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DIVISION S-6—SOIL & WATER MANAGEMENT & CONSERVATION

Herbicide Leaching under Tilled and No-Tillage Fields

Timothy J. Gish,* Adel Shirmohammadi, Raviraj Vyravipillai, and Brian J. Wienhold

ABSTRACT

The effect of no-tillage practices on water quality exiting the root zone of deep, well-drained fields is largely unknown. This project was initiated to determine herbicide leaching characteristics as influenced by tillage practice and herbicide formulation. The research site consisted of four adjacent (0.25-ha) fields, two fields each dedicated to either tilled or no-tillage management. One field in each tillage regime received a controlled-release formulation of atrazine [6-chloro-N-ethyl-N'-(1-methylethyl)-1,3,5-triazine-2,4-diamine] and alachlor [2-chloro-N-(2,6-diethylphenyl)-N-(methoxymethyl)-acetamide, starch encapsulated], while the others received standard herbicide formulations of atrazine and alachlor. Both herbicide formulations were annually applied at the same rate: 1.7 kg ha⁻¹ for atrazine and 2.8 kg ha⁻¹ for alachlor. Atrazine, deethylatrazine [DEAT; 6-chloro-N-(1-methylethyl)-1,3,5-triazine-2,4-diamine], alachlor, and Br⁻ concentrations were monitored with 12 suction lysimeters (six each at 1.5- and 1.8-m depths) in each field. Alachlor was detected in <3% of all samples collected, regardless of tillage practice or herbicide formulation, while atrazine was detected in >41% of the samples. Under no-tillage, atrazine was detected in <28% of the samples with <13% exceeding the U.S. Environmental Protection Agency Health Advisory level of 3 µg L⁻¹ atrazine. Under tilled conditions, 53% of the samples contained atrazine, with 35% exceeding 3 µg L⁻¹ atrazine. Averaged atrazine metabolite concentration of DEAT under no-tillage was 0.52 µg L⁻¹ vs. 0.39 µg L⁻¹ for tilled fields. Similar Br⁻ transport between tillage practices and reduced atrazine levels under no-tillage fields suggest that no-tillage management, on deep well-drained soils, can have a positive impact on groundwater quality.

HERBICIDE ENVIRONMENTAL IMPACT is governed to a large extent by soil hydraulic characteristics and the potential of the soil to degrade complex organic compounds. Tillage practice can modify soil chemical properties by influencing the amount and type of organic matter critical in degrading herbicides (Stevenson, 1972; Stearman et al., 1989) and by altering the physical properties that affect surface and subsurface hydrology (Burwell et al., 1966; Allmaras et al., 1967; Philips and Philips, 1984).

In no-tillage, the soil surface is minimally disturbed and decaying plant residue from the previous crop covers at least 30% of the surface. During chemical application, plant residues can intercept much of the herbicide, affecting both volatilization and dissipation. Wienhold and Gish (1994) found that although volatilization losses were initially greater under no-tillage, cumulative volatilization losses under no-tillage during a 35-d period were about one-half those observed under conventional tillage.

The reduction in herbicide volatility was attributed to herbicide wash-off from plant residues. Once the herbicides are below plant residues, the plant mulch reduces air movement and reduces soil temperature. Since soil organic matter has a tendency to increase in surface layers of long-term no-tilled plots relative to tilled plots (Blevins et al., 1977, 1983), adsorption and herbicide degradation may also be affected. In evaluating herbicides in 17 locations in North Carolina, Upchurch et al. (1966) found that the soil organic fraction accounted for 66% of the variation of herbicide activity. Tyler et al. (1983) reported increases in surface soil organic matter levels after 2 yr of no-till, compared with tilled soils, while Stearman et al. (1989) observed a decrease in herbicide activity in tilled soils. Slack et al. (1978) studied tillage and pH effects of herbicide activity in field and greenhouse experiments and reported less persistence under no-till corn (*Zea mays* L.).

Tillage reduces surface residues, weakens soil structure, leads to the formation of soil crusts, decreases water infiltration, and enhances runoff (Rawls et al., 1980; Freebairn et al., 1989). Increased infiltration under no-till can also lead to enhanced chemical transport via preferential flow to shallow perched groundwater (Isensee et al., 1990; Gish et al., 1991a). However, little is known about the potential accumulation of organic matter and microorganisms in the preferential flow pathways and its effect on water quality underlying a well-drained field site.

Herbicide formulations may also affect environmental impact by altering persistence and mobility. Starch encapsulation is a controlled-release formulation that Schreiber et al. (1987) proposed could reduce both volatilization and leachate losses. Gish et al. (1991b) also observed a reduction in starch-encapsulated atrazine leachate concentrations from shallow no-till soil cores compared with technical-grade atrazine.

The potential for herbicide adsorption and potential enhanced biological activity in the preferential flow pathways may make no-tillage practices attractive for reducing herbicide leachate losses. The purpose of this study was to compare herbicide field-scale leachate levels below the root zone as influenced by tillage practice and herbicide formulation.

MATERIALS AND METHODS

The research site (Fig. 1) is located at the Maryland State Extension Farm in Upper Marlboro, MD. The site consists

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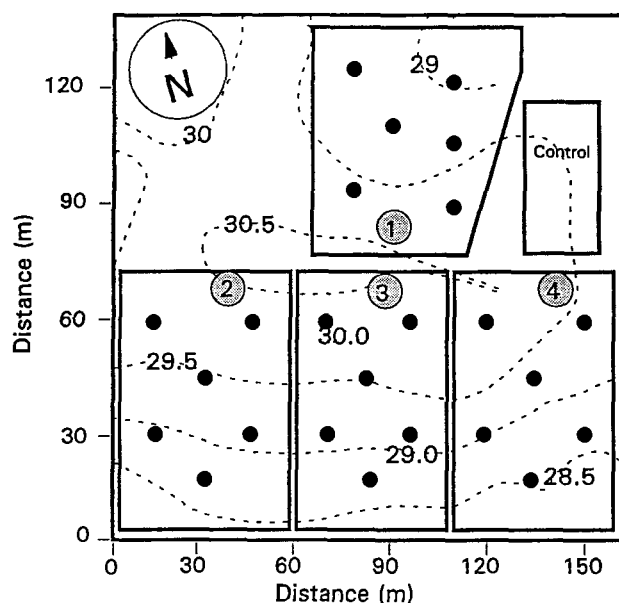


Fig. 1. Topographic representation (meters above mean sea level) of field site: Field 1, no-till, commercial herbicides; Field 2, no-till, starch-encapsulated herbicides; Field 3, tilled, commercial herbicides; and Field 4, tilled, starch-encapsulated herbicides. Each dot represents the location of a pair of suction lysimeters.

of four ≈ 0.25 -ha topographically bounded fields. In 1989, the entire research site was tilled and berms established around each field. In 1990, tillage practices were initiated with Fields 1 and 2 under no-till management and Fields 3 and 4 under tillage. All tillage systems were under continuous corn production, and rye (*Secale cereale* L.) was planted in the fall as a winter cover crop. The two tilled fields were plowed to ≈ 17 cm every spring, incorporating corn and rye plant residues, and subsequently culti-packed in preparation for planting. Except for the use of a no-till drill at planting, the no-tillage fields were not disturbed. In the no-tillage fields, rye was cut but left on the surface.

In 1990, six pairs of suction lysimeters were installed in each field between 1.5 and 1.8 m (dots in Fig. 1) to evaluate solution-phase concentrations of agricultural chemicals below the active root zone. Fields 1 and 3 received a standard commercial formulation of atrazine and alachlor. Fields 2 and 4 received a controlled-release, starch-encapsulated formulation of atrazine and alachlor. Atrazine and alachlor had not been applied to this site prior to 1990. Application rates were $1.7 \text{ kg a.i. ha}^{-1}$ for atrazine and $2.8 \text{ kg a.i. ha}^{-1}$ for alachlor (Table 1). The three herbicide application dates were 1 June 1990, 5 June 1991, and 1 June 1992. To evaluate water movement through the soil profile, a single application of Br^- (80 kg ha^{-1}) was applied with the herbicides in 1991. Although the chemical treatments were initiated in 1990, all of the suction lysimeters were not installed and functional until the end of 1990. Soil cores were periodically removed to a depth of 1.1 m during this study but were reported earlier (Gish et al., 1994).

The experimental site is on an Alfic Normudult (loamy, mixed, mesic) with 0 to 2% slope. Because the surface soil is periodically limed, the pH is ≈ 6.1 to 6.5 for the top 10 cm but becomes increasingly acidic with depth. The soil surface is a fine sandy loam and gradually becomes a sandy clay at $\approx 1 \text{ m}$ (Fig. 2). Although no mottling is present in the top 1.1 m, soil coring revealed numerous small cemented granules at 1 m. Deep coring ($\approx 13 \text{ m}$) for installation of deep wells in 1991 indicated no impermeable boundaries restricting water

Table 1. Tillage and herbicide formulation treatments.

Field	Tillage treatment	Herbicide treatment			
		Herbicide	Formulation†	Form as applied	Year
1	No-till	Atrazine	F	Spray	1990, 1991, 1992
		Alachlor	F	"	1990
		Alachlor	FE	"	1991, 1992
2	No-till	Atrazine	SE	Granular	1990, 1991, 1992
		Alachlor	SE	"	1990, 1991, 1992
3	Conventional	Atrazine	F	Spray	1990, 1991, 1992
		Alachlor	F	"	1990
		Alachlor	FE	"	1991, 1992
4	Conventional	Atrazine	SE	Granular	1990, 1991, 1992
		Alachlor	SE	"	1990, 1991, 1992

† F = flowable, FE = flowable encapsulated, SE = starch-encapsulated. In 1990, the commercial formulation used was a combined premixture of alachlor (as Lasso) with atrazine (as Attrex 4L), Monsanto Co., St. Louis, MO; in 1991, the commercial formulation Bullet (combined mixture of microencapsulated flowable alachlor and flowable atrazine) was used.

or chemical movement to the permanent aquifer located at 12 m. Typical lysimeter installation and textural horizons are also shown in Fig. 2.

Solution sampling occurred after each rain event $\geq 1 \text{ cm}$. Twenty-four hours after a rain event, lysimeters were pumped to dryness by applying suction (-0.12 kPa). Suction was applied a second time and samples for quantitative analysis were collected in glass bottles. Average sample volumes for the 2-yr period was 0.092 L for no-tillage and 0.094 L for the tilled fields. Solution samples were stored at 4°C until Br^- and herbicide concentrations were determined. Although each solution sample was analyzed separately, chemical concentration data from the 1.5- and 1.8-m depths for a particular field treatment were not significantly different and were thus combined to obtain field averages and to establish confidence limits on the data.

Bromide was determined by removing a 5-mL aliquot from the lysimeter sample, passing the sample through a $0.45\text{-}\mu\text{m}$ filter, and quantifying by ion chromatography. Operating conditions for the ion chromatograph were a mobile phase of 1.0 mM potassium hydrogen phthalate titrated to pH 6.5 with lithium hydroxide (Gish and Schoppet, 1989) at a low rate of 1.2 mL min^{-1} , an anion analytical column (Waters Associates, Milford, MA)¹, and sample injection volumes of $100 \mu\text{L}$ each. Detection limits for Br^- were 0.05 mg L^{-1} .

After an aliquot of solution was removed for Br^- determination, atrazine and alachlor were determined from the remaining solution. Atrazine, DEAT, and alachlor were isolated from the solution sample by solid-phase extraction, using a Waters C-18 Sep-Pak (Waters Associates) cartridge (Nash, 1990), and eluted with ethyl acetate. Trifluralin [2,6-dinitro-N,N-dipropyl-4-(trifluoromethyl) benzenamine] was added to the eluant as an internal standard. Atrazine and alachlor solution concentrations were determined using a gas chromatograph equipped with a N-P detector. Operating conditions for the gas chromatograph were 30 m by 0.32 mm i.d. glass capillary column coated with $0.26\text{-}\mu\text{m}$ SPB-5 (Supelco, Bellefonte, PA); injector temperature, 200°C ; oven temperature, 150°C ; detector temperature, 220°C ; and a He carrier gas flow rate of 2.5 mL min^{-1} . Herbicide recoveries from spiked solution samples were 97% for atrazine and 95% for alachlor. Detection limits were $0.01 \mu\text{g L}^{-1}$ for atrazine, $0.10 \mu\text{g L}^{-1}$ for alachlor, and $0.05 \mu\text{g L}^{-1}$ for DEAT.

¹ Trade names included for the benefit of the reader and imply no endorsement or preferential treatment of the product listed by the U.S. Department of Agriculture.

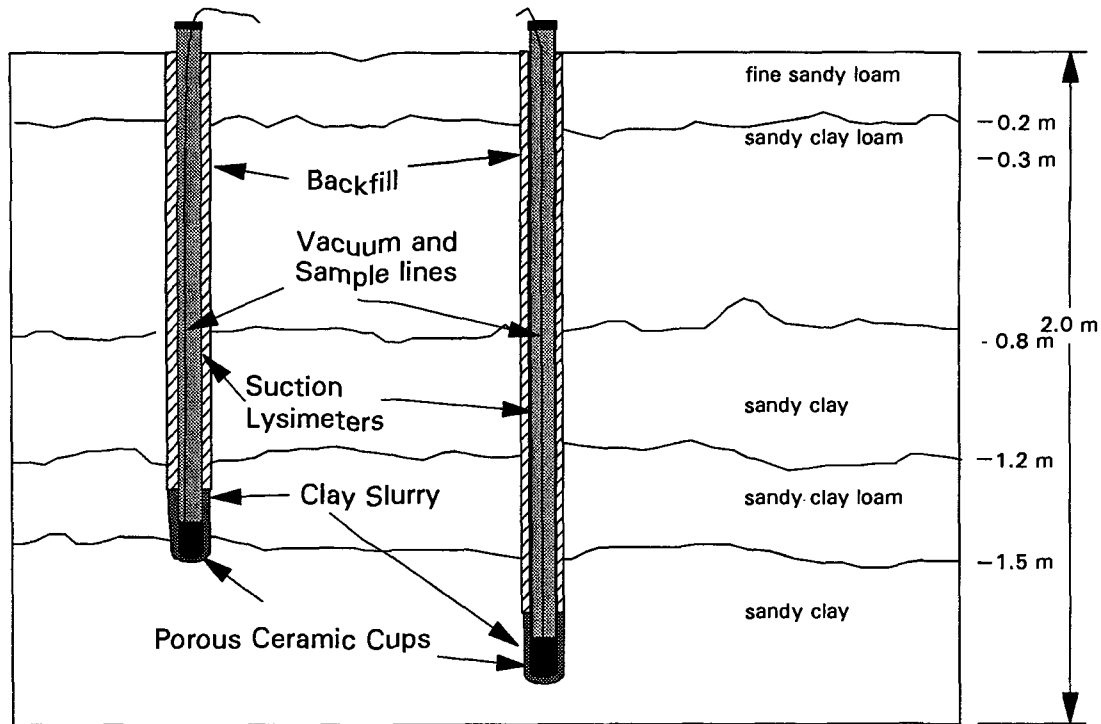


Fig. 2. Schematic of soil profile and installation of suction lysimeters.

RESULTS AND DISCUSSION

Temporal variations in daily temperature and precipitation were large (Fig. 3). Unlike the sinusoidal temperature variations, precipitation was fairly uniform throughout the year. Average yearly rainfall during a 21-yr period is >1 m (Isensee et al., 1990). Groundwater

recharge during the winter and early spring months is common due to decreased ET. Coefficients of variation for suction lysimeter sample volumes (for a given day and field) ranged from 70 to 100%. There was a poor correlation between chemical mass in the samples relative to sample volume (Br^- $r^2 = 0.127$; atrazine $r^2 = 0.094$).

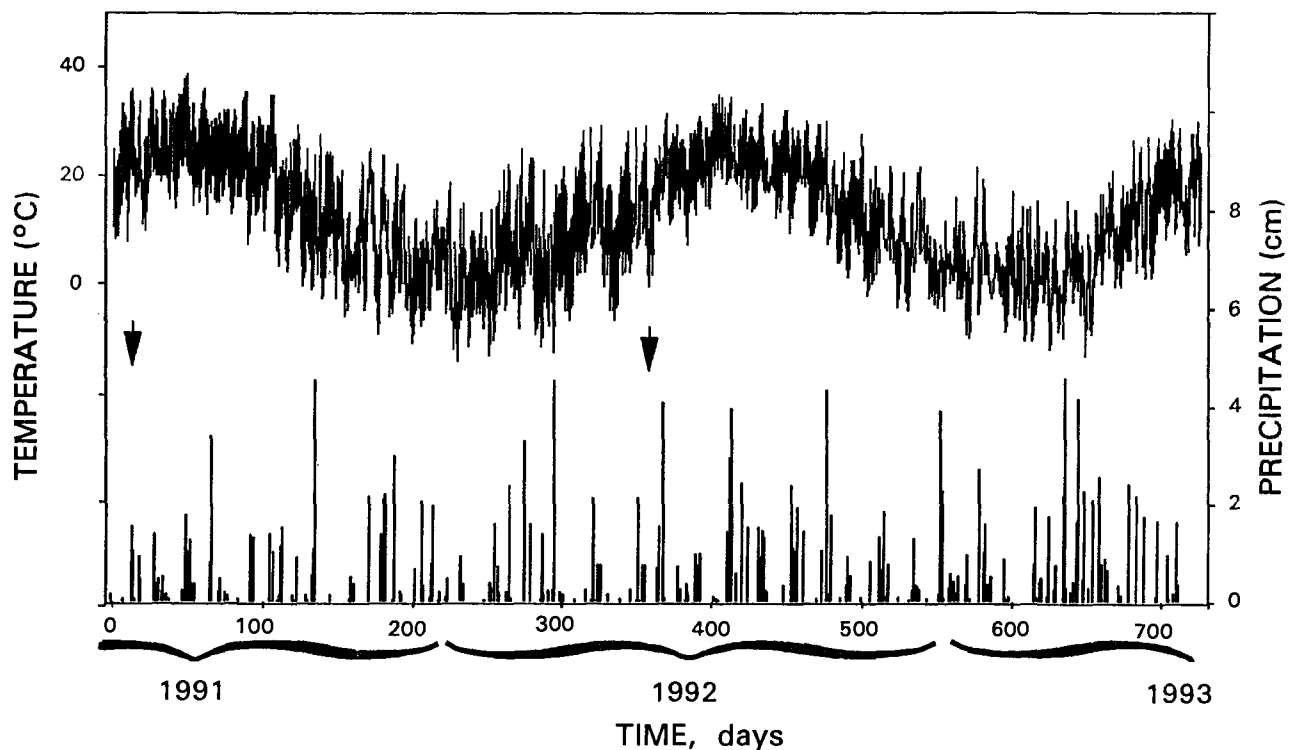


Fig. 3. Daily maximum-minimum air temperature and rainfall data for the research site.

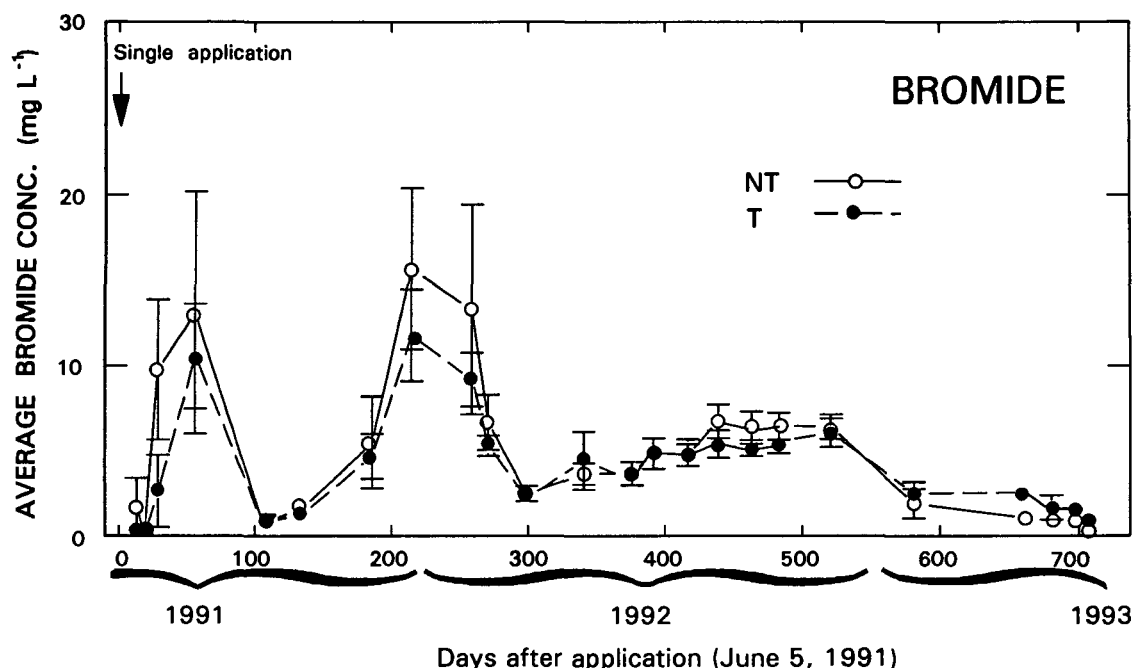


Fig. 4. Bromide breakthrough curves below the root zone for no-tillage and tilled fields. Average concentrations calculated by combining data from 1.5- and 1.8-m depths. Error bars signify ± 1 standard error of the mean.

Bromide leachate concentrations plotted as a function of time revealed a trimodal distribution under both tillage systems (Fig. 4). All of the Br^- recovered in the suction lysimeters is assumed to be due to the 1991 application. There is no significant difference in averaged Br^- solution-phase concentrations between tilled and no-tillage practices ($r^2 = 0.82$). Similar Br^- breakthrough curves for both tilled and no-tillage fields may, in part, be attributed to the sandy texture of this field site (Fig. 2).

To determine Br^- transport behavior, a Br^- pulse was simulated using the classical convective-dispersion equation (CXFT) described by Parker and van Genuchten (1984) and compared with Br^- observations. Although the mathematical solutions proposed by Parker and van Genuchten (1984) are for steady-state conditions, Wierenga (1977) showed that steady-state solutions give good approximations when transient water inputs are time averaged. For simplicity, we also assumed no ET during the first 2 mo (date associated with first Br^- peak). Because some ET will have occurred, the actual Br^- front should be shallower than the calculated Br^- front (ignoring potential ET losses). By Day 60, 21.9 cm of water had fallen onto the research site, giving a calculated Br^- front at ≈ 0.6 m. However, the solution samplers below the root zone of both tillage regimes show significant Br^- transport at the combined 1.5- and 1.8-m depths. Since Br^- was observed at depths greater than twice the calculated depth (ignoring ET), the first Br^- peak may be a result of solute transport in preferential flow pathways. Although preferential flow has been observed in no-tillage soils and soil columns containing void root channels (Gish and Jury, 1983; Isensee et al., 1990), it has also been observed in sandy soils (Glass et al., 1988; Kung, 1990). By the midpoint of the second Br^- peak, 240 d, 75 cm of water had fallen after chemical applica-

tion. With daily pan evaporation and rainfall measurements to estimate net water inputs, the Br^- center of mass should have been at ≈ 1.5 m. Since the second peak is in close agreement with the lysimeter depths, it appears that some of the Br^- moved relatively uniformly through the soil in both tillage systems. The third peak is very broad and took nearly 1 yr to pass by the suction lysimeters. This last Br^- peak is an indication of low water velocities occurring in the smaller pores of the soil matrix and is typically manifested in soil column studies with asymmetric breakthrough curves. Conceptually, the low Br^- concentrations after 300 d reflect the fraction of Br^- being temporarily trapped in relatively immobile regions (soil peds and dead-end pores). On a 1.1-ha watershed with $\approx 20\%$ slope, low Br^- concentrations were observed for several years after a single application of 168 kg ha^{-1} (Owens and Edwards, 1992).

Alachlor was rarely detected in any lysimeter below the root zone, regardless of herbicide formulation or tillage practice. Less than 3% of all lysimeter samples detected any alachlor. Additionally, on these same fields, alachlor was detected in $<2\%$ of all soil samples removed between 0.5 and 1.1 m (Gish et al., 1994). Isensee et al. (1988) reported that $<18\%$ of the solution samples collected at 1 m showed any quantitative alachlor concentrations. Low alachlor levels observed below the root zone is a consequence of herbicide loss through other pathways such as volatilization and degradation. As reported in an earlier study, alachlor volatilization can be significant and is highly dependent on formulation and tillage practice (Wienhold and Gish, 1994). Furthermore, the degradation half-life for alachlor is relatively short, between 14 to 41 d, depending on several soil environmental factors (Helling et al., 1988; Gustafson, 1989). Since 5 to 15% of the applied alachlor volatilized (Wien-

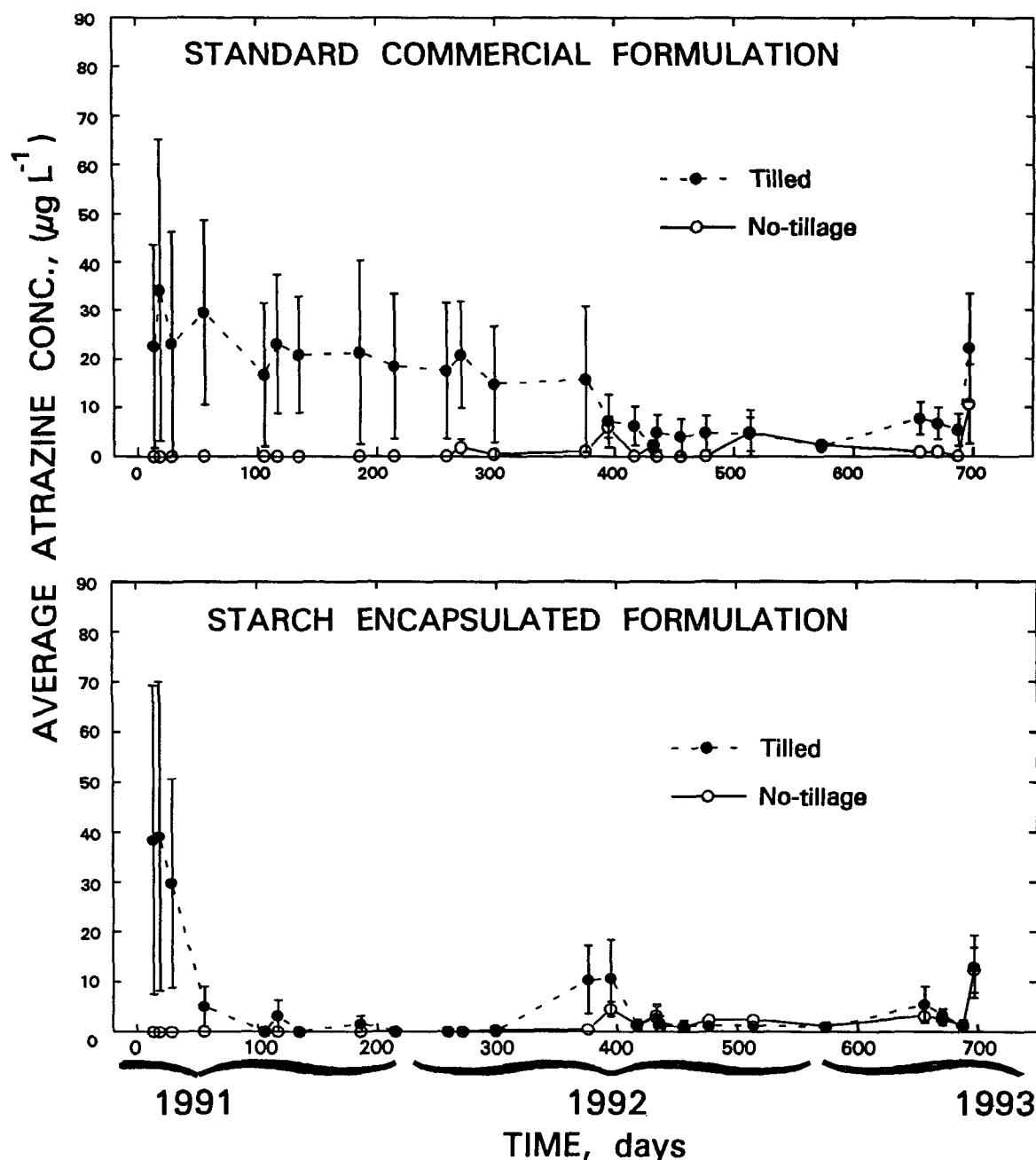


Fig. 5. Atrazine breakthrough curves below the root zone for tilled and no-tillage fields and each herbicide formulation. Average concentrations calculated by combining data from 1.5- and 1.8-m depths. Error bars signify ± 1 standard error of the mean.

hold and Gish, 1994) and runoff was negligible, degradation is probably the predominate loss pathway for alachlor on this research site.

Atrazine was frequently detected in the soil solution exiting the root zone. About 41% of all solution samples contained atrazine. Frequency of atrazine detection was greater with tillage, as 53% of the solution samples collected from tilled fields contained atrazine. Additionally, 35% of the samples collected under tilled fields had atrazine concentrations $>3 \mu\text{g L}^{-1}$, and $>21\%$ of the samples were $>10 \mu\text{g L}^{-1}$. As a result, atrazine levels under the tilled fields were frequently greater than the U.S. Environmental Protection Agency Health

Advisory level for atrazine of $3 \mu\text{g L}^{-1}$ (U.S. Environmental Protection Agency, 1992). For comparison, only 28% of the samples collected under no-tillage had detectable concentrations of atrazine. Furthermore, $<13\%$ of the samples from the no-tillage treatments had atrazine concentrations $>3 \mu\text{g L}^{-1}$.

The highest atrazine concentrations were associated with the use of the standard commercial formulation of atrazine on a tilled field (Fig. 5). Considering all atrazine detections, 47% were associated with one treatment, the tilled field using standard commercial atrazine. In a field plot study, Isensee et al. (1988) detected atrazine in $\approx 75\%$ of the solution samples collected at 1 m. Differ-

ences in atrazine leachate concentrations between tilled and no-tillage treatments is less significant with the use of starch-encapsulated atrazine. In an earlier study, Gish et al. (1994) demonstrated that starch-encapsulated atrazine was less mobile than commercial formulations. The reduction in atrazine mobility with starch encapsulation was due to atrazine release rates being a function of soil water availability and cyclic wetting and drying. With the exception of the first 50 d, starch-encapsulated atrazine concentrations below the root zone were not significantly different for the 2-yr period, regardless of tillage.

A principle factor reducing atrazine levels in soil and soil solution is degradation. Atrazine degradation can occur as a result of either chemical hydrolysis (Armstrong and Chesters, 1968) or microbial N dealkylation (Giardina et al., 1982; Kaufman and Blake, 1970). Chemical hydrolysis results in the formation of hydroxyatrazine (Schiavon, 1988) while N dealkylation results in the formation of several metabolites, the most common being DEAT (Shimabukuro and Swanson, 1969). Although atrazine was observed more frequently under tillage than no-tillage, DEAT was detected more frequently and at larger concentrations under no-tillage (Fig. 6). About 20% of the lysimeter samples under no-tillage contained DEAT, compared with 14% for samples collected under tilled fields. Average DEAT concentrations for the duration of the study were $0.52 \mu\text{g L}^{-1}$ for no-tillage fields and $0.39 \mu\text{g L}^{-1}$ for the tilled fields. Stearman et al. (1989) also observed a decrease in herbicide activity with increasing tillage. The DEAT concentrations under no-tillage indicate that biological degradation might be an important factor in the disappearance of atrazine under no-tillage.

There is concern that although conservation tillage practices tend to reduce surface runoff, they may be

more susceptible to preferential transport and thus could be a potential source of groundwater pollution. Isensee et al. (1990) and Gish et al. (1991a) observed dramatic increases in solution-phase atrazine levels under no-tillage fields following precipitation events that occurred shortly after herbicide application. However, in these studies, the observation wells were located at shallow depths (-1 m) and the samples were collected a few days after application. As a result, biological degradation had little impact on the observed atrazine levels. In this study, the trimodal Br^- breakthrough curves indicated that preferential solute transport had occurred. However, from atrazine concentrations below the root zone, it is apparent that sufficient time had elapsed for biological degradation in preferential flow paths (old root channels) to have an impact on water quality of the leachates at 1.5- and 1.8-m depths.

SUMMARY AND CONCLUSIONS

Impact of tillage on the transport of Br^- , alachlor, and atrazine was evaluated on four 0.25-ha fields. Bromide was used as a tracer and revealed that a small fraction of the solutes moved rapidly through preferred flow paths. In this study, alachlor was rarely detected in any lysimeter below 1.5 m regardless of herbicide formulation or tillage. Atrazine levels were reduced by starch encapsulation, but no-tillage had the greatest effect on reducing atrazine leachate levels below the root zone. Atrazine concentrations under no-tillage were nondetectable in 72% of the samples, while under tilled soils, only 47% of the samples were below detection limits. Reduction of atrazine under no-tillage is probably due to biological degradation, perhaps in preferential flow pathways. Further research on herbicide adsorption and degradation in stabilized preferential flow pathways in no-tillage fields is warranted.

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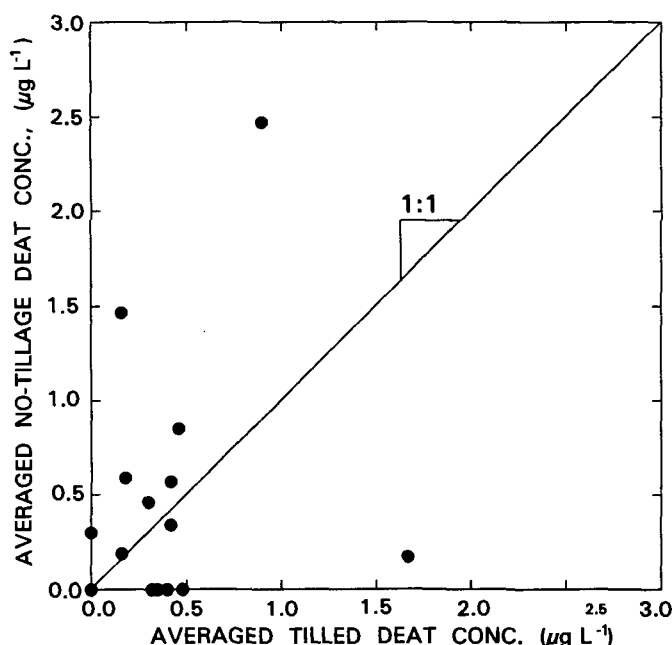


Fig. 6. Comparison of the atrazine metabolite deethylatrazine (DEAT) under tilled and no-tillage fields. Each dot represents a tillage treatment average for a specific sampling date.

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