Dissipation and Distribution of Herbicides in the Soil Profile

D. A. J. Weed,* R. S. Kanwar, D. E. Stoltenberg, and R. L. Pfeiffer

ABSTRACT

The distribution and dissipation of alachlor [2-chloro-2′,6′-diethyl-*N*-(methoxymethyl) acetanilide], atrazine (2-chloro-4-ethylamino-6-isopropylamino-1,3,5 triazine), and metribuzin [4-amino-6-(1,1-dimethylethyl)-3-(methylthio)-1,2,4-triazin-5(4*H*)-one] in soil were studied in 1990, 1991, and 1992. Crop management practices included four tillage methods—chisel plow, moldboard plow, no-till, and ridge-till—and two crop rotations—continuous corn (*Zea mays* L.) and a corn-soybean [*Glycine max* (L.) Merr.] rotation. All herbicides were broadcast-spray applied with no incorporation. No-till plots had the smallest amounts of alachlor and metribuzin, whereas ridge-till plots had the smallest amounts of atrazine. Moldboard-plow plots usually contained the highest amounts of all three herbicides, although ridge-till plots had the highest metribuzin levels in 1992. These differences were seldom significant at the 0.05 level of probability, however. Throughout the growing season, 50 to 84% of the alachlor and metribuzin were retained in the top 10-cm layer of soil, and at least 68% of the atrazine was retained in the top 20 cm. From 84 to 98% of the herbicide applied was lost each year, probably by microbial degradation and, for alachlor, by volatilization after application. First-order half-lives were 36 d for alachlor, 55 d for atrazine, and 32 d for metribuzin. A two-compartment model better fitting the alachlor data returned a half-life of 24 d for that herbicide.

COMPARED with chlorinated hydrocarbon pesticides like DDT, pesticides commonly used today are less acutely toxic to humans, do not accumulate in the food chain, and dissipate more rapidly in the surface soil layer (Hallberg, 1989). But their unexpected mobility through root-zone soil has allowed pesticides to migrate into shallow groundwater supplies, so groundwater contamination by agricultural pesticides is now common. From 1988 through 1989, it was estimated that 11.1 to 16.2% of all private, rural wells used for drinking water in Iowa were contaminated with at least one pesticide, and 1.2% had pesticide concentrations above USEPA health advisory levels (Iowa Dep. of Natural Resources, 1990, unpublished report). Atrazine (2-chloro-4-ethylamino-6-isopropylamino-1,3,5 triazine) was the most frequently detected compound in this and other groundwater studies (Hallberg, 1989). The chronic effects to humans from constant, low-level dosages of agricultural pesticides are not well known, but many people, especially those in rural farming regions, are exposed. To better predict the amounts and types of pesticides that are likely to leach into groundwater, a clear understanding of the dissipation and distribution of these pesticides in soil is necessary.

In the 1960s, pesticide mobility was not expected because water and chemicals were thought to move through the soil by matrix flow, a slow displacement of water through soil pores. If so, most pesticides in use today would dissipate in the surface soil long before they would reach a groundwater aquifer. Recent studies have shown, however, that pesticides can quickly enter subsurface soil and shallow groundwater by flowing with infiltrating water through cracks, worm and root holes, and other macropores in unsaturated, structured soil (Gish et al., 1991a; Kanwar, 1991; Starr and Glotfelty, 1990; Steenhuis et al., 1990) or through finger or funnel flow in sandy, unstructured soils (Baker and Hillel, 1991; Kung, 1993; Rice et al., 1991; Steenhuis and Parlange, 1991). Since tillage disturbs preferential flow pathways, no-till or minimum-till practices may enhance preferential water flow and pesticide movement compared with conventional tillage (Gish et al., 1991a; Sadeghi and Isensee, 1992).

The rate at which a pesticide dissipates in the soil is influenced by many factors, including the method of pesticide application, the chemical and biological properties of the soil, and the soil management history. Applying a pesticide to the soil surface without incorporation, which is typical practice for no-till or minimum-till cropland, can increase the amount of pesticide leaching shortly after application (Baker, 1992; Gish et al., 1991b; Hallberg, 1989; Rice et al., 1991; Starr and Glotfelty, 1990; Steenhuis et al., 1990). After some pesticides migrate into no-till surface soil, however, they may be adsorbed and degraded more quickly than in conventionally tilled soil, since no-till soil contains more organic material in the surface layer and supports a larger and more active microbial population (Fermanich and Daniel, 1991; Locke and Harper, 1991). Helling et al. (1988) felt the fast rate of alachlor [2-chloro-2′,6′-diethyl-*N*-(methoxymethyl) acetanilide] degradation prevented it from leaching as deeply as atrazine. Alachlor dissipated faster in no-till plots compared with moldboard-plowed and disked plots, but metribuzin [4-amino-6-(1,1-dimethylethyl)-3-(methylthio)-1,2,4-triazin-5(4*H*)-one] dissipation was not affected by tillage (Jones et al., 1990). Locke and Harper (1991) found, however, that metribuzin dissipated more rapidly in surface soil amended with soybean residue compared with unamended surface soil. Atrazine was leached into deeper soil layers by frequent precipitation shortly after application, but its rate of dissipation in the soil was not affected by tillage (Gish et al., 1991a).

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Abbreviations: PETG, polyethylene terephthalate, glycol-modified; SE, standard error; CV, coefficient of variation; FO, first-order; 2CM, two-compartment model; NT, no-till; RT, ridge-till; MB, moldboard-plow; SSE, sum of squares due to error; a.i., active ingredient.

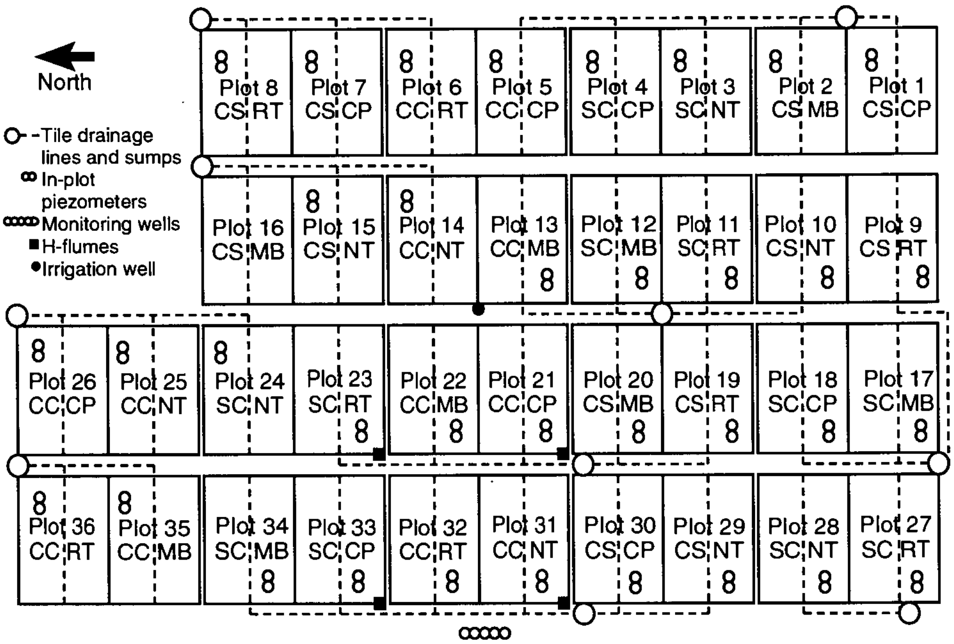

Fig. 1. Layout of the experimental site. Details of between-plot subsurface-drain lines, piping from plots to individual sumps, and individual-plot sumps have been omitted. CP, chisel plow; MB, moldboard-plow; NT, no-till; RT, ridge-till; CC, continuous corn; CS, corn-soybean; SC, soybean-corn.

The distribution of atrazine in no-till and conventionally tilled soil was better correlated to surface topography than to tillage practice (Sadeghi and Isensee, 1992).

The overall objectives of this field-scale study were to evaluate whether tillage methods affected the distribution of alachlor, atrazine, and metribuzin in root zone soil and to determine the overall dissipation rates of these chemicals under field conditions.

MATERIALS AND METHODS

Experimental Site

The experimental site at Iowa State University's Northeast Research Farm near Nashua, IA, was first developed in 1977 to evaluate tillage and crop rotation effects on crop yield and on weed and insect populations. The site included 36 plots; each plot was 0.4 ha (58 by 67 m). The four tillage systems were chisel plow, moldboard plow (MB), no-till (NT), and ridge-till (RT), and the two crop rotations were continuous corn and both current-year corn and current-year soybean crops in a corn–soybean rotation. Each treatment of crop rotation and tillage system was replicated three times in a randomized complete block design, and each plot received the same tillage and crop rotation treatment from 1977 through 1992 (Fig. 1). By 1988, tillage had significantly affected soil properties including pH and total C and N contents (Table 1; Karlen et al., 1991).

To reduce the effect of seasonally high water tables on crop yields, subsurface drain lines were installed in 1979 along the centerline of each plot and on both borders that parallel the plot centerline. The lines were located approximately 1.2 m below the soil surface, and the water table during growing seasons with average or above average precipitation was generally at or above this depth. The water quality monitoring program at the Nashua site was added in 1988, when the drain line in the center of each plot was intercepted so the water draining from the center region of each experimental plot flows to its own sump (Fig. 2). As water accumulated in the sump and was periodically pumped to the main drain line, a flowmeter recorded the cumulative pumped volume. The flow measurements for all plots were recorded once a week.

In addition, an orifice and sampling line were installed on the discharge line of each pump, so about 0.2% of the water flow was diverted to a sample bottle. The sample bottles were collected once a week, and also after every 2.5 cm or larger

Table 1. Soil pH and total C and N content by 5-cm depth increments for each tillage.†

Tillage	pH	Total C	Total N
		g kg^{-1}	
Chisel plow depth range (cm)			
0-5	6.8	21.3	1.58
5-10	6.5	20.4	1.53
10-15	6.1	19.6	1.48
15-20	5.7	18.6	1.43
Moldboard-plow depth range (cm)			
0-5	6.6	20.4	1.55
5-10	6.5	19.9	1.50
10-15	6.4	20.3	1.56
15-20	6.3	19.7	1.51
No-till depth range (cm)			
0-5	7.0	21.4	1.62
5-10	6.1	18.3	1.36
10-15	5.7	17.7	1.39
15-20	5.8	17.3	1.32
Ridge-till depth range (cm)			
0-5	6.7	20.8	1.57
5-10	6.1	19.0	1.44
10-15	5.9	17.6	1.37
15-20	5.9	17.6	1.38
Least significant difference (0.05)	0.2	1.1	0.11
Covariance (%)	6	47	50

† Adapted from Karlen et al. (1991).

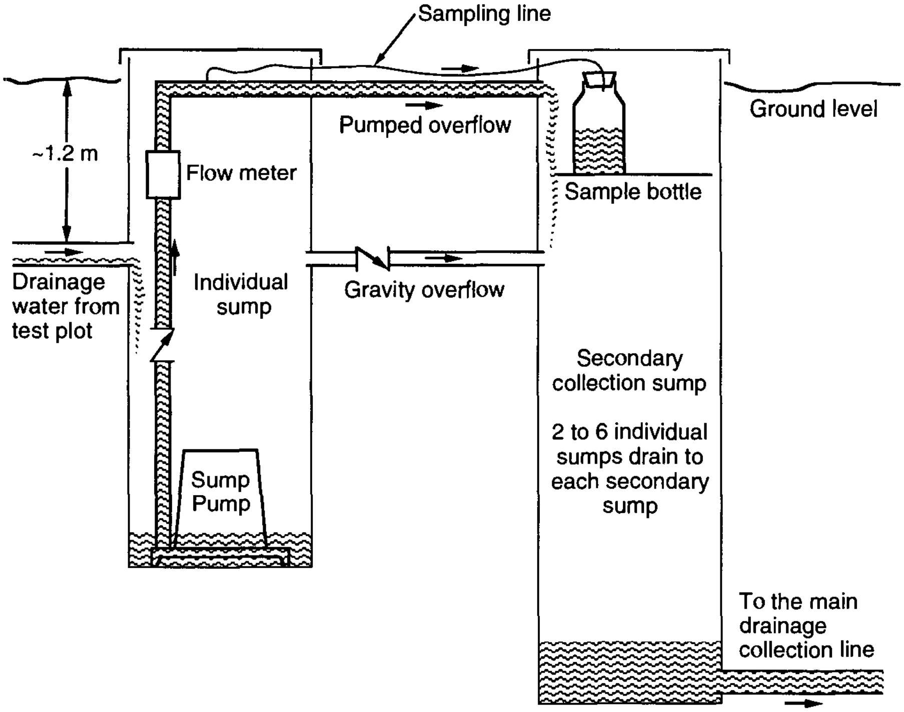

Fig. 2. Schematic of the individual and secondary subsurface-drain sumps showing the equipment for recording water flow and for collecting a representative water sample.

rainfall occurring up to 60 d after herbicides were applied. Water samples were kept refrigerated until analysis.

The herbicide concentrations in the weekly samples were combined with the flow measurements to provide weekly measurements of herbicide leaching into the subsurface drain system. The samples collected after rainfall events were used as nonquantitative indicators of herbicide leaching with preferential flow. More information on the design and management of the water quality monitoring program at this site is given by Kanwar (1991).

Since 1977, alachlor, atrazine, and metribuzin were broadcast-spray applied in one pass over each plot immediately after planting, with no subsequent incorporation (Table 2). Alachlor was applied to all plots at a rate of 2.2 kg ha^{-1} active ingredient (a.i.), atrazine at a rate of 2.8 kg ha^{-1} a.i. only to continuous corn plots, and metribuzin at a rate of 0.45 kg ha^{-1} a.i. only to rotation soybean plots. The formulations used were an emulsifiable concentrate with 480 g L^{-1} a.i. (4 lb gal^{-1} a.i.) for alachlor, a liquid concentrate with 480 g L^{-1} a.i. for atrazine, and a dry-flowable powder with 75% a.i. for metribuzin. These herbicides vary in their chemical properties; alachlor is most strongly adsorbed, atrazine has the lowest vapor pressure, and metribuzin has the greatest water solubility (Table 3).

The soils at the Nashua site are Floyd loam (fine-loamy, mixed, mesic Aquic Hapludolls), Kenyon loam (fine-loamy, mixed, mesic Typic Hapludolls), and Readlyn loam (fine-loamy, mixed, mesic Aquic Hapludolls) (Karlen et al., 1991). These soils belong to the Kenyon-Clyde-Floyd soil association, a group of loamy to silty soils that are moderately well to poorly drained and lie over loamy glacial till (USDA-SCS, 1977) (Table 4).

Soil Sampling Procedures

In 1990, soil samples were collected during the growing season on 30 May and 25 September and after harvest on 30 October. Rainy weather did not allow soil samples to be collected before chemicals were applied. In 1991, samples were collected on 11 May before chemical application, during the growing season on 18 June and 23 September, and after harvest on 13 November. In 1992, samples were collected on 29 April before chemical application, during the growing season on 23 June and 18 September, and after harvest on 21 October (Table 2).

Any effects of the subsurface drain line and the plot edges were minimized by collecting soil cores from the center 25% of each plot, avoiding the center row overlying the drain line. The three coring locations in each of the plots were consistently spaced across this sampling area. A hand sampler was used to remove cores 100 to 180 cm long and 2.5 cm in diam. from row centers. The amount of soil compaction was measured at 30-cm increments for each core. As the sampler was pushed into the soil, the core slid into a clean liner made of PETG (polyethylene terephthalate, glycol-modified) plastic to protect the soil from contamination. The resulting opening in the soil was plugged with bentonite clay granules. Soil cores were frozen promptly after collection. Later, each of the three cores from a plot was cut, compensating for soil compaction, into sections. In 1990, 180 cm long cores were divided into sections representing 0- to 10-, 10- to 20-, 20- to 30-, 30- to 45-, 45- to 60-, 60- to 90-, 90- to 120-, 120- to 150-, and 150- to 180-cm depths. These longer cores were collected mainly to assess the nitrate content in the deeper soil layers. In 1991, 100 cm long cores were divided into sections representing 0- to 10-, 10- to 20-, 20- to 30-, 30- to 45-, 45- to 60-, and 60- to 100-cm depths. In 1992, 120 cm long cores were divided similarly to the 1990 cores. The sections were combined into one set of samples for each plot. Each sample was wrapped in aluminum foil, sealed in a labeled polyethylene bag, and then refrozen for transportation and storage.

Table 2. Dates of planting, chemical application, harvesting, and soil sampling in 1990, 1991, and 1992.†

Date	Days since 1 January	Activity
1990		
2 May	122	Planted corn Surface-broadcast 2.2 kg ha^{-1} a.i. alachlor and 2.8 kg ha^{-1} a.i. atrazine on continuous corn plots
3 May	123	Surface-broadcast 2.2 kg ha^{-1} a.i. alachlor on corn-soybean plots
18 May	138	75% corn emergence
23 May	143	Planted soybean Surface-broadcast 2.2 kg ha^{-1} a.i. alachlor and 0.45 kg ha^{-1} a.i. metribuzin on soybean-corn plots
30 May	150	Late-spring soil sampling
2 June	153	75% soybean emergence
25 Sept.	268	Late-season soil sampling
1 Oct.	274	Corn harvest
16 Oct.	289	Soybean harvest
30 Oct.	303	Postharvest soil sampling
1991		
11 May	131	Preplant soil sampling
27 May	147	Planted all corn plots
28 May	148	Surface-broadcast 2.2 kg ha^{-1} a.i. alachlor on all corn plots and 2.8 kg ha^{-1} a.i. atrazine on continuous corn plots
3 June	154	75% corn emergence
7 June	158	Planted all soybean plots and surface-broadcast 2.2 kg ha^{-1} a.i. alachlor and 0.45 kg ha^{-1} a.i. metribuzin on soybean plots
15 June	166	75% soybean emergence
18 June	169	Early summer soil sampling
23 Sept.	266	Late-season soil sampling
8 Oct.	281	Corn harvest
10 Oct.	283	Soybean harvest
13 Nov.	317	Postharvest soil sampling
1992		
29 Apr.	120	Preplant soil sampling
5 May	126	Planted corn
6 May	127	Surface-broadcast 2.2 kg ha^{-1} a.i. alachlor on all corn plots and 2.8 kg ha^{-1} a.i. atrazine on continuous corn plots
12 May	133	Planted soybean Surface-broadcast 2.2 kg ha^{-1} a.i. alachlor and 0.45 kg ha^{-1} a.i. metribuzin on soybean-corn plots
20 May	141	75% corn emergence
23 June	175	Early summer soil sampling
18 Sept.	262	Late-season soil sampling
2 Oct.	276	Soybean harvest
14 Oct.	288	Corn harvest
21 Oct.	295	Postharvest soil sampling.

† Adapted from R.S. Kanwar, D.L. Karlen, T.S. Colvin, W.W. Simpkins, and V.J. McFadden. 1993. Completion report: Evaluation of tillage and crop rotation effects on groundwater quality—Nashua project. Grant no. 90-41. Leopold Center for Sustainable Agriculture, Ames, IA.

Sample Analysis

Amounts of alachlor, atrazine, and metribuzin in the soil and water samples were determined by the National Soil Tilth Lab, Ames, IA, following standardized, highly automated procedures. Metabolic products of these herbicides were not quantified.

Water samples were analyzed for herbicides by adding propazine surrogate to a 250-mL sample, then passing the sample through an Analytichem International C-18 cartridge, which adsorbs organic compounds, including the herbicides of interest. The herbicides and surrogate were eluted from the cartridge with 2 mL of ethyl acetate that contained internal standards. The herbicide concentrations in the ethyl acetate solution were quantified by mass spectroscopy. The minimum detection limit for herbicides in water samples was 0.2 mg kg^{-1} a.i.

To analyze soil samples for herbicides, a weighed sample of soil was vortexed 5 min with an extraction solvent (4:1 v/v methanol and water). After equilibrating for 12 h, the mixture was centrifuged and the methanol–water solution was decanted. More extraction solvent was added to the soil, the mixture was again vortexed for 2 min and centrifuged, and the solvent was decanted. The entire volume of extraction solvent was then reduced to 3 mL or less by evaporation at 50°C in a N_2 atmosphere. The herbicides were adsorbed from the solvent with an Analytichem International C-18 cartridge, then were selectively eluted from the cartridge with ethyl acetate, which contained an internal standard of 0.55 ng mL^{-1} terbuthylazine [1,3,5-triazine-2,4-diamine, 6-chloro-*N*-(1,1-dimethylethyl]-*N*′-ethyl-terbuthylazine]. Herbicide concentrations in the ethyl acetate were quantitated by a capillary gas chromatograph with an NP detector and helium carrier. The results were reported as mg kg^{-1} a.i. on a dry-soil basis. The minimum detection limit for herbicides in soil samples was 5 mg kg^{-1} a.i. In a 10 cm deep layer of soil, 5 mg kg^{-1} a.i. is equivalent to 6.8 to 9.0 g ha^{-1} a.i. for a corresponding soil bulk density range of 1.35 to 1.80 g cm^{-3} (Table 4).

Table 3. Selected herbicide properties at 20 to 25°C.†

Herbicide	Soil adsorption coefficient, K_d‡	Relative vapor pressure Alachlor = 1§	Water solubility
	mL kg^{-1}		mg L^{-1}
Alachlor	3400	1	240
Atrazine	2000	0.021	33
Metribuzin	1200	<0.5	1220

† Unless noted otherwise, Cooperative Extension Service. 1992. Understanding and reducing pesticide losses. Rep. Pm-1495. Iowa State Univ., Ames, IA.

‡ K_d = (concentration sorbed on soil)/(concentration in water) for a soil with 2% (w/w) organic C content.

§ Saturated vapor pressure of alachlor is 2.94 mPa (2.2 × 10^{-5} mm Hg) at 25°C (Baker, 1992; Chesters, 1989).

Table 4. Selected physical properties of soils at the site.

	Depth range, cm								
Soil properties	0-10	10-20	20-30	30-45	45-60	60-90	90-120	120-150	150-180
Floyd soil properties									
Sand, % by volume	35	37	37	38	38	42	60	34	NA§
Silt, % by volume	42	39	39	38	38	38	30	38	NA
Clay, % by volume	23	24	24	24	24	20	10	28	NA
PAWC†, cm^3 cm^{-3} soil	0.21	0.21	0.21	0.21	0.19	0.12	0.15	0.17	0.17
Bulk density, g cm^{-3}	1.35	1.38	1.4	1.4	1.4	1.45	1.65	1.7	1.7
Permeability‡, cm h^{-1}	1.5-5.1	1.5-5.1	1.5-5.1	1.5-5.1	1.5-5.1	1.5-15.2	0.5-1.5	0.5-1.5	0.5-1.5
Kenyon soil properties									
Sand, % by volume	44	34	37	45	45	45	46	45	NA
Silt, % by volume	37	42	38	28	28	26	27	28	NA
Clay, % by volume	19	24	25	27	27	29	27	27	NA
PAWC, cm^3 cm^{-3} soil	0.21	0.21	0.21	0.21	0.18	0.18	0.17	0.16	NA
Bulk density, g cm^{-3}	1.5	1.5	1.5	1.52	1.55	1.65	1.72	1.77	1.8
Permeability, cm h^{-1}	1.5-5.1	1.5-5.1	1.5-5.1	1.5-5.1	1.5-5.1	0.5-1.5	0.5-1.5	0.5-1.5	0.5-1.5
Readlyn soil properties									
Sand, % by volume	36	36	37	46	46	44	45	45	NA
Silt, % by volume	41	41	40	27	27	28	29	33	NA
Clay, % by volume	23	23	23	27	27	28	26	22	NA
PAWC, cm^3 cm^{-3} soil	0.2	0.2	0.2	0.2	0.2	0.17	0.17	0.16	NA
Bulk density, g cm^{-3}	1.45	1.45	1.45	1.45	1.45	1.6	1.65	1.67	1.7
Permeability, cm h^{-1}	1.5-5.1	1.5-5.1	1.5-5.1	1.5-5.1	1.5-5.1	0.5-1.5	0.5-1.5	0.5-1.5	0.5-1.5

† Plant-available water capacity between −0.033 and −1.5 MPa soil water tension; adapted from USDA-SCS, 1977.
‡ Water permeability, adapted from USDA-SCS, 1977.
§ NA = data not available.

Ten percent of all soil samples extracted and analyzed by the National Soil Tilth Lab were controls that were spiked a minimum of 15 h before initial extraction with 10, 50, or 100 mg kg^{-1} a.i. of the herbicides of interest. In addition, all soil samples were spiked with 10, 50, or 100 mg kg^{-1} of terbutryn [1,3,5-triazine-2,4-diamine, *N*-(1,1-dimethylethyl)-*N*′-ethyl-6-(methylthio)-terbutryn] surrogate shortly before extraction. Typically, control recoveries for all three spike amounts have averaged 77% with a 1.6% standard error of the mean (SE) for alachlor, 93% with a 2.0% SE for atrazine, 88% with a 1.6% SE for metribuzin, and 84% with a 1.6% SE for terbutryne. No adjustments were made to the data to specifically account for analytical variability, since this variability is much smaller than the overall variability among samples. No correction for less than 100% recovery was applied either, since more error is potentially introduced by applying averaged recoveries for control samples to analyses of specific samples. Long-term studies by the National Soil Tilth Lab have shown no detectable change in herbicide levels while soil cores are held in frozen storage.

Statistical Analysis

All laboratory results were converted from mg kg^{-1} a.i. to a kg ha^{-1} a.i. basis using appropriate unit conversions and the bulk soil density for the appropriate depth range and predominant soil type in each plot. The tillage mean, overall mean, and standard error of the mean (SE; equal to the standard deviation divided by the square root of the number of observations), and coefficient of variation (CV; calculated as the standard deviation divided by the mean) were calculated for all depth ranges and sample times. The tillage averages for each sampling time and depth range were tested for significant differences by calculating *t*-test values for all pairs of tillages (Steel and Torrie, 1980) using an overall probability level of 0.05 and assuming unequal variances. Only some of the data are available for the October 1990 sample set, since the herbicide analyses were not fully completed. Tillage-specific comparisons could not be done for the May and June 1991 sample sets since tillage and treatment information was not available.

Because the herbicide content in the 90- to 100-cm range was consistently negligible, 1990 and 1992 data from the 0- to 90-cm depth range were directly compared with 1991 data from the 0- to 100-cm depth range.

Half-Life Calculations

Pesticide dissipation in soil is often assumed to be a first-order reaction (Gish et al., 1991b; Paul and Clark, 1989) defined as

$$C = C_0 e^{-kt} \quad [1]$$

where

C = amount of chemical in the soil at time t
C_0 = amount of chemical in the soil at time $t = 0$
k = dissipation rate constant
t = time

The time required for the amount of pesticide to drop to half of its initial amount in the soil is the half-life, $t_{0.5}$. For a first-order (FO) model, the half-life is

$$t_{0.5} = \frac{0.693}{k} \quad [2]$$

Hill and Schaalje (1985) developed a two-compartment model (2CM) that allows for rapid dissipation of a pesticide shortly after application, followed by a slower, first-order degradation rate. Pesticide applied to the soil is initially assigned to the first compartment where the pesticide either dissipates at a rate determined by coefficient k_s or migrates into the second compartment at a rate proportional to coefficient k_r. Once in the second compartment, the pesticide dissipates at a rate controlled by coefficient k_d. The mathematical form of the 2CM derived by Hill and Schaalje (1985) is

$$C = C_0 e^{-(k_s + k_r)t} + C_0 \left[\frac{k_r}{k_s + k_r - k_d}\right] [e^{-k_d t} - e^{-(k_s + k_r)t}] \quad [3]$$

The half-life for pesticide dissipation following this model is most easily determined by inspecting the model output to find

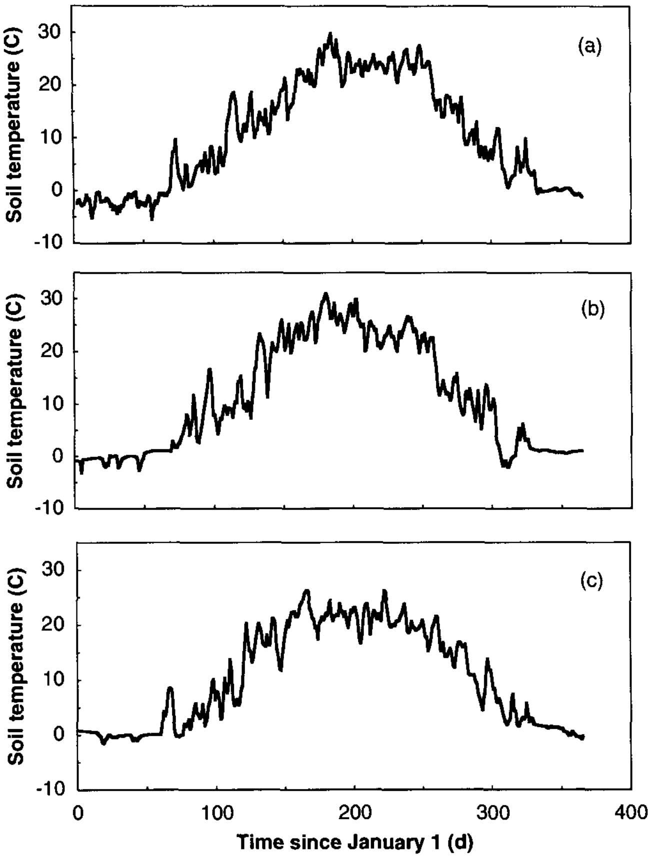

Fig. 3. Soil temperatures at the 10-cm depth for (*a*) 1990, (*b*) 1991, and (*c*) 1992. Herbicides were applied on Days 122 and 143 in 1990, Days 148 and 158 in 1991, and Days 127 and 133 in 1992.

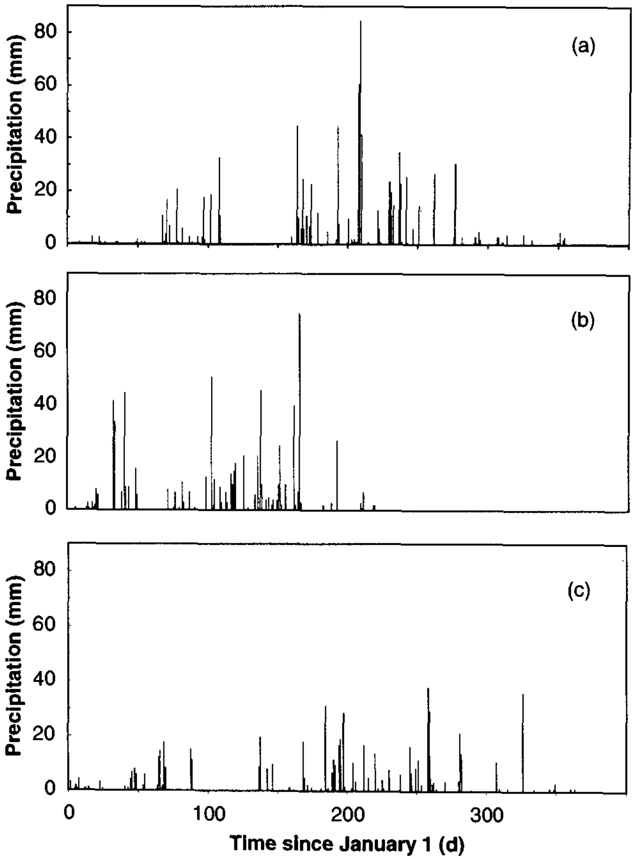

Fig. 4. Precipitation amounts for (*a*) 1990, (*b*) 1991, and (*c*) 1992. Herbicides were applied on Days 122 and 143 in 1990, Days 148 and 158 in 1991, and Days 127 and 133 in 1992.

the time when the pesticide has dropped to half of the amount applied.

The amounts of 2.285 kg ha^{-1} alachlor, 3.351 kg ha^{-1} atrazine, and 0.457 kg ha^{-1} metribuzin in the 100-cm soil profile on the day of application were estimated by combining the herbicide application rate with the average herbicide levels for the 11 May 1991 and 29 Apr. 1992 sample sets. These sets had been collected just before herbicides were applied. The estimated initial herbicide amounts were combined with data collected from all years to calculate the half-life of each herbicide using FO and 2CM models.

RESULTS AND DISCUSSION

Tillage Effects on Herbicide Levels

Shortly after herbicide application, the rainfall pattern and soil temperature may interact with tillage to alter herbicide dissipation rates. In 1990, during the period between herbicide applications to corn and soybean plots and for 30 d afterward, the 10-cm deep soil temperature averaged 17°C (Fig. 3). There was little rain until 2 wk after herbicides were applied to soybean plots; then a total of 136 mm fell within a 2-wk period (Fig. 4). During the same period in 1991, the soil temperature averaged 25°C, and a total of 183 mm precipitation was recorded, of which 49 mm fell between the herbicide applications and 125 mm fell 3 to 8 d after herbicide was applied to soybean plots. For the same interval in 1992, only 49 mm of rain fell in amounts of 20 mm or less, starting 4 d after herbicides were applied to soybean plots. The average soil temperature was 19°C.

Although the rainfall patterns varied among the 3 yr, NT plots consistently had the smallest average amounts of alachlor and metribuzin, while RT plots had the smallest amounts of atrazine (Tables 5–8). Moldboard-plow plots usually contained the highest average amounts for all three herbicides, although RT plots had the highest metribuzin levels in 1992. The statistical analysis generally supported these trends, but differences between tillages were seldom significant at the 0.05 level of probability.

The variable nature of the data contributed to this lack of significance. In the 100-cm soil profile, all CV values for alachlor applied to corn plots were between 25 and 80%, and all CV values for alachlor on soybean plots ranged from 2 to 90%. About 85% of the CV values for atrazine were between 5 and 50%. The remaining atrazine CV values ranging from 70 to 130% were mostly for data from RT plots. For metribuzin, two-thirds of the CV values fell between 1 and 50%. The remainder of the metribuzin CV values ranged from 90 to 170%. Metribuzin data for NT and RT plots most often had the larger CV values.

Similar CV values and lack of significant tillage effects have been reported for atrazine in soil. Sadeghi and Isensee (1992) attributed CV values ranging from 50 to 237% mainly to changes in surface topography and relatively little to rainfall patterns or tillage. Gish et al.

Table 5. Average alachlor content in the 0- to 100-cm soil profile for all tillages and sampling times in corn plots. Groups of tillages with no letters have no significant differences at the 0.05 level overall. Tillages followed by dissimilar letters (a, b, or c) are significantly different at the 0.05 level overall. No data for May and June 1991, and data set is incomplete for October 1990. For each average value, $N = 6$. The number below each date is the time since application (d).

	Alachlor (kg ha^{-1} a.i.) in continuous and rotation corn								
Depth range and tillage	30 May 1990 28	25 Sept. 1990 146	30 Oct. 1990 181	23 Sept. 1991 118	13 Nov. 1991 169	29 Apr. 1992 337	23 June 1992 48	18 Sept. 1992 135	21 Oct. 1992 168
0–10 cm									
Average									
Chisel plow	0.805	0.064	0.042	0.099	0.049	0.036	0.443 a	0.067 ab	0.040
Moldboard-plow	0.698	0.065	0.069	0.142	0.057	0.026	0.573 a	0.106 a	0.040
No-till	0.442	0.038	0.031	0.058	0.035	0.033	0.060 b	0.026 b	0.010
Ridge-till	0.477	0.040	0.040	0.060	0.050	0.037	0.078 b	0.057 ab	0.015
Standard error									
Chisel plow	0.119	0.015	0.006	0.010	0.005	0.005	0.084	0.012	0.012
Moldboard-plow	0.164	0.022	0.014	0.026	0.007	0.004	0.092	0.016	0.013
No-till	0.084	0.004	0.008	0.012	0.008	0.003	0.008	0.003	0.005
Ridge-till	0.113	0.011	0.007	0.008	0.008	0.012	0.023	0.013	0.005
0–20 cm									
Average									
Chisel plow	0.869	0.092	0.063	0.170 a	0.069 ab	0.045	0.461 ac	0.076 a	0.043
Moldboard-plow	0.768	0.075	0.090	0.209 ab	0.099 ab	0.053	0.608 a	0.130 a	0.045
No-till	0.463	0.056	0.044	0.076 b	0.047 a	0.052	0.069 b	0.028 b	0.010
Ridge-till	0.528	0.065	0.054	0.081 ab	0.120 b	0.054	0.128 bc	0.068 ab	0.015
Standard error									
Chisel plow	0.122	0.015	0.009	0.023	0.009	0.005	0.084	0.011	0.012
Moldboard-plow	0.152	0.022	0.016	0.053	0.013	0.006	0.095	0.017	0.015
No-till	0.081	0.009	0.008	0.015	0.010	0.012	0.009	0.004	0.005
Ridge-till	0.122	0.019	0.008	0.007	0.018	0.012	0.045	0.017	0.005
0–30 cm									
Average									
Chisel plow	0.906	0.099		0.191	0.083 ab	0.046	0.466 a	0.076 a	0.043
Moldboard-plow	0.811	0.095		0.228	0.123 a	0.067	0.614 a	0.136 a	0.045
No-till	0.477	0.066		0.087	0.051 b	0.054	0.071 b	0.028 b	0.010
Ridge-till	0.561	0.067		0.089	0.144 a	0.060	0.128 b	0.068 ab	0.015
Standard error									
Chisel plow	0.128	0.018		0.031	0.013	0.006	0.081	0.011	0.012
Moldboard-plow	0.150	0.023		0.052	0.012	0.009	0.096	0.019	0.015
No-till	0.082	0.012		0.017	0.011	0.012	0.009	0.004	0.005
Ridge-till	0.130	0.019		0.007	0.023	0.013	0.045	0.017	0.005
0–100 cm									
Average									
Chisel plow	0.950	0.099		0.191	0.083 ab	0.049	0.543 ab	0.076 a	0.043
Moldboard-plow	0.827	0.110		0.241	0.147 a	0.067	0.628 a	0.136 a	0.045
No-till	0.490	0.066		0.087	0.051 b	0.060	0.071 b	0.028 b	0.010
Ridge-till	0.587	0.067		0.106	0.149 ab	0.060	0.159 b	0.068 ab	0.015
Standard error									
Chisel plow	0.125	0.018		0.031	0.013	0.007	0.133	0.011	0.012
Moldboard-plow	0.146	0.022		0.055	0.023	0.009	0.101	0.019	0.015
No-till	0.086	0.012		0.017	0.011	0.013	0.009	0.004	0.005
Ridge-till	0.132	0.019		0.021	0.026	0.013	0.037	0.017	0.005

(1991a) felt the highest CV values in an overall range of 56 to 245% were caused by preferential flow that washed atrazine into a small portion of the soil volume.

At the Nashua site, smaller average alachlor and atrazine levels in NT and RT soil show that these tillages did increase the rate of herbicide dissipation compared with MB tillage. Somewhat higher CV values suggest that atrazine and metribuzin distribution may also be more uneven in NT and RT soil, although this has not been confirmed. Experiments to evaluate the effects of surface topography and macropore network on the herbicide distribution in the soil may be more useful at this site than additional studies focusing strictly on tillage.

Herbicide Distribution with Time and Depth

For all years and tillages, 84% of the alachlor, 70% of the atrazine, and 82% of the metribuzin present in the soil profile were retained in the top 10 cm up to 48 d after application (Fig. 5 and 6). Analyses of samples taken in September (108 to 146 d after herbicide application) showed that only 5% of the alachlor applied, 20% of the atrazine applied, and 5% of the metribuzin applied still remained in the soil. But at least one-half of the alachlor and metribuzin in the 100-cm soil profile at this time was still retained in the top 10-cm layer. Atrazine had migrated somewhat deeper, with 68% of the total remaining in the top 20 cm.

Of the alachlor and metribuzin applied each year, 92 to 98% was gone from the soil profile by the postharvest sampling time (159–181 d after application), regardless of tillage (Fig. 5 and 6). On the average, 84% of the atrazine applied each year was also gone by the postharvest sampling time (Fig. 6). Since atrazine dissipated more slowly and was applied at a higher rate, an average of 0.551 kg ha^{-1} of atrazine was carried over into the next growing season, compared with 0.085 kg ha^{-1} of alachlor and 0.007 kg ha^{-1} of metribuzin carryover.

Long-term biological degradation was most likely the

Table 6. Average alachlor content in the 0- to 100-cm soil profile for all tillages and sampling times in soybean plots. Groups of tillages with no letters have no significant differences at the 0.05 level overall. Tillages followed by dissimilar letters (a, b, or c) are significantly different at the 0.05 level overall. No data for October 1990 and May and June 1991. For each average value, N = 3. The number below each date is the time since application (d).

	Alachlor (kg ha^{-1} a.i.) in rotation soybean							
Depth range and tillage	30 May 1990 7	25 Sept. 1990 125	23 Sept. 1991 108	13 Nov. 1991 159	29 Apr. 1992 327	23 June 1992 42	18 Sept. 1992 129	21 Oct. 1992 162
0–10 cm								
Average								
Chisel plow	1.385	0.085	0.092	0.078 ab	0.043	0.098	0.078	0.047 a
Moldboard-plow	2.223	0.126	0.154	0.097 ab	0.027	0.267	0.081	0.063 ab
No-till	0.760	0.030	0.064	0.038 a	0.026	0.253	0.024	0.018 b
Ridge-till	1.723	0.089	0.130	0.079 b	0.039	0.380	0.064	0.051 ab
Standard error								
Chisel plow	0.337	0.021	0.003	0.013	0.003	0.051	0.025	0.001
Moldboard-plow	0.790	0.033	0.025	0.012	0.003	0.113	0.026	0.013
No-till	0.381	0.003	0.007	0.005	0.001	0.096	0.008	0.002
Ridge-till	0.223	0.019	0.026	0.004	0.007	0.192	0.007	0.016
0–20 cm								
Average								
Chisel plow	1.488	0.091	0.131	0.116 abc	0.062	0.125	0.091	0.051
Moldboard-plow	2.354	0.176	0.201	0.150 a	0.049	0.279	0.112	0.078
No-till	0.823	0.040	0.127	0.059 b	0.031	0.268	0.027	0.022
Ridge-till	1.808	0.115	0.167	0.100 c	0.079	0.397	0.064	0.051
Standard error								
Chisel plow	0.365	0.023	0.011	0.010	0.007	0.037	0.028	0.005
Moldboard-plow	0.754	0.040	0.016	0.004	0.002	0.114	0.035	0.014
No-till	0.369	0.007	0.052	0.004	0.003	0.104	0.011	0.006
Ridge-till	0.213	0.018	0.046	0.004	0.036	0.201	0.007	0.016
0–30 cm								
Average								
Chisel plow	1.565	0.098	0.136 a	0.132 abc	0.062 ab	0.133	0.091	0.051
Moldboard-plow	2.422	0.210	0.237 b	0.189 a	0.072 a	0.279	0.123	0.078
No-till	0.850	0.043	0.133 ab	0.072 b	0.031 b	0.268	0.027	0.022
Ridge-till	1.989	0.119	0.167 ab	0.113 c	0.079 ab	0.406	0.064	0.051
Standard error								
Chisel plow	0.384	0.018	0.011	0.010	0.007	0.030	0.028	0.005
Moldboard-plow	0.737	0.045	0.011	0.004	0.005	0.114	0.040	0.014
No-till	0.382	0.006	0.054	0.003	0.003	0.104	0.011	0.006
Ridge-till	0.182	0.020	0.046	0.003	0.036	0.210	0.007	0.016
0–100 cm								
Average								
Chisel plow	1.641	0.103	0.136 a	0.132 ab	0.062	0.139	0.102	0.060
Moldboard-plow	2.428	0.210	0.244 b	0.244 ab	0.077	0.279	0.123	0.078
No-till	0.866	0.043	0.145 ab	0.081 a	0.031	0.268	0.027	0.022
Ridge-till	2.008	0.119	0.176 ab	0.113 b	0.154	0.426	0.064	0.051
Standard error								
Chisel plow	0.436	0.014	0.011	0.010	0.007	0.030	0.020	0.008
Moldboard-plow	0.734	0.045	0.016	0.017	0.008	0.114	0.040	0.014
No-till	0.389	0.006	0.051	0.002	0.003	0.104	0.011	0.006
Ridge-till	0.192	0.020	0.055	0.003	0.056	0.213	0.007	0.016

main dissipation process for the herbicides, but volatilization shortly after application may also have been a significant pathway for alachlor dissipation (Beestman and Deming, 1974; Chesters et al., 1989; Helling et al., 1988). Herbicide dissipation may have occurred by such secondary processes as surface water runoff, leaching, soil erosion, chemical degradation, plant uptake, photodegradation, and irreversible sorption to clay minerals or soil organic matter (Baker, 1992; Chesters et al., 1989).

Although the total amount of herbicide that leached into the subsurface drain system was often significantly larger in NT plots, only 0.0002 to 0.10% of the alachlor, 0.02 to 0.35% of the atrazine, and 0.14 to 0.87% of the metribuzin applied each year reached the subsurface drain system, regardless of tillage. Most of this leaching occurred in the first month after application (R.S. Kanwar et al., 1993, unpublished report). The soil sample data sets for all plots do not indicate that a large amount of concentrated herbicide solution was displaced deeper into the soil by matrix water flow (data not shown). These observations suggest that matrix displacement involved only dilute herbicide solutions, and that preferential flow leached small amounts of concentrated herbicide solution only for a short time after herbicides were applied.

The amount of water infiltration that bypasses the subsurface drain system has not been determined, so the total amount of herbicide leaching at this site is not known. But even if bypass leaching increases the amount of herbicide removed from the surface soil by an order of magnitude, this would still account for 10% or less of the yearly herbicide loss from the 100-cm soil profile. For comparison, 9% of the atrazine applied to NT plots was estimated to have leached into 1 m deep groundwater, while leaching from conventionally tilled plots was estimated to be negligible (Gish et al., 1991b). This amount of leaching loss may be significant from a water quality standpoint, but it is a minor loss compared with the total

Table 7. Average atrazine content in the 0- to 100-cm soil profile for all tillages and sampling times. Groups of tillages with no letters have no significant differences at the 0.05 level overall. Tillages followed by dissimilar letters (a, b, or c) are significantly different at the 0.05 level overall. No data for May and June 1991. For each average value, $N = 3$. The number below each date is the time since application (d).

	Atrazine (kg ha^{-1} a.i.) in rotation soybean								
Depth range and tillage	30 May 1990 28	25 Sept. 1990 146	30 Oct. 1990 181	23 Sept. 1991 118	13 Nov. 1991 169	29 Apr. 1992 337	23 June 1992 48	18 Sept. 1992 135	21 Oct. 1992 168
0–10 cm									
Average									
Chisel plow	2.618	0.513	0.276	0.204	0.135	0.098	0.675 a	0.140	0.109
Moldboard-plow	2.487	0.586	0.386	0.340	0.148	0.131	1.551 b	0.291	0.159
No-till	2.007	0.379	0.261	0.270	0.225	0.131	0.312 c	0.118	0.075
Ridge-till	2.197	0.151	0.229	0.167	0.126	0.097	0.192 ac	0.130	0.070
Standard error									
Chisel plow	0.156	0.053	0.021	0.017	0.011	0.011	0.040	0.033	0.016
Moldboard-plow	0.172	0.303	0.096	0.052	0.032	0.029	0.068	0.065	0.023
No-till	0.083	0.065	0.026	0.060	0.060	0.012	0.040	0.008	0.019
Ridge-till	0.839	0.114	0.052	0.034	0.013	0.045	0.125	0.028	0.013
0–20 cm									
Average									
Chisel plow	3.239	0.725	0.448	0.361	0.265	0.150	0.730 a	0.220	0.165
Moldboard-plow	2.880	0.862	0.566	0.488	0.269	0.215	1.695 b	0.375	0.215
No-till	2.334	0.617	0.435	0.406	0.320	0.203	0.404 c	0.200	0.131
Ridge-till	2.774	0.278	0.339	0.288	0.272	0.194	0.259 ac	0.194	0.113
Standard error									
Chisel plow	0.277	0.101	0.054	0.031	0.006	0.032	0.041	0.033	0.031
Moldboard-plow	0.186	0.336	0.105	0.126	0.051	0.027	0.100	0.064	0.022
No-till	0.045	0.079	0.035	0.080	0.043	0.030	0.037	0.011	0.022
Ridge-till	0.913	0.157	0.025	0.061	0.029	0.045	0.134	0.038	0.011
0–30 cm									
Average									
Chisel plow	3.350	0.881	0.542	0.475	0.363	0.170	0.759 a	0.242	0.180
Moldboard-plow	3.173	0.951	0.671	0.579	0.408	0.290	1.735 b	0.407	0.234
No-till	2.483	0.726	0.481	0.490	0.381	0.252	0.448 c	0.244	0.167
Ridge-till	3.069	0.396	0.413	0.354	0.366	0.266	0.308 ac	0.224	0.134
Standard error									
Chisel plow	0.290	0.034	0.106	0.062	0.035	0.039	0.042	0.032	0.037
Moldboard-plow	0.211	0.368	0.113	0.127	0.100	0.058	0.115	0.065	0.018
No-till	0.088	0.069	0.042	0.095	0.047	0.042	0.029	0.015	0.027
Ridge-till	0.971	0.138	0.026	0.068	0.037	0.038	0.149	0.044	0.006
0–100 cm									
Average									
Chisel plow	3.627	0.919	0.676	0.539	0.434	0.170	0.809 ab	0.254	0.180
Moldboard-plow	3.249	1.037	0.748	0.695	0.525	0.317	1.791 a	0.411	0.234
No-till	2.598	0.852	0.633	0.592	0.504	0.306	0.482 b	0.268	0.176
Ridge-till	3.243	0.515	0.490	0.449	0.458	0.333	0.568 ab	0.236	0.161
Standard error									
Chisel plow	0.288	0.053	0.190	0.069	0.049	0.039	0.071	0.037	0.037
Moldboard-plow	0.201	0.351	0.127	0.135	0.115	0.076	0.146	0.061	0.018
No-till	0.067	0.069	0.038	0.068	0.049	0.060	0.032	0.021	0.032
Ridge-till	0.950	0.146	0.045	0.103	0.074	0.030	0.134	0.049	0.019

amount of each herbicide that is applied to and dissipates from the soil each year.

Herbicide Dissipation Rates

The calculation of half-life values for the three herbicides was based on the overall average amounts of each herbicide in the 0- to 100-cm soil profile for all 3 yr. First-order half lives were calculated two ways: by using all data including the preapplication early spring data (0–374 d after application) and by using the growing season data collected only in the summer and fall (0–181 d after application). Figure 7 shows the FO model based on all data greatly underpredicts the amounts of all three herbicides in the soil during the first 100 d after application.

The growing season FO model is more satisfactory; the atrazine and metribuzin half-lives are comparable to published values, and the sum of squares due to error (SSE) for all herbicides has decreased (Table 9). The half-lives of 55 d for atrazine and 32 d for metribuzin are also similar to findings from other studies. The growing season FO model, however, underestimates the carryover of atrazine into the next growing season and still underpredicts the alachlor content in the soil during the first 50 d after application.

The two-compartment model (Hill and Schaalje, 1985) best fits the dissipation of alachlor. All data were used to determine model parameters. The alachlor half-life of 24 d calculated from the 2CM is comparable to other published values. The 2CM structure also provides a reasonable process of alachlor dissipation: rapid initial volatilization of the surface-applied herbicide followed by slower microbial degradation. The SSE values indicate the more complicated 2CM is not an improvement over the growing season FO model for atrazine and metribuzin, however, particularly during the growing season.

Table 8. Average metribuzin content in the 0- to 100-cm soil profile for all tillages and sampling times. Groups of tillages with no letters have no significant differences at the 0.05 level overall. Tillages followed by dissimilar letters (a, b, or c) are significantly different at the 0.05 level overall. No data for October 1990 and May and June 1991. For each average value, $N = 3$. The number below each date is the time since application (d).

	Metribuzin (kg ha^{-1} a.i.) in rotation soybean							
Depth range and tillage	30 May 1990 28	25 Sept. 1990 146	30 Oct. 1990 181	23 Sept. 1991 118	13 Nov. 1991 169	29 Apr. 1992 337	23 June 1992 48	18 Sept. 1992 135
0–10 cm								
Average								
Chisel plow	0.356	0.015	0.023	0.018	0.003	0.055	0.024	0.011 a
Moldboard-plow	0.457	0.026	0.043	0.038	0.005	0.123	0.032	0.012 ab
No-till	0.249	0.006	0.017	0.017	0.000	0.115	0.009	0.000 b
Ridge-till	0.393	0.011	0.028	0.017	0.028	0.176	0.020	0.014 ab
Standard error								
Chisel plow	0.071	0.008	0.003	0.004	0.003	0.028	0.005	0.001
Moldboard-plow	0.109	0.004	0.011	0.004	0.003	0.036	0.009	0.002
No-till	0.129	0.006	0.000	0.002	0.000	0.012	0.005	0.000
Ridge-till	0.039	0.006	0.003	0.001	0.028	0.063	0.002	0.007
0–20 cm								
Average								
Chisel plow	0.386	0.015	0.032	0.024 ab	0.003	0.059	0.024	0.011 a
Moldboard-plow	0.488	0.037	0.065	0.058 a	0.008	0.123	0.032	0.012 ab
No-till	0.271	0.006	0.032	0.017 b	0.000	0.124	0.009	0.000 b
Ridge-till	0.417	0.017	0.043	0.024 b	0.028	0.180	0.020	0.014 ab
Standard error								
Chisel plow	0.079	0.008	0.006	0.006	0.003	0.024	0.005	0.001
Moldboard-plow	0.102	0.011	0.013	0.005	0.005	0.036	0.009	0.002
No-till	0.126	0.006	0.011	0.002	0.000	0.016	0.005	0.000
Ridge-till	0.033	0.006	0.008	0.004	0.028	0.066	0.002	0.007
0–30 cm								
Average								
Chisel plow	0.409	0.015	0.032	0.024	0.003	0.059	0.024	0.014
Moldboard-plow	0.504	0.037	0.074	0.062	0.008	0.123	0.032	0.012
No-till	0.281	0.006	0.032	0.017	0.000	0.124	0.009	0.000
Ridge-till	0.466	0.017	0.048	0.027	0.028	0.180	0.020	0.014
Standard error								
Chisel plow	0.083	0.008	0.006	0.006	0.003	0.024	0.005	0.004
Moldboard-plow	0.099	0.011	0.009	0.008	0.005	0.036	0.009	0.002
No-till	0.130	0.006	0.011	0.002	0.000	0.016	0.005	0.000
Ridge-till	0.023	0.006	0.010	0.007	0.028	0.066	0.002	0.007
0–100 cm								
Average								
Chisel plow	0.429	0.015	0.032	0.024	0.015	0.059	0.024	0.014
Moldboard-plow	0.504	0.037	0.074	0.068	0.008	0.123	0.032	0.012
No-till	0.281	0.006	0.032	0.017	0.000	0.124	0.009	0.000
Ridge-till	0.471	0.017	0.052	0.027	0.028	0.180	0.020	0.014
Standard error								
Chisel plow	0.098	0.008	0.006	0.006	0.011	0.024	0.005	0.004
Moldboard-plow	0.099	0.011	0.009	0.013	0.005	0.036	0.009	0.002
No-till	0.130	0.006	0.011	0.002	0.000	0.016	0.005	0.000
Ridge-till	0.027	0.006	0.014	0.007	0.028	0.066	0.002	0.007

SUMMARY AND CONCLUSIONS

Tillage had little significant effect on the overall distribution and dissipation of alachlor, atrazine, and metribuzin in the soil, although no-till plots tended to have the smallest amounts of alachlor and metribuzin in the soil, and ridge-till plots tended to have the smallest amounts of atrazine. Moldboard-plow plots usually had the largest amounts of all three herbicides. Throughout the growing season, 50 to 84% of the alachlor and metribuzin was retained in the top 10-cm soil layer, while at least 68% of the atrazine was found in the top 20 cm. The best-fit half-lives of 24 d for alachlor, 55 d for atrazine, and 32 d for metribuzin were comparable to those reported for other studies, although a first-order

Table 9. Experimental herbicide half-lives, $t_{0.5}$.

	First-order model				Two-compartment model, all data used		Published values
	All data used		Growing-season data used				
Herbicide	$t_{0.5}$ (d)	SSE†	$t_{0.5}$ (d)	SSE	$t_{0.5}$ (d)	SSE	$t_{0.5}$ (d)‡
Alachlor	93	5.9	36	1.7	24	0.8	10 to 25
Atrazine	134	10.2	55	3.4	40	3.4	60 to 73
Metribuzin	45	0.1	32	0.02	47	0.02	30 to 40

† SSE = sum of squares due to error; as SSE approaches zero, the model better fits the experimental data.

‡ Chesters et al., 1989; Gish et al., 1991b; Helling et al., 1988.

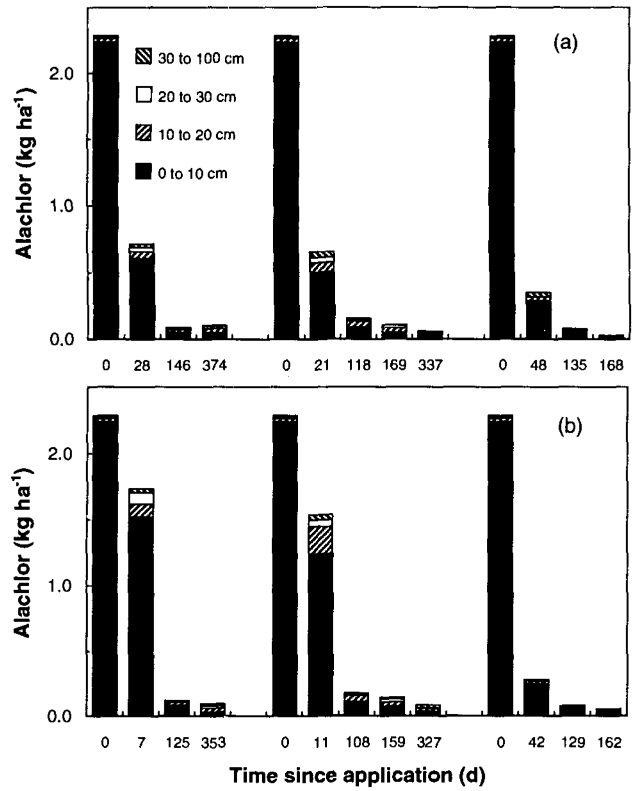

Fig. 5. Dissipation and distribution of (*a*) alachlor in continuous and rotation corn, (*b*) alachlor in rotation soybean in the 0- to 100-cm soil profile for 1990 (left-hand set of columns), 1991 (center), and 1992 (right). Amounts on Day 0 are estimated.

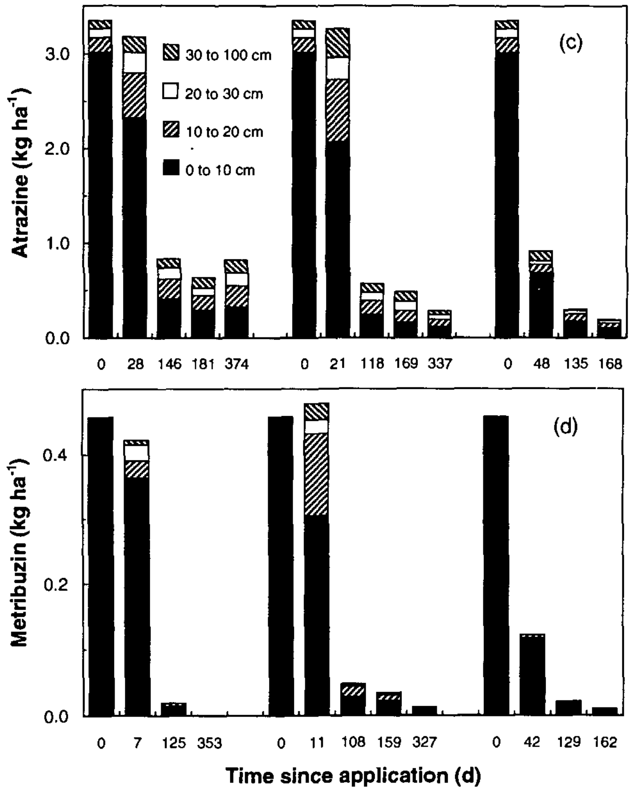

Fig. 6. Dissipation and distribution of (*c*) atrazine in continuous corn and (*d*) metribuzin in rotation soybean in the 0- to 100-cm soil profile for 1990 (left-hand set of columns), 1991 (center), and 1992 (right). Amounts on Day 0 are estimated.

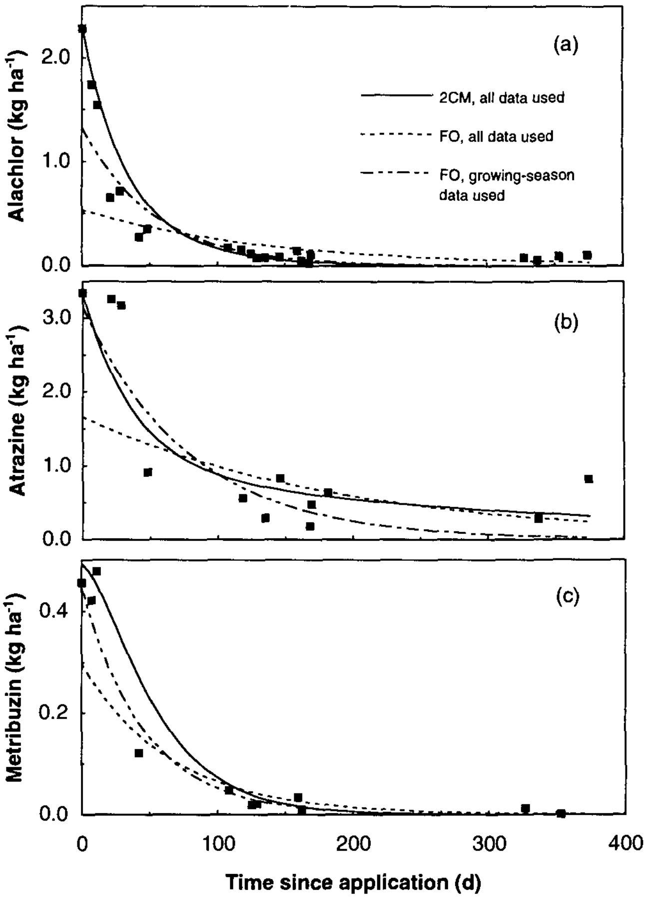

Fig. 7. Dissipation of (*a*) alachlor, (*b*) atrazine, and (*c*) metribuzin in the 0- to 100-cm soil profile based on data from 1990, 1991, and 1992. 2CM, two compartment model; FO, first-order model.

degradation model fitted to all of the data poorly described the initial dissipation of each of the herbicides. Future studies at this site to characterize the spatial and temporal distribution of herbicides in the soil may be more useful than those based strictly on tillage comparisons.

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