Tillage and application effects on herbicide leaching and runoff

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Abstract

Herbicides are key products in sustaining agricultural production and, to minimize agro-environmental concerns regarding their use, continued assessment of their behavior under different management practices is required. Leaching and runoff losses of four herbicides applied preplant-incorporated (PPI) were evaluated in two tillage systems over a 3-year period (1989–1991). Scant leaching during the droughty 1991 growing season limited treatment evaluations to 2 years. Herbicides were applied at recommended rates (1.7 and 2.2 kg active ingredient (a.i.) ha⁻¹) to conventional tillage (CT) and mulch tillage (MT) corn (Zea mays L.) fields on Hagerstown silty clay loam (fine, mixed, mesic Typic Hapludalf). Tillage treatments were defined as moldboard plow–disk–harrow (CT) and single-disking (MT). During this study, CT followed 5 years of corn production in a comparable CT system on this site and, similarly, MT followed a 5-year no-tillage (NT) system. Herbicides were applied preemergence (PRE) to CT and NT in the 5-year study and preplant-incorporated (PPI) in this study. Herbicide mobility in subsurface drainage was evaluated from herbicide mass transported to pan lysimeters installed 1.2 m deep. Surface drainage losses of these chemicals were determined from residues in runoff collected with automated sampling and recording equipment.

Leachate volumes were greater from MT than CT in 1989 and 1990 and exceeded all seasonal losses during the previous 5 years under NT management. Comparisons of total seasonal leachate discharged to pan lysimeters within and among studies and herbicide mass leached showed that timing of leachate-inducing precipitation relative to herbicide application was the key factor in regulating herbicide translocation. Herbicide mass transported through the root zone averaged from less than 0.1% to 0.9% of applied rates in CT and from 1.4% to 5.1% in MT.

Leachate-availability of herbicide residues and extent of herbicide longevity in this soil under MT conditions were similar to previous findings under NT management. Despite these behavioral

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similarities for herbicides among tillages, herbicide mass discharged per unit of percolate was most often lower for MT compared with NT, particularly in early growing seasons of comparable precipitation. Thus, the PPI treatment in MT appeared to reduce leaching of these chemicals compared with PRE application in NT.

Runoff losses of PPI herbicides ranged from 0.35% to 0.77% of applied rates in CT and from 0.13% to 0.28% in MT. Losses of PRE-applied herbicides from NT averaged less than 0.1% of applied rates; maximum yearly losses ranged from 0.06% to 0.18%. Thus, the character of the disked, minimally tilled surface provided a level of impedance to runoff that was greater than achieved with the tilled surface on this 3 to 5% slope, but less than previously obtained with an untilled, mulch-covered surface.

Keywords: Leaching; Pan lysimeters; Runoff; Herbicides; Conventional tillage; Mulch tillage; No-tillage; Zea mays L.

1. Introduction

One basic thrust of agronomic research is to define best management practices for pesticide application in crop production systems that will maintain a high level of chemical efficacy without accentuating non-point source pollution of non-target areas. Since agricultural sustainability will continue to require the safe and proper use of pesticides, the effects of tillage system environments and pesticide application techniques on pesticide behavior and fate require further investigation.

The main pathways of non-point source pollution, surface and subsurface transport of pesticides are not mutually exclusive and abatement of pesticide concentration and mass in one pathway by some management scheme often exacerbates or provides little attenuation of pesticide residues in the other. Moreover, determining the transport process that has the greatest impact on water quality is difficult to assess since widely diverse opinions exist on which process may be more detrimental to water resources. Our research (Hall et al., 1991; Hall and Mumma, 1994) clearly demonstrated that environmental impact 'trade-offs' exist with different tillage practices. An untilled, mulched surface markedly reduced runoff of preemergence and postemergence applied herbicides, but its undisturbed topsoil matrix promoted more leaching of these chemicals, presumably by preferential macropore flow, as considerable evidence indicates (Edwards et al., 1989; Andreini and Steenhuis, 1990; Shipitalo et al., 1990). Conversely, the disrupted macropore matrix in a tilled surface limited herbicide leaching but the lack of mulch predisposed the surface to a greater loss of these chemicals in runoff water. Greater chemical loss in runoff water from tilled surfaces has been documented by Wauchope (1978).

The indigenous character of these tillage practices in our studies (Hall et al., 1991; Hall and Mumma, 1994) was consistent over 5 years for herbicide compounds representing different herbicide classes, namely, chloro-s-triazines, a substituted amide, and a benzoic acid derivative. Quality and quantity assessments of herbicide mobility varied between the two transport processes temporally and between and within herbicide classes. However, in a broad sense, each of these tillage environments influenced these processes uniformly on an annual basis in the well-drained soil. The net effect was greater losses from the untilled soil due to greater percolate discharge of chemicals.
In continuing studies on this same site, we chose an alternate approach to tillage and herbicide application practices in an attempt to identify a management scheme that harbored the best characteristics of conventional tillage (CT) and the conservation tillage (CnT) system, no-tillage (NT), in ameliorating herbicide transport. Several researchers (Baker and Laflen, 1979; Hall et al., 1983) showed that blending of herbicides within the topsoil effectively reduced losses of these chemicals in runoff water. However, little attention has been given to the effect of herbicide incorporation within the topsoil surface on transport of these chemicals by leaching. Consequently, the previous 5 year NT system was converted to mulch tillage (MT) and the CT area was left intact. Coupled with tillage rotation, herbicides were soil surface incorporated before planting, permitting the objective evaluation of this management practice on surface and subsurface losses of herbicides in the two tillage systems. It was postulated that these changes would have several effects: firstly, the MT system may function more like CT since macropore continuity would be disrupted in early season, thereby altering prominent pathways for rapid leaching of herbicide residues from the surface when they are most concentrated; secondly, random distribution of preplant-incorporated herbicides through a greater topsoil volume compared with a concentrated zone on a NT surface may lead to reduced herbicide load in leachates; lastly, the MT area would possess a surface ‘roughness’, delineated by the randomness of corn stover residue incorporation, that could provide a level of impedance to runoff flow not markedly different from that achieved with the NT surface. Consequently, the expected net effect of rotating tillage from NT to MT with herbicide incorporation would be reduced leaching load of the chemicals without excessively increasing their losses in runoff.

2. Materials and methods

This research was conducted from 1989 through 1991 at the Russell E. Larson Agricultural Research Center, Rock Springs, Pennsylvania, on a Hagerstown silty clay loam (fine, mixed, mesic Typic Hapludalf). The study site (0.52 ha) was separated equally into two tillage treatments that had been maintained as distinct leachate and runoff sampling areas since 1984. Each area contained three excavated and framed pits that individually housed three pan lysimeters at a depth of 1.2 m to collect root zone percolates. Areas were segregated from each other and surrounded by earthen-dikes to entrap and facilitate collection and measurement of runoff water using an HS-flume and automated recording and sampling equipment positioned at the natural drainage outlet of each area. Land slope, determined from a topographic survey, ranged from 3 to 5% within each area. A comprehensive discussion of the site, including soil description, equipment placement and installation, and previous soil, crop and herbicide management practices and sampling procedures are cited elsewhere (Hall et al., 1989, 1991).

Tillage practices maintained on these separate areas from 1984 through 1988 were CT and NT. The CT area was moldboard plowed, disked and spring-tooth harrowed. The NT surface was disturbed only by the fluted-coulter on the NT-planter. Four herbicides were preemergence (PRE) applied to corn on each tillage area at recommended rates. These chemicals included simazine (6-chloro-N,N'-diethyl-1,3,5-triazine-
2,4-diamine); atrazine (6-chloro-N-ethyl-N'-(1-methylethyl)-1,3,5-triazine-2,4-diamine); cyanazine (2-[[4-chloro-6-(ethylamino)-1,3,5-triazin-2-yl]amino]-2-methylpropanenitrile) and metolachlor (2-chloro-N-(2-ethyl-6-methylphenyl)-N-(2-methoxy-1- methylethyl) acetamide). Application rates were 1.7 kg active ingredient (a.i.) ha\(^{-1}\) (simazine, atrazine) and 2.2 kg a.i. ha\(^{-1}\) (cyanazine, metolachlor). In addition, dicamba (3,6-dichloro-2-methoxybenzoic acid) was postemergence applied at 0.56 kg a.i. ha\(^{-1}\) and the insecticide, carbofuran (2,3-dihydro-2,2-dimethyl-7-benzofuranyl methylcarbamate), was row-applied (1.0 kg a.i. ha\(^{-1}\)) at planting.

In 1989, the NT area was converted to a MT system. Mulch tillage consisted of disking approximately 15 cm deep. Percent corn stover residue remaining on the surface after disking was not determined, however, cover averaged 42% in line transect measurements after similar MT treatment of the same area in current studies. The CT area was managed as previously described. The same pesticides and rates were applied with the exception that the insecticide, terbufos (S-[[1,1-dimethylethyl]thiomethyl]O,O-diethyl phosphorodithioate), replaced carbofuran at the same rate. Prior to herbicide application, the pit and flume areas were sealed with plastic to prevent herbicide contamination of the collection vessels by direct application or drift. The four herbicides previously PRE applied were preplant-incorporated (PPI) in both tillage areas with a single pass of a disk set approximately 8 cm deep. Herbicides were applied on 25 May 1989 and 24 May 1990.

Both areas were fertilized and limed according to annual soil test recommendations. Corn was planted to achieve a population of 66,000 plants ha\(^{-1}\). Areas between pit frames and runoff flumes that could not be accessed by normal farm equipment were fertilized and planted by hand at the same rates to insure that uniform soil fertility conditions and plant populations existed throughout the research site. Rain was recorded on site from April 1 through October 31 of each year. During the remaining months, data were obtained from a meteorological station located approximately 1.5 km from the research site. Pan lysimeter leachates were collected throughout the entire year whenever rain or snow-melt was of sufficient magnitude to produce a leaching event. Leachate volumes were recorded and subsampled. Herbicide mass leached was calculated from herbicide concentrations in water and corresponding percolate volume. These data were used to calculate mean areal leaching discharge and percentage loss of herbicides within the corn root zone of each tillage area. Runoff water was sampled after each erosion event from the time of herbicide application through September 30. Herbicide concentrations in these samples and total recorded runoff volume were used to calculate total herbicide losses during the season. Water samples were stored at \(-14^\circ\)C before extraction and analysis.

Although results and discussion will focus solely on the PPI chemicals, a method was developed that permitted the simultaneous extraction of all six pesticides (Watts et al., 1994). This method utilizes two types of solid phase extraction columns, a reverse phase and an anion exchange column connected in series to extract all six compounds from a single sample. After elution of the reverse phase column, a gas chromatograph equipped with a N–P detector was used to analyze for the chloro-s-triazines (simazine, atrazine, cyanazine) and metolachlor. Detectable limits were 3 \(\mu\)g l\(^{-1}\) for the triazines and 6 mg l\(^{-1}\) for metolachlor. Grand mean percent recoveries for water samples were atrazine
Herbicide residues detected in leachates and runoff water were not corrected for recoveries. Compilation of means and mean separation between tillage systems (pooled, two sample t-test) were determined on leaching data using the programs of the SAS Institute, Inc., Cary, NC, and Minitab, Inc., State College, PA, as recommended by the Statistical Consulting Center of the University.

3. Results and discussion

Although environmental factors vary annually and can influence degradation, persistence and mobility of herbicides within and from soils, periodic reference and association is made between results achieved during this research and the previous 5-year study. Particular focus will be given to the CnT practices and comparisons will be made, in general, among tillage systems over comparable sampling periods and within specific time intervals. Soil spatial variability and the limited number of observations between lysimeter-sampling points placed limitations on the degree of statistical significance achieved for mean comparisons among tillage areas. For most means, the confidence intervals were less than 73% ($P < 0.27$). These statistical results were disappointing since many comparisons among tillage systems in the 5-year study were significant at confidence intervals of 90% or greater. Nonetheless, substantial ‘differences’ noted among tillage systems will be discussed.

3.1. Precipitation and leaching summary

Total rain recorded in 1989 (98.3 cm) was comparable to the 30-year average (97.9 cm) for this area. In 1990, precipitation totals exceeded the 30-year average by 25 cm, but 1991 precipitation was 20 cm less than the norm. Herbicides are most susceptible to leaching or runoff transport during the early growing season from herbicide application through July (Wauchope, 1978; Triplett et al., 1978; Hall et al., 1983, 1991). Within this early period, total rainfall was 39.2 cm in 1989 and 23.6 cm in 1990. These amounts accounted for approximately 58% and 29% of the total precipitation recorded from May through December (Figs. 1 and 2). An additional 38.6 cm or 48% of the total precipitation for this 8-month period occurred during August through October 1990, which exceeded the 30-year average for this locale. In contrast, the 1991 season was very dry and was not a good year for herbicide transport studies. From herbicide application in May through September, 30.5 cm of rain was measured. Three leachate samples were collected during this interval. Most of the leachates collected were discharged prior to herbicide application or from October through December. Comparatively few herbicide residues were detected in leachates, concentrations were minimal, total losses were infinitesimal and no runoff events occurred. Consequently, only results for 1989 and 1990 will be presented.

In 1989, 15 leaching events yielded 122 pan lysimeter samples; in 1990, 22 events produced 191 samples. In general, leachate discharge was substantially greater under MT than CT conditions during both years (Figs. 1 and 2). Also, leachate discharge from both tillage systems closely followed the rainfall distribution during May through July.
Fig. 1. Total monthly leachate volume and precipitation recorded after herbicide application in 1989 and the 30-year average monthly precipitation for this region. Where no leachate is delineated, none was collected.

and October through November during each year. Greater leachate discharge in May 1990 compared with May 1989 after the same amount of precipitation may have been related to antecedent soil moisture since total precipitation for the month was greater in 1990 (14.3 cm) than in 1989 (11.7 cm).

3.2. Herbicide mass in root zone leachates

In general, herbicide mass leached during the 1989 and 1990 collection seasons was coincident with leachate discharge and was greater from MT than CT management.

Fig. 2. Total monthly leachate volume and precipitation recorded after herbicide application in 1990 and the 30-year average monthly precipitation for this region. Where no leachate is delineated, none was collected.
Fig. 3. Total herbicide mass leached after herbicide application in 1989. Where leachate was collected and no herbicide residue is delineated, none was detected.

(Figs. 3 and 4). The most notable variance to this trend occurred in May 1989 where herbicide residues were only detected under CT conditions in the small leachate volume collected. Mean areal losses of the three chloro-s-triazines were comparable in tilled soil during 1989, ranging from 1530 to 1570 μg m⁻², which represented losses of 0.69% to 0.93% of rates applied (data not presented). Triazine losses were more variable under MT conditions (6813 to 8503 μg m⁻²; 3.0% to 5.1%). These herbicides also exhibited a higher leaching potential than metolachlor, which was displaced at levels of 0.37% and 2.46% of the rates applied to CT and MT, respectively.

Leaching trends noted in 1989 for all herbicides continued in 1990. Herbicide mass displaced was less, particularly in CT, where losses were reduced by approximately 79% to 94% for all herbicides compared with mass leached in 1989. Likewise, herbicide mass leached from MT in 1990 was 8% to 44% less than 1989 leaching losses. Only cyanazine leached in amounts slightly more than loads measured in 1989. Although total leachate discharge in 1990 exceeded 1989 levels and substantially so under MT conditions (Figs. 1 and 2), the dominant early season rainfall in 1989 and substantial leachate discharge in June 1989 contributed to the greater herbicide loads with both tillage practices during this year.

Herbicides were generally more 'leachate-available' under MT than CT conditions regardless of year. The most leachate-available chemicals in this soil were also the most persistent compounds, atrazine and simazine. Their availability and longevity were expressed by their dominance in early season leachates and also by their late season
Fig. 4. Total herbicide mass leached after herbicide application in 1990. Where leachate was collected and no herbicide residue is delineated, none was detected.

Discharge in both tillage systems (Figs. 3 and 4). Residues of these chemicals in leachates were dominant in MT, especially during September through December 1990 when rainfall for the most part exceeded the long-term average for this region. During this period also, 1- to 2-μg residues of the less persistent cyanazine were also detected in leachates from both tillages, despite considerable discharge of this compound from MT during the first 3 months. These same characteristics were noted for atrazine and simazine under NT management (Hall et al., 1991) and appear to be a consistent feature of CNt systems.

Considerable percolation within the MT root zone was contrary to theoretical considerations that a minimal tilling of the NT surface would disrupt macropores and limit water translocation through this disturbed matrix, particularly in early season. On the other hand, several researchers (Quisenberry and Phillips, 1976; Phillips et al., 1989) identified macropore flow beneath tilled matrices and showed that water under negative pressure can enter simulated macropores after a continuous water film is established on macropore walls. Consequently, the substantial percolate volumes collected in 1989 (198 l) and 1990 (454 l) from MT, which exceeded the volumes (5 to 114 l) obtained in previous seasons (1984 through 1988) of NT management (Hall et al., 1991), may be largely attributed to macropore flow. Phillips et al. (1989) also reasoned that soluble compounds in water entering a tilled surface may equilibrate with this entire soil matrix, thus, soluble compounds in water entering macropores beneath a tilled layer may
provide a greater solute concentration than in water flowing in macropores open to the soil surface, wherein solute would originate from the soil surface or from macropore surfaces. Based on the leaching patterns observed on this site in 1989 and 1990, it appeared that this concept aligns more with herbicide solute transport in a minimally tilled surface than in a moldboard-plowed, disked and harrowed surface. Moreover, movement of water and herbicide solute into untilled soil surfaces also maintained higher subsurface loading of herbicides than in tilled soil (Hall et al., 1991). Percolate volume and herbicide load from the CT system varied yearly with seasonal distribution and frequency of precipitation but absolute chemical mass leached was always less than the mass transported from MT management (Figs. 3 and 4) and from NT management (Hall et al., 1991). Depth and manner of tilling did not vary during the last 7 years of CT management. Thus, matrix effects on herbicide solute 'retention' and transport within a CT surface compared with a MT surface appeared to be different.

3.3. Areal losses among tillage practices

Direct rotation of NT to MT eliminated the opportunity to make yearly comparisons of herbicide mobility between these different CnT systems. In retrospect, having a NT system of the same age for comparison with the converted NT system would have been ideal since this area would have served as a control in evaluating the hypothesized effects of tillage disruption and chemical incorporation on herbicide mobility. Soil properties and characteristics in continuous, long-term tillage practices have been evaluated but the effects of tillage rotation on crop production and the time required to achieve a 'fixed' set of physico-chemical characteristics within the new system is less understood. Some farmers practicing NT corn production will intuitively rotate this system to CT for a 1-year to 2-year period, reasoning that this change improves the physical nature of the soil and aids in weed and insect control. Since our study area contained only two confined tillage systems, rotation choices to evaluate the hypotheses were limited. Converting from 5 years of NT to MT and continuing with the 5-year-old CT system in place seemed to be the logical choice. Conversion of the CT area to NT may not have provided the same matrix effects typified by the 'aged', 5-year NT system (Dick and Daniel, 1987; Edwards et al., 1988). In the absence of an intact NT system, atrazine and cyanazine leaching in MT was compared with that achieved on the same site in the previous 5 years. Although tillage rotation had little effect on altering percolation through the MT solum to 1.2 m compared with a NT system, prescribed differences in application management appeared to affect the magnitude of leaching losses within CnT and CT management when compared among years.

Rainfall from application in May through July was comparable for 1984, 1985 and 1990 (26.0, 26.7, 23.6 cm; Figs. 2 and 5). Likewise, comparable totals were recorded for 1986 and 1989 (34.6 and 39.2 cm; Figs. 1 and 5). Similarities notwithstanding, total recorded leachate for this period was considerably less for NT than MT conditions, regardless of year (Table 1). Thus, based upon leachate discharge during the early period, herbicide mass leached in 1989 and 1990 should have surpassed loads recorded during the 5 years of NT management.

Atrazine mass leached in 1986 during the early period exceeded loads recorded in
Table 1
Total leachate measured in CT and CnT from herbicide application through December of each year

<table>
<thead>
<tr>
<th>May</th>
<th>CT</th>
<th>NT/MT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.3</td>
<td>0.9</td>
</tr>
<tr>
<td>June</td>
<td>(1)</td>
<td>0.3</td>
</tr>
<tr>
<td>July</td>
<td>(1)</td>
<td>0.3</td>
</tr>
<tr>
<td>3-month totals</td>
<td>0.6</td>
<td>2.1</td>
</tr>
<tr>
<td>Yearly</td>
<td>1.7</td>
<td>6.7</td>
</tr>
<tr>
<td>Early season losses (%)</td>
<td>35.3</td>
<td>31.3</td>
</tr>
</tbody>
</table>

a Values reported for May represent the period from herbicide application through 31 May of each year.
b No leachate recorded during this time.
c From herbicide application through 31 December.
d Percent of total yearly losses collected from herbicide application through 31 July.
1989 and 1990; also, losses in 1985 exceeded those obtained in 1989 (Table 2). During these 4 years, 83 to 95% of the total atrazine losses occurred during the early growing season. Considering that rainfall was below normal in early 1990 (Fig. 2) and only 18% of the total leachate discharge was recorded early (Table 1), atrazine yield (50 μg) after July in 374 l of percolate was minuscule (Table 2). In comparison, an additional 40 l in 1985 and 18 l in 1986 yielded 96 and 53 μg, respectively. In 1989, 74% of the total leachate was measured in early season and an additional 51 l discharged through December yielded 112 μg of atrazine. Given that early season leaching magnitude would affect leaching losses later, the ratio of atrazine mass transported to measured root zone leachate for this period was greater in 1985 and 1986 than 1989 and 1990 (Tables 1 and 2). With few exceptions, greater mass to leachate ratios were also obtained in the other seasons of NT management compared with MT conditions. In summary, where rainfall was comparable during the early period but percolate transmission varied between MT and NT conditions, albeit among studies, atrazine mass transported was not predictable. If gravitational water in macropores at the surface or beneath the disked layer was principally involved in herbicide solute transport, then it may be concluded from a comparison of CN1T systems that the PPI treatment reduced atrazine mass leached. These suggestions were strengthened by results for cyanazine mobility. The higher water-solubility of cyanazine compared with atrazine was expressed by the greater cyanazine load discharged during the early seasons of 1985 through 1990 (Tables 2 and 3). However, the leachate-availability of cyanazine, as expressed by the transported mass to leachate ratio, was greater in NT during 1985 through 1988 than in MT during 1989 and 1990 (Tables 1 and 3), supporting the premise that areal losses of this chemical were reduced by the PPI treatment.

Areal losses of atrazine and cyanazine in CT were also influenced, in part, by the PPI treatment. Leached quantities of these herbicides in 1989 were greater than in any other
Table 2
Comparison of early season and yearly atrazine losses in leachate from CT and CN\textsuperscript{T} following PRE application in 1984 through 1988 and PPI in 1989 and 1990

<table>
<thead>
<tr>
<th></th>
<th>CT</th>
<th>NT/MT</th>
</tr>
</thead>
<tbody>
<tr>
<td>May ( a ) (( \mu g ))</td>
<td>- ( b )</td>
<td>-</td>
</tr>
<tr>
<td>June (( \mu g ))</td>
<td>1.3</td>
<td>58.3</td>
</tr>
<tr>
<td>July (( \mu g ))</td>
<td>0.5</td>
<td>51.7</td>
</tr>
<tr>
<td>3-month totals (( \mu g ))</td>
<td>1.8</td>
<td>110.0</td>
</tr>
<tr>
<td>Yearly totals ( c ) (( \mu g ))</td>
<td>2.3</td>
<td>110.2</td>
</tr>
<tr>
<td>Early ( d ) season losses (%)</td>
<td>78.3</td>
<td>99.8</td>
</tr>
</tbody>
</table>

\( a \) Values reported for May represent the period from herbicide application through 31 May of each year.

\( b \) No leachate recorded during this time.

\( c \) From herbicide application through 31 December.

\( d \) Percent of total yearly losses collected from herbicide application through 31 July.
Table 3
Comparison of early season and yearly cyanazine losses in leachate from CT and CnT following PRE application in 1984 through 1988 and PPI in 1989 and 1990

<table>
<thead>
<tr>
<th></th>
<th>CT</th>
<th>NT/MT</th>
</tr>
</thead>
<tbody>
<tr>
<td>May a (μg)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- b</td>
<td></td>
</tr>
<tr>
<td>June (μg)</td>
<td>1.6</td>
<td>51.3</td>
</tr>
<tr>
<td>July (μg)</td>
<td>0.1</td>
<td>79.6</td>
</tr>
<tr>
<td>3-month totals (μg)</td>
<td>1.7</td>
<td>80.9</td>
</tr>
<tr>
<td>Yearly c totals (μg)</td>
<td>1.7</td>
<td>80.9</td>
</tr>
<tr>
<td>Early d season losses (%)</td>
<td>100.0</td>
<td>100.0</td>
</tr>
</tbody>
</table>

a Values reported for May represent the period from herbicide application through 31 May of each year.
b No leachate recorded during this time.
c From herbicide application through 31 December.
d Percent of total yearly losses collected from herbicide application through 31 July.
season (Tables 2 and 3). However, ratios of herbicide mass transported to percolate discharge in early season were greater from PRE-applied chemicals in 1985 and 1986 compared with PPI chemicals in 1989 and 1990. Ratios were also higher in 1984, 1987 and 1988 compared with 1990. Thus, blending of atrazine and cyanazine into the topsoil by disking appeared to reduce their leachability in CT management.

Collectively, these results demonstrated that a NT system rapidly transmits herbicides through the root zone during early season rainfall as other work demonstrated (Isensee et al., 1990; Shipitalo et al., 1990; Hall et al., 1991). Herbicide solute within the micropore network of this system may subsequently diffuse and merge with macropore water and move preferentially and/or move by diffusion and displacement through the micropore matrix (Germann et al., 1984; Shipitalo et al., 1990), accounting for herbicide load discharged in late season. In previous studies (Hall and Mumma, 1994) on this Hagerstown silty clay loam, dicamba residues were detected in PL leachates from CT and NT systems as late as 6 months after application during several seasons. Entrapment and translocation within the micropore matrix of this well-drained soil were postulated as being critical factors involved in the atypical residence time and late season ‘breakthrough’ of this highly soluble, anionic, low persistence herbicide. Additionally, the hydrophobic organic matter that accumulates on the NT surface and within earthworm burrows can aid in the preferential movement of water and dissolved solutes under dry soil conditions with radial capillary movement of water out of earthworm burrows and into the surrounding micropore matrix occurring with prolonged exposure to water (Edwards et al., 1989). Stehouwer et al. (1993) showed that sorption of atrazine was increased on the organic C-enriched linings of macropore burrows created by the earthworm, Lumbricus terrestris L., compared with sorption in the bulk soil. Thus, retention and release of residual herbicides in these large biopores can regulate the leachability and distribution of these chemicals throughout the entire pore network.

On the other hand, random orientation and anchoring of crop residues (corn stover) in a CnT surface such as MT provide micro-depressional topography that pools surface water reducing runoff potential, yet also provide ‘conduits’ for water entry and flow between the organic litter and aggregated topsoil (Onstad and Voorhees, 1987). A micro-saturated soil zone at the interface between a minimally tilled and untilled matrix in the upper regions of the soil profile may provide for water entry into macropores beneath this zone despite having a water-unsaturated pore ‘column’ above this zone. Likewise, water under negative pressure may enter macropores in response to a water film on macropore walls (Phillips et al., 1989). These conditions may permit as much or more drainage of water through macropores beneath minimally tilled layers as through the same sized pores connected to the soil surface. Consequently, if these characteristics prevailed under MT management, accounting for the large amount of percolation in this system, reduced chemical mobility compared with NT was a function of the PPI treatment.

3.4. Herbicides in runoff water

Seven runoff events were recorded during the 1989 growing season; no runoff occurred in 1990. On a seasonal basis, total runoff volume was 336 and 229 m³ ha⁻¹.
Table 4
Mean areal and percent losses of herbicides in runoff water

<table>
<thead>
<tr>
<th></th>
<th>1989</th>
<th>1985 to 1988</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CT (g ha⁻¹)</td>
<td>MT (g ha⁻¹)</td>
</tr>
<tr>
<td>Simazine</td>
<td>9.2 a</td>
<td>3.7</td>
</tr>
<tr>
<td>Atrazine</td>
<td>12.9</td>
<td>4.1</td>
</tr>
<tr>
<td>Cyanazine</td>
<td>8.7</td>
<td>3.8</td>
</tr>
<tr>
<td>Metolachlor</td>
<td>7.8</td>
<td>3.0</td>
</tr>
</tbody>
</table>

a Calculated from water volume and mean herbicide concentrations for each erosion event and the total number of events within each growing season.

b Calculated from areal losses of herbicides and herbicide rates applied.

' Mean (maximum) percent runoff losses in the previous study.

under CT and MT management, respectively. The largest single runoff event, 25 days after herbicide application, produced 99 m³ ha⁻¹ from the CT area and 66 m³ ha⁻¹ from the MT area. Therefore, MT management reduced total seasonal runoff and maximum event losses by one-third compared with CT. In the previous study (Hall et al., 1991), NT reduced seasonal runoff by 54 to 78% compared with CT during 1986 through 1988. Consequently, in this single season, the partially mulch-covered, rough surface of MT was not as effective in reducing runoff as the mulch, untilled surface.

Total areal and percent herbicide losses in runoff were higher under CT than MT conditions (Table 4). Maximum percent losses were 0.77% for atrazine under CT and 0.28% for atrazine under MT. Although percentage losses represented very low herbicide amounts, one may conclude that the PPI treatment did not effectively alter runoff losses of these chemicals from CT compared with maximum quantities transported in runoff from PRE-applied chemicals in the previous study. Other work in Pennsylvania showed that runoff losses of PPI atrazine in CT were reduced compared with PRE-application, however, the incorporation technique differed (Hall et al., 1983). On the other hand, since maximum herbicide losses from CnT systems were not widely divergent and were generated from 80 m³ ha⁻¹ (NT) and 229 m³ ha⁻¹ (MT) of runoff, it may be concluded that herbicide incorporation in MT compensated for the reduction in surface mulch cover in this system compared with maximum cover under NT management.

4. Summary and conclusions

Minimum tillage of a previously untilled Hagerstown silty clay loam surface after 5 years of corn production had little effect on reducing the volume of percolate through the solum as postulated. Leachate-availability of herbicides was greater under MT than CT conditions, consequently, greater mass yield was detected yearly, in general, from this CnT system. Herbicide load in percolate was greater for the chloro-s-triazines (atrazine, simazine and cyanazine) than metolachlor and was more dependent on the amount of leachate-inducing precipitation within the first 2 to 3 months after application than in total seasonal precipitation. The characteristic herbicide availability and extent of
herbicide longevity found under MT conditions were similar to herbicide behavior observed previously under NT conditions on this soil. Despite similarities in herbicide behavior among the CnT practices, herbicide load discharged to pan lysimeters per unit of percolate was most often lower for MT compared with NT, particularly when early season herbicide loads were compared among years of similar rainfall. As a consequence, it was concluded that incorporating sprayed herbicides preplant within the MT system appeared to reduce the transport of these chemicals in root zone leachates compared with preemergence application in NT.

Additionally, the partially mulched character of the MT surface provided a level of impedance to runoff flow that was greater than achieved in an adjacent CT system, but probably less than expected from a NT system based upon an intuitive evaluation from previous results in Pennsylvania and elsewhere. Since erosional losses of herbicide mass principally occur in the aqueous phase, any management scheme that reduces surface drainage can provide a significant element in conservation and retention of applied herbicides. The disked, MT system with PPI herbicides exhibited this capability.

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