2-[[4-chloro-6-(ethylamino)-1,3,5-triazin-2-yl]amino]-2-methylpropionitrile] were broadcast- or band-applied to plots managed in a moldboard plow, chisel plow, or ridge till system. Herbicide concentration in runoff was largest for the first runoff event occurring after application and then decreased in subsequent events proportional to the cumulative rain since the herbicide application. When herbicides were broadcast-applied, losses of alachlor and cyanazine in runoff followed the order: moldboard plow > chisel plow > ridge till. Conservation tillage systems reduced runoff loss of herbicides by reducing runoff volume and not the herbicide concentration in runoff. Herbicide banding reduced the concentration and loss of herbicides in runoff compared with the broadcast application. Herbicide losses in the water phase averaged 88 and 97% of the total loss for alachlor and cyanazine, respectively. Cyanazine was more persistent than alachlor in the soil.

HERBICIDES move into surface water via agricultural runoff (Pereira and Hostettler, 1993). Schottler et al. (1994) detected atrazine, alachlor, and cyanazine in the Minnesota River with peak concentrations closely following spring application each year. The timing of the peak herbicide concentrations in the Minnesota River relative to the peak flow rates for the same events suggested that herbicides were primarily transported to the river via overland flow. Runoff events occurring shortly after herbicide application pose the greatest off-site movement risk (Wauchope, 1978; Shipitalo et al., 1997).

Herbicides can be transported to surface water in both solution phase and with eroded sediments. Runoff transport of strongly sorbed herbicides can be reduced through the use of conservation tillage systems. However, many moderately sorbing, water-soluble herbicides are transported primarily in the water phase and losses may only be reduced with management practices that reduce runoff volume as well as sediment loss (Wauchope, 1978). Studies evaluating herbicide loss in surface runoff from different tillage practices have had mixed results. Some studies show greater concentrations and greater losses of herbicides in runoff from conservation tillage systems than from conventional tillage approaches due to greater runoff volumes, greater herbicide concentrations, or both (Baker et al., 1978; Isensee and Sadeghi, 1993; Gaynor et al., 1995). In other studies, herbicide losses are reduced for conservation tillage practices due to a reduced runoff volume and sediment loss (Felsot et al., 1990; Hall et al., 1991).

Another approach to reduce runoff losses of herbicides is to reduce application rates (Baker and Mickelson, 1994). Applying herbicides in a band over the row is one method used to reduce herbicide application rates. With banding, application rates and costs are one-half to one-third of conventional broadcast applications. Weeds between the treated bands are controlled by mechanical cultivation (Buhler et al., 1994). In addition to reducing application rates, banding and cultivation also affect herbicide transport through changes in weed growth and surface hydrology including runoff (Hansen et al., 2000).

Our objective was to evaluate the effects of herbicide application method and tillage practice on herbicide losses in surface runoff. Herbicide losses in both solution and sorbed phases of runoff are compared for band vs. broadcast application methods. The herbicides applied were alachlor and cyanazine. Tillage systems evaluated were moldboard plow, chisel plow, and ridge till. Runoff losses of sediment and phosphorus for these systems were reported previously (Hansen et al., 2000).

MATERIALS AND METHODS

Runoff Plot Design

This study was conducted in 1996 and 1997 using rectangular runoff plots (3 × 22 m) on a Clarion silt loam (fine-loamy, mixed, superactive, mesic Typic Hapludoll) soil in Scott County, Minnesota. Before the study, the site was in a ridge till–based corn (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.] rotation for 10 yr. The experimental treatments were duplicated in a randomized complete block design. Treatments were fall moldboard or chisel plowing followed by spring disking, and ridge till planting with row cultivation for ridge maintenance with broadcast or banded herbicide application. Ridge till plots were established using existing ridges. The soil organic matter for the 0- to 6-cm depth varied with tillage and averaged 230, 240, and 300 g kg^{-1} for the moldboard plow, chisel plow, and ridge till treatments. Soil pH (water 1:1) was 7.1.

Each plot consisted of four rows spaced 75 cm apart and managed with tillage up-and-down an 8 to 10% slope. Each plot was isolated around the perimeter with vertical metal borders driven 10 cm into the soil to prevent leakage. Galvanized metal runoff collectors at the bottom of the plots chan-

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neled runoff to a 10-cm-diameter PVC pipe and to a tipping bucket flow gauge. A data logger recorded the number and rate of tips with the use of a magnetic closure switch on each tipping bucket. Volume of runoff was calculated by the use of a calibration equation relating flow rate to the rate of tipping. A composite runoff sample for each plot and each runoff event was collected by mechanically capturing a fraction of the water from each tip. Rain amounts were measured with an electronic, tipping bucket–type rain gauge as well as a manual rain gauge.

Cultural Practices

Corn stalks were chopped after corn harvest each year for all tillage systems. Moldboard plowing was done on 7 Nov. 1995 and 4 Oct. 1996. Chisel plowing was done on 8 Nov. 1995 and 20 Nov. 1996. Pioneer Hi-Bred International (Des Moines, IA) Hybrid 3751 corn was planted on 2 May 1996 at a rate of 8.0 seeds m^{-2} with a Model 4500-8H Buffalo Till two-row ridge planter (Fleisher Manufacturing, Columbus, NE). Pioneer Hybrid 3893 corn was planted on 10 May 1997 at a rate of 8.4 seeds m^{-2} with a Hiniker Econ-O-Till 7000 K Series two-row planter (Hiniker Co., Mankato, MN). Ridges were rebuilt with cultivation on 26 June 1996 and 27 June 1997 with a Hiniker Series I Econ-O-Till row cultivator. All moldboard and chisel plowed plots were cultivated on the same dates with the Hiniker row cultivator with the ridging shares in the up position, leaving only 56-cm-wide sweeps running at 5 cm deep.

The herbicides alachlor and cyanazine were applied on 17 May 1996 and 20 May 1997 using a pressurized backpack sprayer at a delivery rate of 180 L ha^{-1}. Properties of the herbicides are reported in Table 1. Broadcast application was made at rates of 2.2 kg ha^{-1} for alachlor and 2.1 kg ha^{-1} for cyanazine. Banded applications were made in a 25-cm-wide band centered over corn rows spaced 75 cm apart. Application rates for the banded treatment were thus equal to one-third of the broadcast rates.

Extraction and Analysis of Herbicides in Runoff

Water samples were retrieved within 12 h after each runoff event. Phase separation was done by filtering runoff samples through 12.5-cm glass fiber filters with a nominal pore size of 0.7 μm (Whatman [Maidstone, UK] GFF). The sediment was air-dried (22 ± 1°C) on the glass filters for 12 to 24 h and frozen until analyzed. Herbicides were extracted from isolated sediment robotically by the method of Koskinen et al. (1991) as modified by Lemme et al. (1997). A Varian (Palo Alto, CA) Model 3400 gas chromatograph was configured with both DB-5 (5% phenyl–95% methyl) and DB-1701 columns (14% cyanopropylphenyl–86% methyl) (J&W Scientific, Folsom, CA). Columns were 30 m × 0.25 mm i.d. Alachlor and cyanazine standards were spiked into duplicate sediment samples for 10% of the sediment samples to assess recovery. Recoveries averaged 98 and 102% for alachlor and cyanazine, respectively.

Water-phase extraction and analysis of herbicides were done according to the method developed by Larson et al. (1996). Herbicides were extracted from filtered runoff water by passing 300 mL of the sample through a preconditioned 5-g C-18 solid-phase extraction cartridge (Bond-Elut, Varian Corp.). All samples were spiked with the surrogate compounds butachlor and terbuthyazine. The solid-phase extraction cartridges were dried and then eluted with diethyl ether through a column of anhydrous Na_2SO_4. The volume of each sample was reduced under forced N_2 and the internal standards anthracene-d_{10} and 4,4′-dibromobiphenyl were added. Separation, verification, and quantification were done with high resolution, fused silica capillary gas chromatography (Hewlett–Packard [Palo Alto, CA] 5890 GC) coupled with a mass spectrometer (HP 5971 MS). Three ion fragments were used for verification of each compound. Quantification was done using the internal standard method. Procedural blanks were also analyzed and no interference or contamination was found. Recoveries of alachlor and cyanazine from spiked deionized water averaged 95 ± 5% and 113 ± 7% for alachlor and cyanazine, respectively. Recoveries of the surrogates averaged 120% for terbuthylazine and 90% for butachlor. Concentrations reported herein have not been corrected for recovery. Losses of alachlor and cyanazine in surface runoff were computed as the product of runoff volume and concentration.

Table 1. Environmental fate properties of the herbicides alachlor and cyanazine (from Jury et al., 1987).

Chemical	Solubility in water	K_{oc}	Half life
	mg L^{-1}	L kg^{-1}	days
Alachlor	240	120	18
Cyanazine	170	170	14

Residual Herbicide in Soil

At the conclusion of the study, on 10 Nov. 1997, soil samples were taken from all plots to assess the residual concentrations of alachlor and cyanazine in the soil. Composite samples were taken at 0- to 1- and 1- to 5-cm depths both in the herbicide-treated band and between the treated bands (and corresponding areas for broadcast treatments). Samples were air-dried at room temperature for 24 h, crushed and sieved through a 2.0-mm sieve, and then frozen until analyzed. Extraction and analysis of alachlor and cyanazine in the soil were done in the same manner as described for sediment.

Statistical Analysis

Analysis of variance was carried out using Statistical Analysis System software (SAS Institute, 1996). Herbicide loss data were transformed to logarithmic (base 10) values to control nonhomogeneous variances. The means reported here are the geometric means. Treatment effects were considered significant at the 90% confidence level ($\alpha = 0.10$).

RESULTS AND DISCUSSION

Herbicide Concentrations in Runoff

Solution Phase

Alachlor and cyanazine concentrations in runoff from individual runoff events in 1996 and 1997 were affected by herbicide banding but not by tillage practice. For both herbicides, the concentrations were greatest for the first runoff event in each year and decreased rapidly in subsequent events (Table 2). In 1996, the first runoff event occurred 1 d after herbicide application. For this event, the alachlor concentrations averaged 270 μg L^{-1} for the broadcast-treated plots and 110 μg L^{-1} for the band-treated plots. For the same event, cyanazine concentrations averaged 1400 μg L^{-1} for the broadcast treatment and 740 μg L^{-1} for the band treatment. In 1997, the first runoff event occurred 30 d after the herbicide application. Conditions during this 30-d period were dryer than normal, with a total rainfall of 29 mm (Table 2). The longer time period between application and the first

Table 2. Effects of herbicide application method, days after application, and cumulative rainfall on the mean concentrations of alachlor and cyanazine in runoff water and suspended sediment from individual runoff events in 1996 and 1997.

Days after application	Cumulative rainfall†	Alachlor in water		Alachlor in sediment		Cyanazine in water		Cyanazine in sediment	
		Broadcast	Banded	Broadcast	Banded	Broadcast	Banded	Broadcast	Banded
	mm	μg L^{-1}		μg kg^{-1}		μg L^{-1}		μg kg^{-1}	
1996									
1	16	270	110	7100	3700	1400	740	7200	2500
19	84	180	86	1800	690	810	360	2700	900
20	100	110	46	820	530	490	210	1400	610
29	150	23	11	210	8.0	210	84	230	8.0
35	160	14	10	–	–	150	87	–	–
82	230	7.7	4.3	8.0	8.0	59	39	8.0	8.0
94	240	4.7	3.0	20	12	36	13	28	22
1997									
30	29	180	38	2100	530	350	97	2400	480
35	47	61	24	1000	190	210	83	1200	220
40	100	39	17	360	98	75	39	430	130
54	150	11	5.4	34	23	1.8	13	200	48
59	180	1.2	0.89	210	71	6.6	2.4	110	21
65	220	1.1	0.86	36	19	6.5	2.3	75	11
86	350	0.82	0.59	–	–	4.4	1.6	–	–
91	420	0.55	0.40	–	–	2.9	1.1	–	–
104	450	0.37	0.26	12	8.0	1.9	0.70	19	8.0
119	480	0.24	0.18	8.0	8.0	1.2	0.47	10	9.9

† Cumulative rainfall since the day of herbicide application.

runoff event, along with the intervening precipitation, resulted in lower herbicide concentrations than for the first runoff event in 1996. For the first runoff event in 1997, alachlor and cyanazine concentrations averaged 180 and 350 μg L^{-1} for the broadcast treatments and 38 and 97 μg L^{-1} for the banded treatment, respectively. Other studies have also shown that the concentration of herbicides in runoff is highly dependent on time since application of the first runoff event (Wauchope, 1978; Shipitalo et al., 1997). The herbicide concentration in solution for the band treatment was approximately one-third that of the broadcast treatment. However, the relative difference between concentrations for broadcast and banded treatments varied among event dates and tillage practices. This variability occurred because the amount of runoff and sediment loss differed among event dates and treatments.

Many herbicide fate studies (Triplett et al., 1978; Gaynor et al., 1995; Shipitalo et al., 1997) have described the change in runoff herbicide concentration over time with a linear relationship between ln(concentration) and ln(days after application). Here, this type of relationship described the change in alachlor or cyanazine concentration in solution when each study year and herbicide application method was compared separately ($0.68 < r^2 < 0.95$). However, when both years' data were combined, the relationships were poor ($0.16 < r^2 < 0.24$). The amount and frequency of rainfall were very different for the two years (Table 2) and these differences probably affected herbicide dissipation and the resulting concentrations in runoff. For alachlor and cyanazine, there was a relationship between log(concentration) and the cumulative amount of precipitation since the date of herbicide application (Fig. 1). Plotting herbicide concentration against cumulative precipitation incorporates time and the effect that precipitation has on the dissipation and movement of herbicides. These results suggest that the relationship between ln(concentration) and ln(days after application) is sensitive to annual variability in weather and may not be a good variable for simple estimates of herbicide concentration in runoff. However, cumulative precipitation may be a better variable for estimating concentration in runoff.

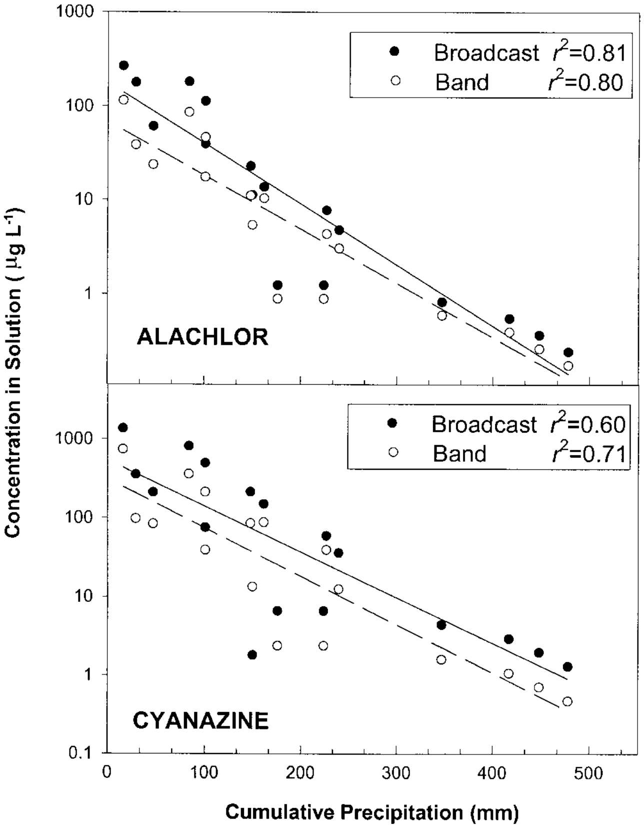

Fig. 1. Water-phase concentrations of alachlor (upper graph) and cyanazine (lower graph) for broadcast and band-applied herbicide methods as a function of cumulative precipitation. Data are from 1996 and 1997 study years and include three tillage practices.

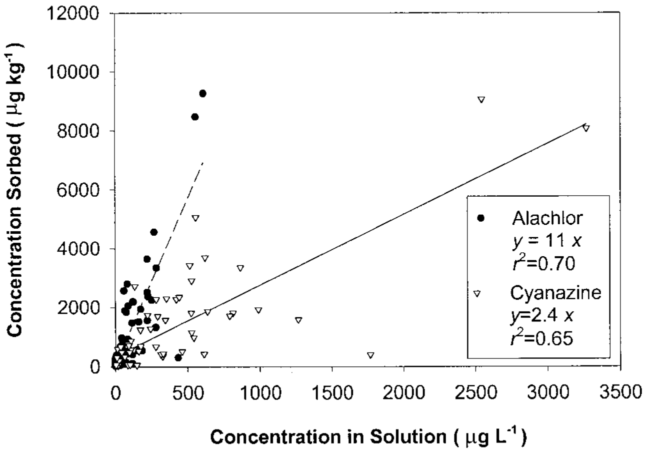

Fig. 2. The relationship of herbicide concentration in sediment versus runoff water for alachlor and cyanazine. The slope of this line is an estimate of the distribution coefficient of these herbicides in sediment eroded from a Clarion silt loam soil.

Sediment Phase

On a mass basis, the concentrations of alachlor and cyanazine in the sediment phase of runoff were greater than in the water phase (Table 2). Herbicide application method affected alachlor concentration in sediment ($P = 0.001$), but tillage practice did not ($P = 0.910$). Cyanazine concentration in sediment was affected by herbicide application method ($P < 0.001$) but not by tillage practice ($P = 0.813$). For both herbicides, sediment-phase concentration was greater for the broadcast treatments than for the banded treatments. A plot of concentration in sediment versus solution phases for all events and all treatments shows that the distribution coefficient, K_d, was 11 L kg^{-1} for alachlor and 2.4 L kg^{-1} for cyanazine (Fig. 2). These values are similar to those obtained in other runoff studies. For example, Felsot et al. (1990) reported K_d values for alachlor and eroded sediment ranging from 5.6 to 8.4 L kg^{-1} and Baker et al. (1978) reported values for alachlor as high as 10.8 L kg^{-1}. For cyanazine and eroded sediments, a K_d value of 2.8 was reported (Hall et al., 1984).

Alachlor Losses in Runoff

Total alachlor losses (water + sediment) for 1996 and 1997 are shown in Fig. 3. In 1996, the total loss of alachlor was affected by tillage ($P = 0.001$) and herbicide application method ($P = 0.001$) and there was a tillage by application method interaction ($P = 0.003$). For the broadcast treatment, alachlor losses follow the order: moldboard plow (22 g ha^{-1}) > chisel plow (9.3 g ha^{-1}) > ridge till (1.5 g ha^{-1}). These alachlor losses represent 1.0, 0.4, and 0.1% of the amount of broadcast-applied alachlor for moldboard plow, chisel plow, and ridge till treatments, respectively. Losses were least for the conservation tillage systems due to a reduction in runoff volume and sediment loss, since tillage did not affect alachlor concentration. For the banded treatment alachlor losses were 4.3, 3.0, and 2.2 g ha^{-1} for the moldboard plow, chisel plow, and ridge till treatments, respectively. In the moldboard plow treatment, band-applying herbicides resulted in one-fifth the herbicide loss in runoff compared with broadcasting, although the amount applied was only one-third of the broadcast amount. The additional reduction in herbicide loss was due to a lower amount of total runoff. Weed growth in the interrow area before cultivation reduced runoff, especially in the moldboard plow system that had little cover from crop residue (Hansen et al., 2000).

In 1997, total alachlor loss was affected by tillage ($P =$

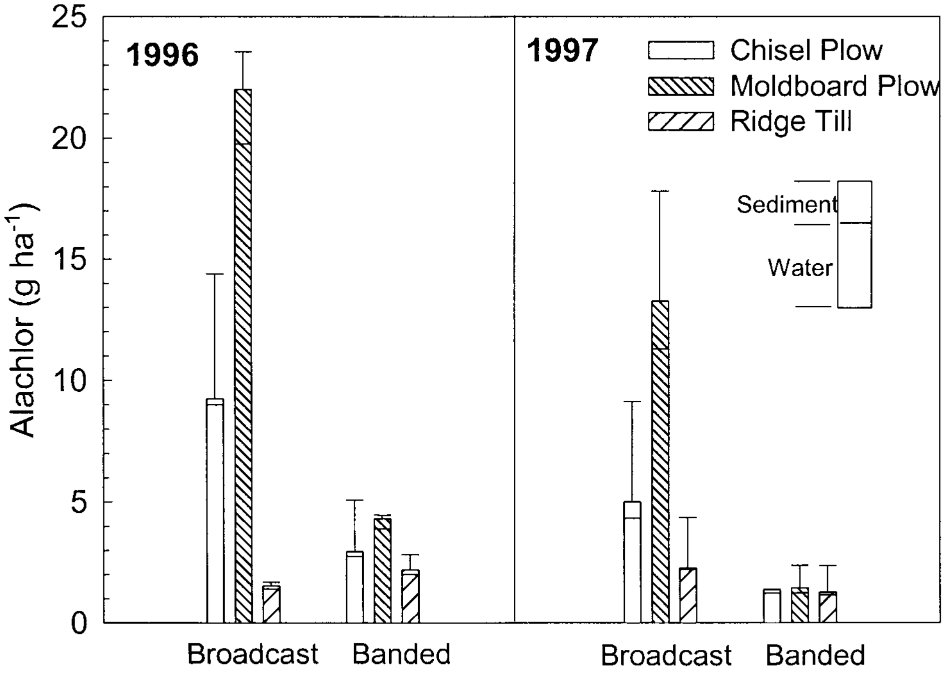

Fig. 3. The effects of tillage practice and herbicide application method on alachlor losses in runoff (water + sediment) during 1996 and 1997. Error bars represent one standard deviation.

0.076) and herbicide application method ($P = 0.018$) and there was a tillage by herbicide interaction ($P = 0.082$). For the broadcast-treated plots, total alachlor losses followed the order: moldboard plow (13 g ha^{-1}) > chisel plow (5.0 g ha^{-1}) > ridge till (2.3 g ha^{-1}). For the banded plots, total alachlor losses were similar among tillage treatments and averaged 1.4 g ha^{-1}. In general, the loss of alachlor was lower in 1997 than in 1996. This occurred even though the cumulative rainfall (Table 1) and runoff (Hansen et al., 2000) were higher in 1997 than in 1996. Delay in the timing of runoff relative to herbicide application had a greater effect on reducing alachlor loss than the amount of runoff. In addition, the effect of tillage on runoff volume was more important for herbicide transport than the effect of tillage on herbicide concentration. The reduction in alachlor loss associated with band application was greater than the threefold reduction in application rate. This was due to a reduction in runoff volume from the banded treatment (Hansen et al., 2000).

For both study years, total alachlor loss was dominated by water-phase losses, but sediment-phase transport was also important (Fig. 3). The percent of total alachlor lost in the water phase was not different among tillage ($P = 0.970$) or herbicide application method ($P = 0.600$) and averaged 88% for both years. Other studies have shown similar percentages of total alachlor loss in the water phase (Felsot et al., 1990; Khakural et al., 1994). Although the concentration of alachlor was much greater per unit mass of sediment than per unit mass of water, the total mass of sediment lost in runoff was small compared with the mass of water. Here, the differences in herbicide losses among tillage were largely driven by a reduction in runoff volume associated with the conservation tillage approaches. In the case of herbicide banding, lesser alachlor losses occurred because of a reduction in herbicide application as well as reductions in runoff volume.

Since water-phase losses of herbicides often predominate, some (e.g., Wauchope, 1978) have argued that management practices that reduce sediment loss but do not reduce runoff volume will be ineffective in reducing herbicide loss. However, it may be inappropriate to draw such a conclusion from this study or others like it. The relative proportion of herbicide transported in solution and sediment phases was determined based on the herbicide partitioning after sample collection and storage, since phase separation did not occur immediately. It is very possible that much of the solution-phase herbicide desorbed from suspended sediments during runoff or sample storage. This would underestimate the importance of the solid phase as a source of herbicides in runoff. Less desorption may occur when detachment of soil particles is reduced by conservation tillage. More research is needed to understand these mechanisms.

Cyanazine Losses in Runoff

Cyanazine losses were substantially greater than alachlor losses (Fig. 4). In 1996, cyanazine losses were affected by tillage ($P = 0.001$) and herbicide application method ($P = 0.001$) and there was a significant tillage by herbicide application method interaction ($P = 0.002$). When herbicides were broadcast-applied, cyanazine losses were 92 g ha^{-1} for moldboard plow, 43 g ha^{-1} for chisel plow, and 8.0 g ha^{-1} for ridge till. These losses represent 4.4, 2.0, and 0.38% of the amount applied, respectively. The lesser losses for chisel and ridge

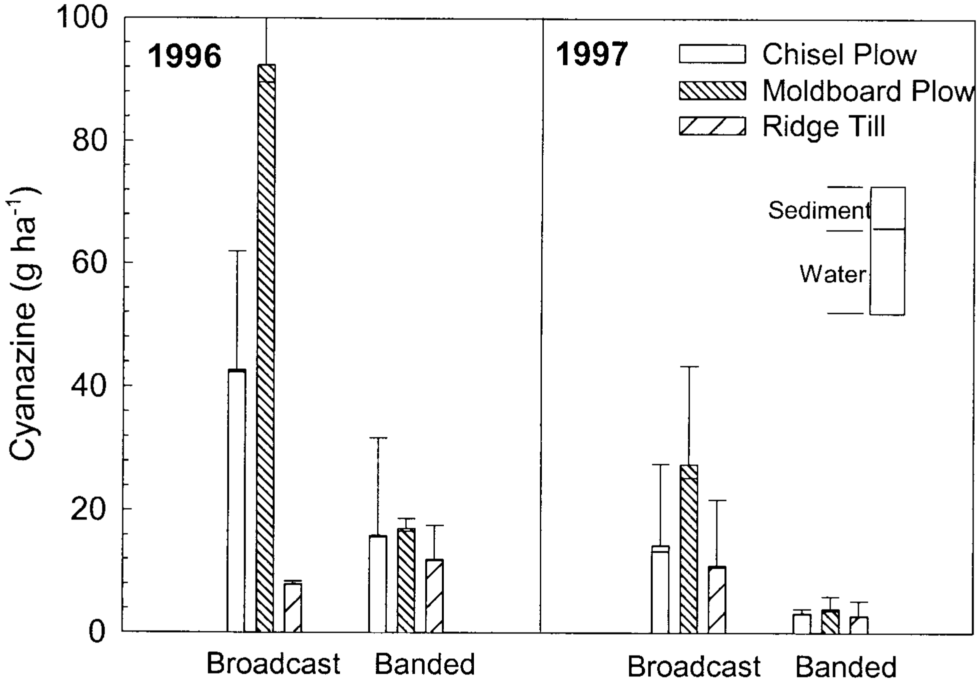

Fig. 4. The effects of tillage practice and herbicide application method on cyanazine losses in runoff (water + sediment) during 1996 and 1997. Error bars represent one standard deviation.

till systems were due to a reduction in volume of runoff (Hansen et al., 2000). When the herbicides were applied in a band, cyanazine losses were less than from the broadcast treatment for the moldboard (17 g ha^{-1}) and chisel plowed plots (16 g ha^{-1}) and similar for the ridge tilled plots (12 g ha^{-1}).

In 1997, cyanazine losses were less than in 1996. Cyanazine losses in 1997 were affected by herbicide application method ($P = 0.055$), but not by tillage system ($P = 0.476$). There was no tillage by herbicide banding interaction ($P = 0.550$) on cyanazine losses in 1997. Losses averaged 18 g ha^{-1} for the broadcast-treated plots and 3.3 g ha^{-1} for the band-treated plots. Of the total loss of cyanazine, 97% was lost in the water phase, and this percentage was not different among tillage systems ($P = 0.443$) or herbicide application methods ($P = 0.574$). Sediment-phase losses were much smaller for cyanazine than for alachlor. However, as stated earlier, the importance of suspended sediment in mobilizing herbicides may be underestimated, since it is not known how much of the water-phase herbicides may be due to desorption during runoff and sample storage.

One result suggests that cropping and tillage systems that reduce runoff during the period immediately following the herbicide application have the most promise for reducing off-site herbicide movement in runoff. The potential of band application for reducing off-site transport of herbicides is high because application rates are lower and also because runoff amounts are lower due to the presence of weed cover between the rows, especially before cultivation. Results indicate that a reduction in runoff due to the presence of weeds is more important for tillage systems that leave little crop residue on the soil surface, such as the moldboard plow, than for conservation tillage approaches.

Residual Herbicide In Soil

Residual Alachlor

For samples taken in the row, alachlor was found at low concentrations in the 0- to 1-cm depth for all treatments, averaging 42 μg kg^{-1}. No differences among tillage ($P = 0.625$) or herbicide application method ($P = 0.208$) were noted. At the 1- to 5-cm depth in the row, alachlor concentrations were below the detection limit of 8 μg kg^{-1} for the moldboard and chisel plowed plots but averaged 44 μg kg^{-1} for the ridge tilled plots. The presence of alachlor in the 1- to 5-cm depth of the ridge till treatment occurred because the ridge-building cultivation buried the original soil surface of the in-row position. This observation will be developed further below for residual cyanazine. Concentrations of alachlor were below the detection limit for all samples taken between the row regardless of sampling depth or herbicide application method. The lower concentrations between the row result from the cultivation. Conventional cultivation diluted the herbicides by mixing soil from below. For ridge tillage, cultivation reduced between-row herbicide concentrations by moving the herbicide-treated interrow soil to the ridge. In either case, the mixing may also promote more rapid degradation.

Residual Cyanazine

In-row residual cyanazine concentrations were greater than residual alachlor concentrations, suggesting a longer persistence of cyanazine in this soil. There was a tillage by depth interaction ($P = 0.061$) for the in-row residual cyanazine concentration (Fig. 5). The interaction occurred because cyanazine concentrations in the 1- to 5-cm depth were lesser than in the 0- to 1-cm depth for the moldboard and chisel plowed plots, but concentrations were similar with depth for the ridge tilled plots. These differences are the result of soil movement and disturbance from cultivation. The ridge-building cultivation moved herbicide-treated soil from the furrow into the row, covering the original herbicide-treated soil surface. The similar herbicide concentration with depth in the row reflects this mixing. For the band-treated ridge till plots, the soil that was moved from the furrow into the row was not treated with herbicides, thus resulting in a cyanazine concentration at the 0- to 1-cm depth that was lesser than the concentration of other tillage systems. This suggests that ridge cultivation coupled with banded herbicide application could reduce the availability of herbicides to runoff. However, these results were not seen in this study because most of the herbicide losses in surface runoff occurred before ridge-building cultivation when the above effects were absent.

Residual concentrations of cyanazine for the be-

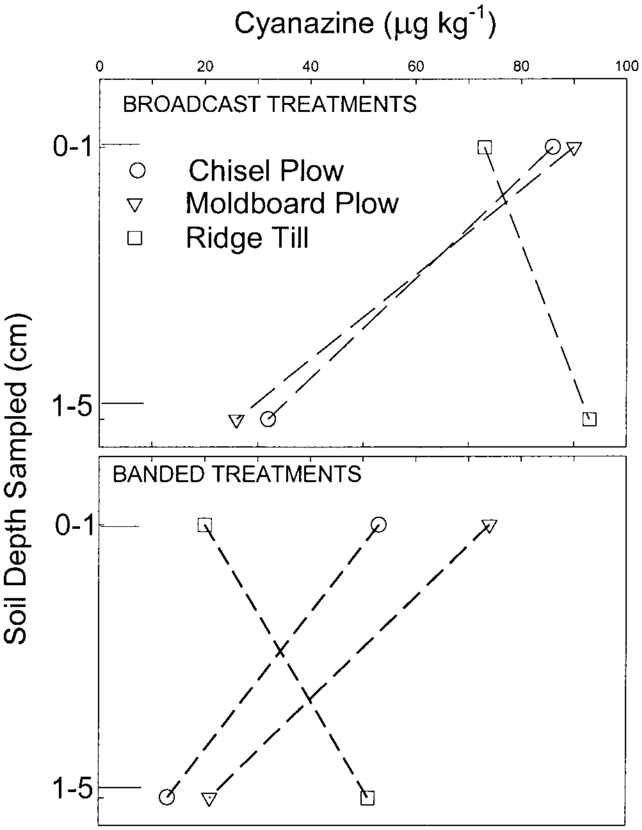

Fig. 5. The interaction of tillage practice and depth on the residual concentrations of cyanazine in the herbicide-treated band and the corresponding area for the broadcast-treated plot. The unique distribution of cyanazine in the ridge till treatment is due to mechanical soil movement that occurred during the ridge-building cultivation.

tween-row position were low for the banded treatments, because this area was not sprayed. For the banded treatments, the residual cyanazine concentrations at the 0- to 1-cm depth were similar among tillage practice and averaged 6.8 μg kg^{-1}. At the 1- to 5-cm depth, residual cyanazine concentrations for all banded treatments were below the detection limit. For the broadcast treatment, between-row cyanazine concentrations for the 0- to 1-cm depth were 39, 23, and 22 μg kg^{-1} for the ridge till, moldboard, and chisel plow systems, respectively. At the 1- to 5-cm depth, cyanazine concentration was similar among tillage practices and averaged 11 μg kg^{-1}. Regardless of tillage practice, the between-row concentrations were lesser than those observed for in-row samples. This difference is due to a dilution caused by mixing with soil from below during cultivation (moldboard and chisel plowed treatment) and may also reflect more rapid degradation with cultivation. In the case of ridge tillage, this is because of the movement of herbicide-treated soil to the row position.

Comparison of the residual concentrations of cyanazine in the 0- to 1-cm depth with (Fig. 5) the concentrations of cyanazine measured in eroded sediment for the last runoff events in 1997 (Table 2) provides insight into the transport of herbicides in runoff. The average residual cyanazine concentrations, weighted by the relative area of the two sampling positions, were 55 μg kg^{-1} for the broadcast treatments and 21 μg kg^{-1} for the band treatments. These values are greater than the cyanazine concentrations in eroded sediment in the last runoff event in 1997 ($P = 0.031$). This would support the hypothesis that desorption of herbicide from the eroded sediments during transport or sample storage is likely and implies that reducing suspended sediment in runoff can reduce herbicide loss in the aqueous phase. However, more research is needed to separate this effect from other possible causes, such as mixing of sediment from below the 0- to 1-cm depth due to rill erosion.

CONCLUSIONS

Concentration and losses of alachlor and cyanazine in runoff were smaller with herbicide banding than with broadcast application. This occurred not only because of smaller application rates, but also because runoff amounts were smaller from band-treated plots due to greater between-row weed cover. Concentrations of the herbicides alachlor and cyanazine in runoff were largest for the first runoff event occurring after application and decreased with subsequent events. This decrease in concentration was related to cumulative rain since the herbicide application. Alachlor concentrations were less than cyanazine concentrations in runoff due to a greater degree of sorption and more rapid dissipation. Herbicide losses were dominated by the water phase and comprised 88% of the total loss of alachlor and 97% percent of total cyanazine losses. When herbicides were broadcast-applied, tillage practice affected the loss of herbicides in runoff and followed the order: moldboard plowed > chisel plowed > ridge till. For the banded treatments, losses were small for all tillage systems. Thus, either conservation tillage or herbicide banding were effective in reducing the off-site transport of herbicides. Concentrations of cyanazine in the soil at the end of the study period were greater than the concentrations of cyanazine measured in suspended sediments from the most recent runoff, indicating that desorption of cyanazine from sediments in runoff during storage may be important.

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