

Alachlor Dissipation in Shallow Cropland Soil

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ABSTRACT

A soil-column laboratory experiment and a 2-yr field-sampling study evaluated the overall dissipation of alachlor [2-chloro-*N*-(2,6-diethylphenyl)-*N*-(methoxymethyl) acetamide]. These studies also measured the effect of no-till and chisel-plow tillages on alachlor leaching and dissipation. In the top 30 cm layer of soil, the overall half-life was 3 d or less, and the time to 90% dissipation ranged from 17 to 30 d. In no-till soil, alachlor dissipated slightly faster, and more was transported into the 10 to 30 cm soil layer. Weather conditions promoting the movement of alachlor into the soil, however, weakened the effect of tillage on the dissipation rate. Most of the alachlor present in the soil, regardless of tillage, was found in the top 10 cm at all times. Of the alachlor applied to 30-cm tall soil columns, only 0.4% was removed by water flowing from chisel-plow columns and 1.6% from no-till columns. The results show that tillage was not a key factor in alachlor dissipation and leaching. Alachlor leaching was also a minor component in overall dissipation.

ALACHLOR is a herbicide that controls annual grasses and broadleaf weeds and is usually applied to corn [*Zea mays* (L.)] and soybean [*Glycine max* (L.) Merr.] cropland in the Corn Belt. At ambient temperatures, pure alachlor is a solid, slightly soluble, and slightly volatile material (Table 1).

OVERALL DISSIPATION

Alachlor dissipates in the field mainly by microbial degradation and volatilization (Chesters et al., 1989). Other routes of dissipation, such as photolytic and chemical degradation, leaching, runoff, and plant uptake, are minor processes, although even small amounts of leaching and runoff may be an environmental concern. Weather conditions; tillage practice; and soil sorption, composition, temperature, and water content cause the rate of alachlor dissipation to be highly variable as the following field studies show.

The alachlor half-life (time to 50% dissipation) was 24 d with no significant effect from tillage or crop treatments (Weed et al., 1995), 18 to 45 d based on date of application and type of soil (Walker et al., 1992), and 1 to 39 d in no-till soil depending mainly on weather conditions (Helling et al., 1988). Other studies found half-lives of 6 d in either no- or conventional-till soil (Wienhold and Gish, 1994), 20 to 40 d depending on the number of previous alachlor applications (Walker and Welch, 1991), and roughly 7 to 20 d with slightly faster dissipation in no-till or straw-covered soil and slower in moldboard-plowed or bare soil (Jones, Jr. et al., 1990).

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Published in J. Environ. Qual. 27:767-776 (1998).

VOLATILIZATION

Alachlor sprayed on the soil surface is fairly volatile compared with other agricultural pesticides. Volatilization is strongly dependent on the water content in surface soil and the amount of alachlor that has sorbed to soil particles. In the first 21 d after spray application, 780% more alachlor than atrazine [2-chloro-4-ethylamino-6-isopropylamino-1,3,5-triazine] volatilized, based on equal rates of application for both herbicides (Glotfelty et al., 1989).

Even in controlled conditions, volatilization rates vary widely. The half-life of surface-applied alachlor in air-dried soils ranged from 108 to 203 d depending on soil type, while the half-life in soils nearly saturated with water ranged from 12 to 27 d (Beestman and Deming, 1974). Alachlor sorption further reduces volatilization rates; Peter and Weber (1985) reported that about 50% of the alachlor volatilized 8 d after it was applied to a glass plate, while only 0.1% volatilized during the same period when applied to soil.

In the field, tillage and residue cover are not clearly related to rates of volatilization. Compared with conventional-till practices (chisel plow or moldboard plow), conservation-till (ridge-till or no-till) may increase volatilization losses, because alachlor must usually be sprayed on the surface without incorporating it into the soil. If spraying is done on a sunny day, turbulent air flow near the soil surface and high air and soil temperatures would increase volatilization. Plant-residue cover and higher soil-water content at the surface of conservation-till soil would also slow sorption of alachlor to soil particles so volatilization could occur over a longer period. Alternatively, volatilization may be slowed on conservation-till soil once the alachlor is incorporated into the soil structure, because the residue cover would shade the soil and lower the surface-soil temperature. Large amounts of residue cover might also increase the surface roughness to decrease air turbulence at the soil surface. The following studies show that one cannot predict volatilization in the field knowing only the tillage or amount of residue cover.

Within 1 d after alachlor application, Tremwel (1985) found no dissipation of alachlor spray applied to the surface of bare soil. About 33% of the alachlor applied to soil with a 95% plant-residue cover had dissipated in the same time, however. Roughly half of that loss was attributed to volatilization from plant residues. After 7 d of rainless weather, 92% of the alachlor applied to bare soil remained, while only 48% remained in the residue-covered treatment.

A higher-than-expected rate of dissipation on no-till soil was attributed to spraying alachlor over plant residue on a hot (32°C) day (Helling et al., 1988). Alachlor volatilized faster from moist soil when solar radiation maximized the soil temperature and air turbulence near the soil surface. Volatilization from dry soil was much slower; the highest rates occurred at night when dew formed on the soil surface (Glotfelty et al., 1984, 1989; Turner et al., 1977).

In another study, volatilization from no-till soil was slightly faster than from conventional-tilled soil in the first week after application. After 35 d, about 9% of the alachlor applied had volatilized from the no-till field, while about 14% had volatilized from conventional-tilled soil (Wienhold and Gish, 1994).

Abbreviations: a.i., active ingredient; NSTL, National Soil Tilth Lab; ET, evapotranspiration.

Table 1. Properties of alachlor. Except as noted, adapted from Chesters et al. (1989).

Physical or chemical property		
Color	White	
Physical state	Solid	
Odor	None	
Molecular weight	269.8	g mol ⁻¹
Melting point	40–41	°C
Boiling point	100	°C at 0.003 kPa
Specific gravity	1.133	at 25°C
Water solubility	240	mg L ⁻¹
Vapor pressure	2.9 × 10 ⁻⁶	kPa at 25°C
Vapor density	3.2 × 10 ⁻⁴	mgL ⁻¹
Henry's law coefficient, K_H	1.3 × 10 ⁻⁶	L air L ⁻¹ water
Octanol-water partition coefficient, K_{ow}^\dagger	430	
Soil sorption coefficient, K_d^\ddagger	3.4	L kg ⁻¹

[†] Organic C partition coefficient, $K_{oc} = (K_{ow})$ (organic C content in soil).
[‡] Cooperative Extension Service (1992).

MICROBIAL DEGRADATION AND SORPTION

Microbial degradation of alachlor usually fits a first-order model, and the half-life ranges from 8 to 40 d (Beestman and Deming, 1974; Chesters et al., 1989; Walker and Welch, 1991). Variations in soil water content, organic matter content, soil temperature (Walker et al., 1992) and microbial composition (Sun et al., 1990; Walker and Welch, 1991), however, may alter the microbial degradation rate considerably, sometimes by as much as an order of magnitude.

Sorption is controlled by the organic matter content, clay content, and surface area of the soil (Peter and Weber, 1985; Shea, 1989). Initial binding of alachlor to soil is rapid (Bosetto et al., 1993; Pignatello and Huang, 1991), but the release (desorption) of alachlor from soil is slow and incomplete (Bosetto et al., 1993; Chesters et al., 1989; Pignatello and Huang, 1991; Xue and Selim, 1995). Xue and Selim (1995) speculated that some of the alachlor they could not recover by desorption had actually been microbially decomposed rather than irreversibly sorbed. If their opinion is correct, then sorption and degradation are inseparable processes under field conditions.

The effect of tillage on degradation and sorption is unclear. Conservation-tilled soil typically contains more organic material in the surface layer and supports a larger and more active microbial population than conventional-tilled soil (Fermanich and Daniel, 1991; Locke and Harper, 1991) compared with conventional-till soil. These qualities would enhance both sorption and microbial degradation of alachlor in conservation-tilled soil, but tillage alone is not a reliable predictor of the degree of degradation and sorption.

LEACHING AND SURFACE-WATER RUNOFF

Alachlor loss by leaching and in surface-water runoff is small, but this loss can be a water-quality concern. The water solubility of alachlor is moderately high (Table 1), but the potential for leaching and runoff losses is offset by rapid rates of alachlor degradation, volatilization, and sorption (Guo et al., 1993). Alachlor tends to remain in the top 10 to 20 cm of soil and does not leach in significant amounts through soil (Beestman and Deming, 1974; Buhler et al., 1993; Jones, Jr. et al., 1990). Small amounts (<1%) may leach below the root zone shortly after alachlor has been applied (Weed et al., 1995). Survey results predict that of alachlor would be detected in fewer than 1% of the 6 million domestic wells in those counties where alachlor is sold (Holden and Graham, 1992). If heavy rains and surface-water runoff occur immediately after alachlor application, alachlor can be transported to

streams and lakes. Alachlor in two Nebraska lakes, however, did not exceed 1 $\mu\text{g L}^{-1}$ in water samples and did not exceed 1 ng L⁻¹ in sediment cores (Spalding et al., 1994).

Compared with conventional-till, conservation-till may enhance leaching shortly after alachlor application, because soil macropores, such as root holes, worm burrows, and cracks, are not as disturbed (Gish et al., 1991a; Sadeghi and Isensee, 1992), and the preferential-flow network is better developed (Granovsky et al., 1993). Leaching immediately after application may also be enhanced by conservation-till because pesticides are not usually incorporated into conservation-tilled soil (Baker, 1992; Gish et al., 1991b; Rice et al., 1991; Starr and Glotfelty, 1990; Steenhuis et al., 1990). These factors increase the probability that alachlor will be washed from the surface soil into the macropore network and transported rapidly below the root zone soil.

GOALS OF STUDY

One goal of the field and laboratory experiments described here was to measure the overall dissipation rate of alachlor in the top 30 cm layer of field soil. The second goal was to determine whether no-till or chisel-plow tillage affected alachlor leaching and overall dissipation.

MATERIALS AND METHODS

These experiments occurred at a 36-plot experimental site at Iowa State University's Northeast Research Farm near Nashua, IA. The site was first developed in 1977 to evaluate tillage and crop rotation effects on crop yields and weed and insect populations. In 1988, a water quality monitoring program was added. General information about this site is provided elsewhere (Kanwar, 1991; Karlen et al., 1991; Weed et al., 1995). From 1977 through 1994, alachlor was broadcast sprayed over all of the 0.4-ha plots immediately after planting with no subsequent incorporation into the soil. The herbicide solution was a commercially available emulsifiable concentrate diluted with water according to manufacturer's directions. It was applied immediately after planting at a rate of 2.2 kg ha⁻¹ active ingredient (a.i.). While this project was active, alachlor was applied on 26 May 1993 and 19 May 1994.

Field Sampling Experiment

Sample Collection

In 1993 and 1994, soil samples were collected from 12 plots that were separated into three clusters; each cluster contained four adjacent plots (Fig. 1). The clusters were located as far apart as possible to reduce the effect of topography on the experiment. Plots 1, 3, 10, and 11 were one cluster, plots 7, 15, 23, and 24 were the second, and plots 27, 28, 29, and 30 were the third. Soils in these plots 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).

Each cluster had two plots in chisel-plow tillage, and two in no-till. All six chisel-plow plots had been in ridge till from 1977 to 1992, but were converted in the fall of 1992 to chisel-plow tillage to accommodate another study. All six no-till plots, however, had been consistently in no-till since 1977.

All 12 plots had been planted since 1977 in a corn-soybean rotation. In each year, one chisel-plow plot and one no-till plot in each cluster were planted with corn and the other two plots were planted to soybean. We sampled only those plots planted with soybean. These plots were covered with corn

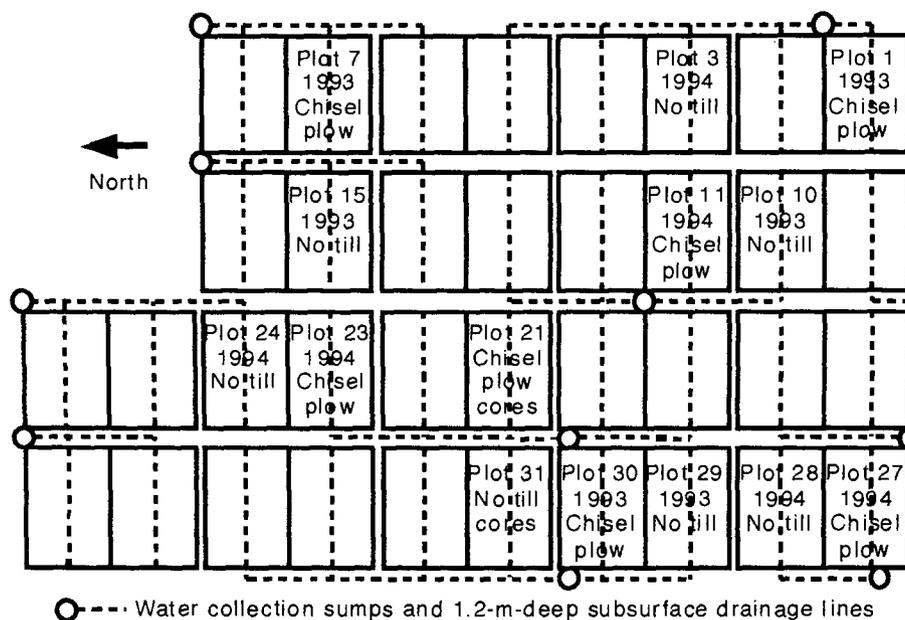


Fig. 1. Site layout showing the location and tillage treatment of the 12 plots from which samples were collected in either 1993 or 1994 and of plots 21 and 31 from which soil columns were removed in November 1993.

stover from the previous year that would enhance tillage differences, compared with plots covered with soybean residue.

Eight sets of soil samples were collected annually from the six plots planted to soybean. All samples were taken from 1 to 90 d after the day that alachlor was applied. The time between sample sets was 2 to 5 d initially, but the interval was lengthened to 40 d based on other dissipation data collected at this site (Weed et al., 1995).

We decided to include the loss of spray mist during application as an integral part of the overall dissipation rate, since this loss is an unavoidable part of typical broadcast-spraying methods. The initial alachlor content in the 0 to 10 cm soil layer was set at the calibrated application rate of 2.2 kg ha^{-1} . The residual alachlor in the 10 to 30 cm soil layer at the time of application was set at 0.024 kg ha^{-1} . This is the average alachlor content in 10 to 30 cm deep soil samples collected on 29 Apr. 1992, shortly before alachlor was applied to plots at the experimental site.

We also did not collect soil samples immediately after application. Although this is not a conventional approach, it is consistent with our decision to include spray loss as part of the dissipation rate. Additionally, we felt that data collected at this time would not be meaningful because the rate of alachlor loss was expected to be extremely fast and vary considerably within each plot. To gather statistically valid information, we would have had to sample a large part of the soil surface in each plot with precise timing, which was impractical. The alachlor dissipated by spray-mist loss and initial volatilization is equal to the difference between the initial alachlor content of 2.2 kg ha^{-1} and the alachlor content remaining in the 0 to 10 cm soil layer at the time of the first sampling.

In their study of volatilization and wind erosion of surface-applied pesticides, Glotfelty et al. (1989) also did not measure the initial amount of pesticide that reached the soil. Even though they observed spray-mist loss during application, they chose to compare the amount of pesticide volatilizing from the soil with that applied by the spray equipment.

At each sampling time, five replicate soil cores, each 30 cm deep and 2.5 cm diam., were taken from every plot using a hand sampler. Plant residues were not collected, since the small surface area of the soil cores made it difficult to accu-

rately relate the amount of alachlor on plant residue to that in the soil. Soil cores were frozen promptly after collection. The five cores from each plot were cut into two sections representing 0 to 10 and 10 to 30 cm depths, and sections were composited into one pair of samples. The samples were wrapped in aluminum foil, sealed in a labeled polyethylene bag, then refrozen for transportation and storage.

Sample Analysis

The National Soil Tilth Lab (NSTL), Ames, IA, tested all soil samples for alachlor using a standardized, highly automated procedure. Metabolic products of alachlor were not quantified. To analyze soil samples for alachlor, 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 extraction solvent was reduced to 3 mL or less by evaporation at 50°C in a N atmosphere. Organics were adsorbed from the solvent with an Analytichem International C-18 cartridge that adsorbs organic compounds, including alachlor. Alachlor was then selectively eluted from the cartridge with ethyl acetate, which contained an internal standard of 0.55 ng mL^{-1} terbutylazine [1,3,5-triazine-2,4-diamine, 6-chloro-*N*-(1,1-dimethylethyl)-*N'*-ethyl-terbutylazine]. Alachlor concentrations in the ethyl-acetate solution 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 alachlor 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} .

Ten percent of all soil samples extracted and analyzed by the NSTL were controls that were spiked a minimum of 15 h before initial extraction with 10, 50, or 100 mg kg^{-1} a.i. of alachlor. 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] surro-

gate shortly before extraction. Typically, control recoveries for all three spike amounts have averaged 77% with a 1.6% SE of the mean for alachlor. No adjustments were made to the data to account for analytical variability, since this variability is much smaller than the overall variability among samples. No correction for <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 NSTL have shown no detectable change in alachlor levels while soil cores are held in frozen storage (R.L. Pfeiffer, 1996, personal communication).

All results were converted from mg kg^{-1} a.i. to kg ha^{-1} a.i. basis using the appropriate conversions and bulk soil density and predominant soil type in each plot. The mean and SE of the mean (equal to the SD divided by the square root of the number of observations) were calculated for each depth range and sample time. The means were tested for significant differences by calculating *t*-test values (Steel and Torrie, 1980).

Laboratory Column Experiment

Column Collection

A total of 16 large-diameter soil columns were removed in November 1993 for an alachlor dissipation and leaching experiment. Eight replicates were taken from plot 21 that had been in chisel-plow corn since 1977. The remaining eight replicates were collected from plot 31 (Fig. 1) that had been in no-till corn during the same period. By November, all other plots with corn residue on them had been tilled or fertilized; plots 21 and 31 had not been disturbed since harvest. To minimize variability due to soil composition, all 16 columns

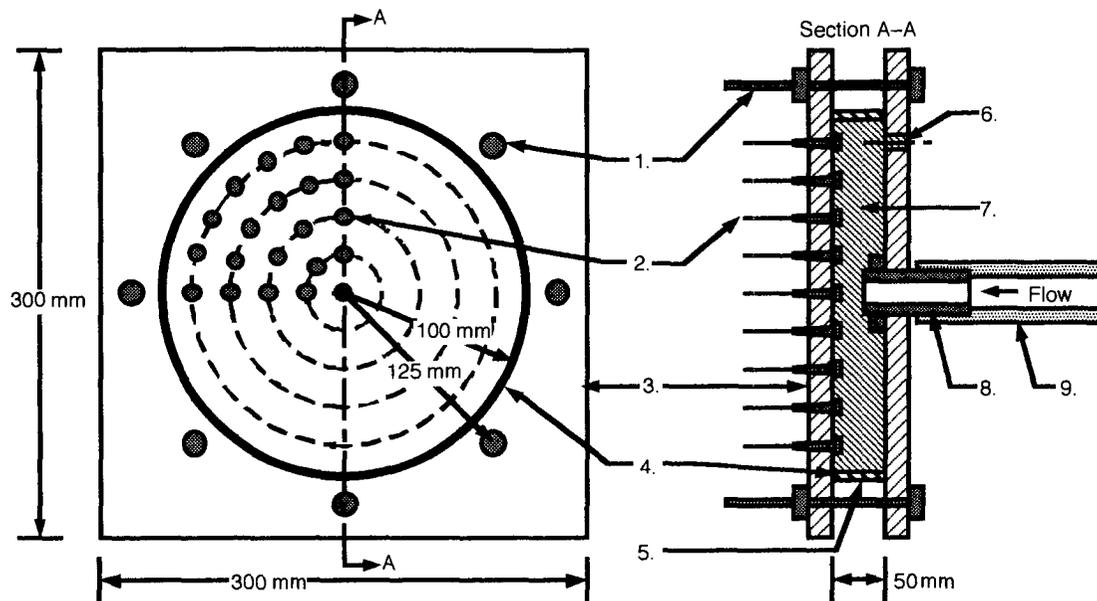
were collected as close together as was practical from Readlyn loam soil.

Galvanized steel, 20 cm diam. pipe was cut into lengths about 45 cm long. A bevel was filed on one cut edge to reduce the force needed to press the pipe into the soil. To indicate the desired depth of the soil core, the inside circumference of each pipe was marked 30 cm from the beveled edge. Two opposing, 1.2-cm holes were drilled with their centers about 2.5 cm from the unbeveled edge. These holes allowed the pipe section to be pinned to a pressure plate on the hydraulic ram of a tractor-mounted soil sampler.

In the field, the plant residue was removed from a selected location. A pipe section was pinned to the pressure plate and positioned on the cleared soil. To reduce compaction, the pipe was pushed into the soil as slowly as possible. When the soil in the pipe rose to the 30-cm mark, the soil column and encasing pipe were pulled out of the soil and detached from the pressure plate. The cleanly broken subsurface face of each column was left undisturbed to avoid altering the pore structure. The plant residue saved earlier was returned to the surface of each column for future use. Both ends of the column were gently covered with aluminum foil, and a rigid protective cover was taped over the ends. The columns were frozen within 4 h of collection.

Experimental Procedure

The 16 soil columns were thawed at room temperature, and the protective wrappings were removed. The plant residue was removed from the columns, and large pieces of roots, corn cobs, and thick stems were removed from the residue. The remainder was chopped into pieces about 3 cm square.



Not to scale. All dimensions are approximate

1. Bolt, 2 washers, nut (8 assemblies) Tighten to compress gaskets for a watertight seal
2. Hypodermic needles, approximately 61 each, press-fit into holes drilled through one faceplate, typical placement shown
3. Acrylic faceplate (2 each), 10 mm thick
4. Neoprene gasket (2 each) fitted into a routed recess in the faceplate
5. Acrylic cylinder (1 each), 4 mm wall thickness
6. Air vent with water-tight plug
7. Water reservoir formed by body cylinder and faceplates distributes water at constant pressure to all needles
8. Nipple and nut (1 assembly) connecting plastic tubing to faceplate
9. Tubing connecting the rain simulator to a metering pump

Fig. 2. Rain simulator used to apply water to soil columns.

A 20 cm circle of fine steel-wire mesh was laid over the subsurface end of each column, and a reinforcing square of coarser wire mesh was wrapped over the fine screen and secured to the outside of the column. The columns were saturated from the bottom with deionized water over a 17-d period. After draining for 4 d, they were placed, in random order, in a 4 by 4 grid. The bottom of each column rested in a large metal funnel that would channel drainage water into a collection jar. Since minimal alachlor was expected to leach through the columns by matrix flow, no suction was applied to the column bottoms, so only water flowing through the soil by gravity was collected.

Two soybean seeds were planted in the center of each soil column. Plant residue was spread in a thin layer over 60% of the surface area of no-till columns and over 30% of the surface of chisel-plow columns. A solution of deionized water and commercial-grade emulsifiable alachlor was then sprayed by hand over the surface of each column at a rate of 2.2 kg ha^{-1} a.i. The product literature recommended that 23 mL m^{-2} be applied to cropland, which is equivalent to 0.75 mL per column. A more practical volume of 5 mL was sprayed on each column instead, for a rate of 154 mL m^{-2} . This larger volume of liquid just wet the soil, however, so most of the alachlor remained on the surface, as desired.

After the alachlor solution had dried, a fan was turned on to provide a driving force for alachlor volatilization. The wind speed at the surface of the columns was adjusted using a mechanical windspeed gauge to 4 m s^{-1} or less. This value is the 50-yr average windspeed at the Nashua site in June. The fan was permanently shut off after 9 d of continuous ventilation.

Beginning 7 d after alachlor was applied, 25 mm of deionized water was applied to each column once a week at an intensity of 50 mm h^{-1} and a duration of 30 min. No surface-water runoff was allowed. The 25-mm amount is the average weekly precipitation in Iowa during the months of June, July, and August for the years 1950 through 1990. The intensity and duration are typical of about 50% of the rain storms that occur at Nashua (i.e., this is the 2-yr return period rainfall). The only exception to this plan occurred when 31 mm were applied to offset the marked drying caused by the fan ventilation.

Eight days after application, as most of the soybean seeds were emerging, four 40 W full-spectrum fluorescent lights (Vita-lite, Duro-Test Corporation, 9 Law Drive, Fairfield, NJ, USA 07004) were turned on continuously. The lights were positioned as close to the columns as was practical for the best plant growth, then were gradually raised as the plants

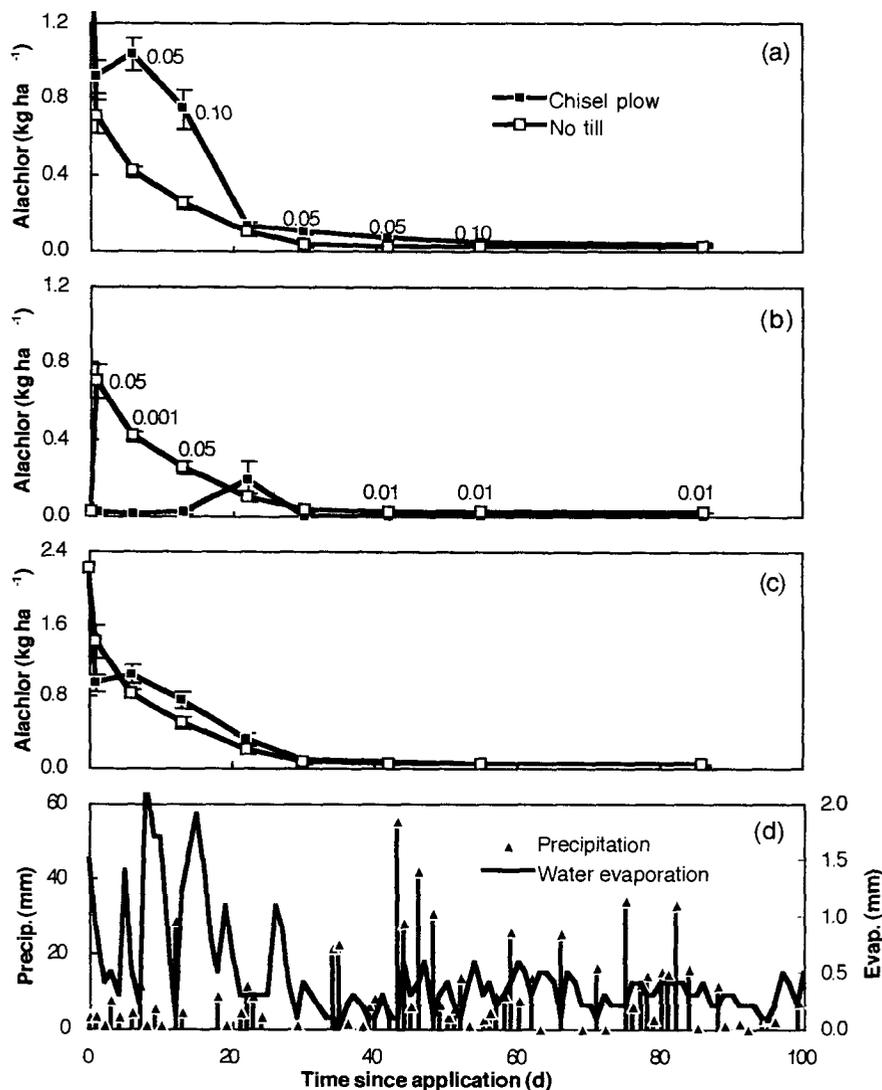


Fig. 3. Overall field dissipation of alachlor for 1993 in (a) the 0 to 10 cm soil layer, (b) the 10 to 30 cm soil layer, and (c) the entire 0 to 30 cm soil layer. Error bars indicate the standard error of each mean. Probability values adjacent to some data pairs indicate significant differences of 0.10 or smaller between tillage treatments. 1993 precipitation and soil-water evaporation are shown in (d).

grew taller. Room temperature throughout the experiment ranged from 15 to 24°C.

The precipitation was applied with a rain simulator made from hypodermic needles and acrylic plastic (Fig. 2). When the soybean plants were small, the rain simulator rested on top of the pipe that extended about 15 cm above the surface of each soil column. After the plants grew out of the enclosing pipe, a 30-cm long acrylic extension was temporarily attached to each pipe, and the simulator was put on top of the extension. All water that drained from each column was collected, the total volume was measured and recorded, and samples were submitted for alachlor analysis. In some cases, small samples were combined to create a 200 mL minimum sample needed for reliable analysis.

One no-till column and one chisel-plow column were removed from the experiment on each of the following days after alachlor was applied: 1, 5, 9, 15, 29, 35, 54, and 75 d. Sampling was more frequent at first so the rapid rate of dissipation during that time could be monitored closely.

The sacrificed columns were cut radially with a bandsaw into sections representing the 0 to 10 cm and 10 to 30 cm depths. Each pipe section was then cut axially to release the

soil block inside. The soil and plant residue in each section were removed, crumbled, thoroughly mixed, and sampled, using a method similar to that described previously for compositing field-soil samples.

Sample Analysis

All soil and water samples from this soil-column experiment were analyzed by the NSTL using the soil-testing procedure previously described. Water samples were analyzed for alachlor by adding propazine surrogate to a 250 mL sample, then passing the sample through an Analytichem International C-18 cartridge that adsorbed organic compounds, including the herbicides of interest. The herbicides and surrogate were eluted from the cartridge with 2 mL of ethyl acetate containing internal standards. The alachlor in the ethyl acetate solution was then quantified by mass spectroscopy. The minimum detection limit for alachlor in water samples was 0.2 mg kg⁻¹ a.i. As in the field-sampling experiment, all laboratory results were converted from mg kg⁻¹ a.i. to a kg ha⁻¹ a.i. basis. The mean, SE, and *t*-test values were calculated when there were replicate data from the rainfall experiments. Since one column

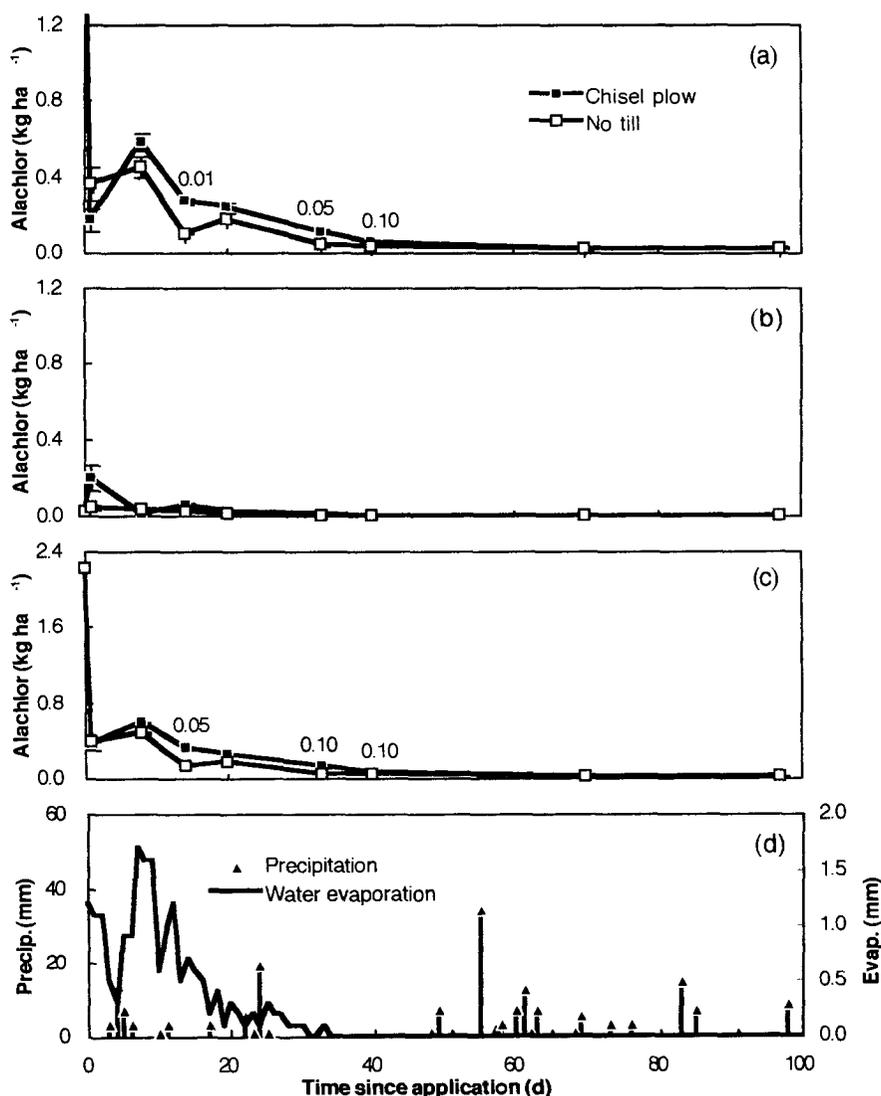


Fig. 4. Overall field dissipation of alachlor for 1994 in (a) the 0 to 10 cm soil layer, (b) the 10 to 30 cm soil layer, and (c) the entire 0 to 30 cm soil layer. Error bars indicate the standard error of each mean. Probability values adjacent to some data pairs indicate significant differences of 0.10 or smaller between tillage treatments. 1994 precipitation and soil-water evaporation are shown in (d).

from each tillage was sacrificed at a given time, statistical analysis of the soil data was not possible.

RESULTS AND DISCUSSION

Field Sampling Experiment

A comparison of tillage treatment data shows slightly less alachlor in the 0 to 30 cm layer in no-till plots for both 1993 (Fig. 3) and 1994 (Fig. 4), but these tillage differences were small. Based on the nominal application rate of 2.2 kg ha^{-1} , the time to 90% dissipation of alachlor in the 0 to 30 cm soil layer was roughly 25 d in 1993, but only about 17 d in 1994.

In both years, the half-life (time to 50% dissipation) of the newly applied alachlor was $<1 \text{ d}$ in both tillage treatments. It is likely that the actual half-life for both tillages would have been somewhat longer if the amount of herbicide remaining on residue had been measured. In the laboratory column experiment in which the alachlor on residues and the soil was measured, the half-life was 3 d for both tillage treatments. Other studies suggest that the amount of alachlor on plant residues can be a large part of the amount applied. Helling et al. (1988) reported that about 75% of the alachlor applied to no-till soil was on plant residues on the day of application. Tremwel (1985) found 61% of the alachlor applied to conservation-tilled soil was on plant residues 1 d after application. Chisel-plow soil would contain more alachlor than no-till soil in inverse proportion to the amount of residue cover.

In the first 20 d after alachlor was applied in 1993, there was more alachlor in the 0 to 10 cm layer of chisel-plow soil, although this may not have been a significant finding if the alachlor remaining on plant residue had been measured. Significantly more alachlor, however, was transported to the 10 to 30 cm layer of no-till soil (Fig. 3). After Day 20, there were only slight differences between tillage treatments, regardless of depth.

In 1993, 18 mm of rain fell in the first 5 d after alachlor was applied. Daily amounts ranged from 1 to 8 mm. The total water evaporation from the soil during that time was 3.6 mm, with daily amounts from 0.2 mm to a moderate 1.5 mm. Water evaporation rates indicate the intensity of factors such as solar radiation, air temperature, relative humidity, and wind speed that drive not only water evaporation, but alachlor volatilization. Daily evaporation rates were estimated by first calculating the daily grass evapotranspiration (ET) (Cuenca, 1989) and fraction of soil covered by foliage and plant residue (Cuenca, 1989; Hanks and Richie, 1991). Water evaporation from the soil was then estimated from the grass ET (Walker and Barnes, 1981) and ground cover fraction.

In the first 40 d in 1994, three of the seven sample sets contained significantly more alachlor in the 0 to 10 cm layer of chisel-plow soil (Fig. 4). These differences may have been eliminated if the alachlor on crop residue had been measured. There were no differences between tillage treatments after Day 40. These trends were echoed in the data for the entire 30 cm soil profile, since alachlor in the 10 to 30 cm soil layer was minimal. No rain fell the first 3 d after alachlor was applied, then a total of 17 mm of rain fell on Days 4 and 5. Water evaporation during that time was 4.2 mm; daily amounts ranged from 0.3 to 1.2 mm.

The light rains that fell during the first 3 d after application in 1993 may have increased alachlor persistence that year, compared with 1994. These rains would have washed more alachlor off the soil surface and plant residue and into the soil, thus reducing the amount available for volatilization and increasing the pool of alachlor available for microbial degradation. During these crucial rains, alachlor also appears to have been transported deeper into no-till soil by preferential flow, while alachlor in chisel-plow plots may have been leached into surface soil mainly by matrix flow. In the first 3 d after

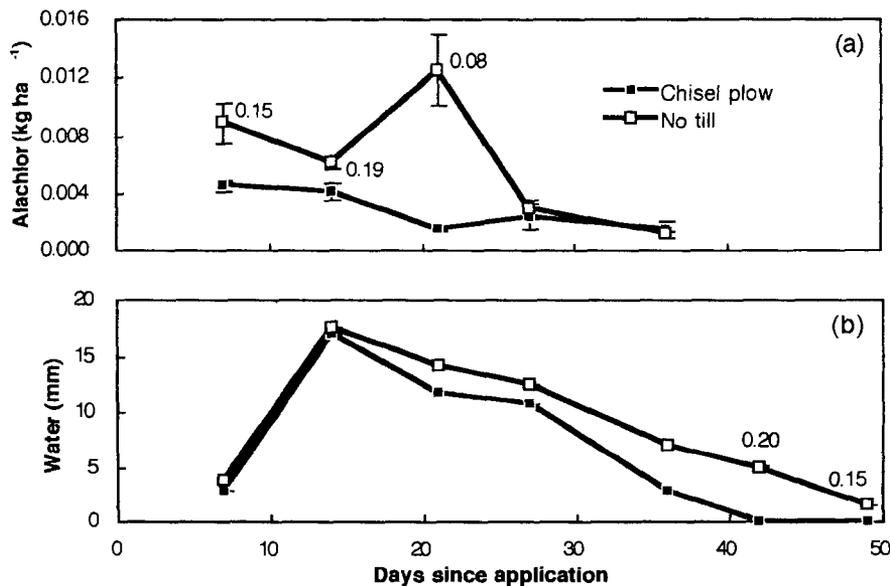


Fig. 5. Losses from all soil columns of (a) alachlor and (b) water. Error bars indicate the standard error of each mean. Probability values adjacent to some data pairs indicate significant differences of 0.20 or smaller between tillage treatments.

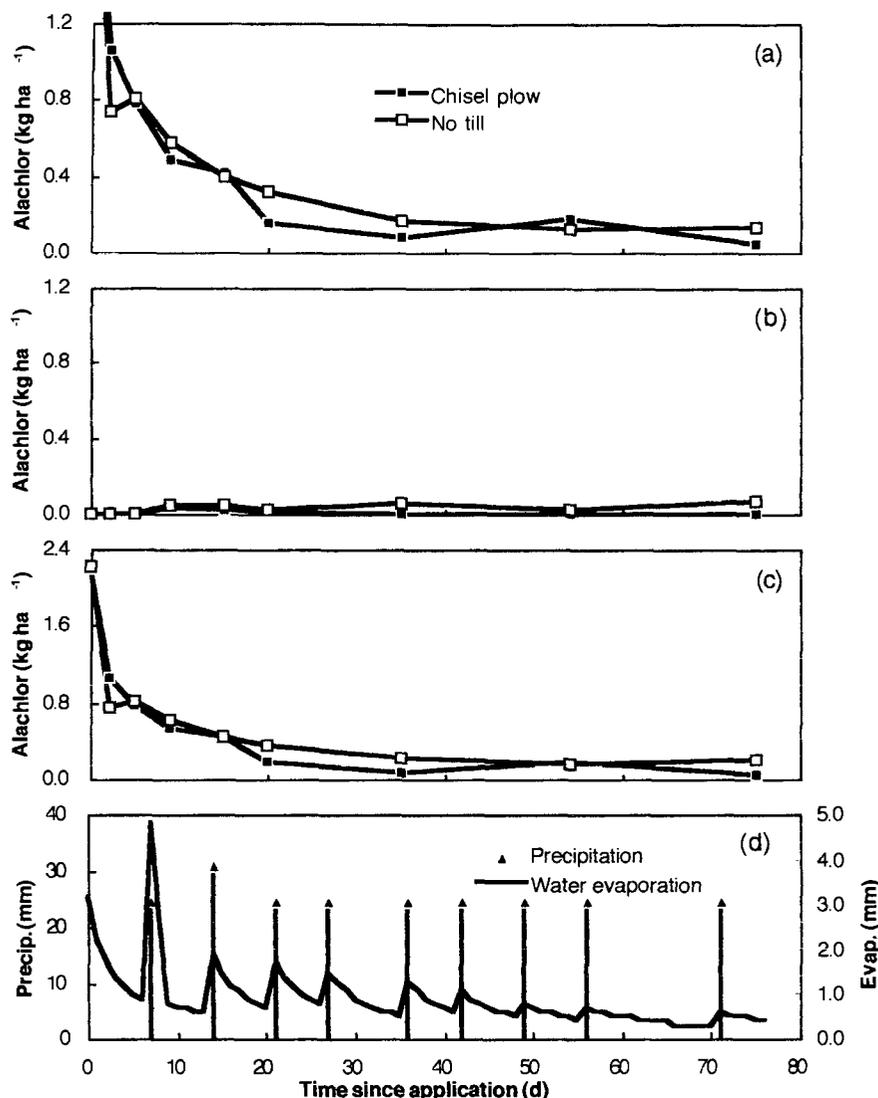


Fig. 6. Overall dissipation of alachlor in (a) the 0 to 10 cm soil layer, (b) the 10 to 30 cm soil layer, and (c) the entire 0 to 30 cm soil layer of sequentially-sacrificed pairs of soil columns. Precipitation amounts and estimated water evaporation from the soil are shown in (d).

alachlor application in 1994, however, most of the alachlor would have remained on the soil surface and plant residue, since there was no rain. This probably increased volatilization and shortened overall persistence.

Laboratory Column Experiment

Before the first simulated 25-mm rainfall on Day 7, fan ventilation had dried the soil, so minimal amounts of water drained from the columns (Fig. 5). After the fan was turned off on Day 9, much more water flowed from the columns until Day 27, when water drainage was cut again by soybean transpiration. When there was appreciable drainage, more water was collected from no-till soil columns than from chisel-plow columns, although none of the differences were significant at a probability of 0.10 or smaller. In previous field studies at the Nashua site, tillage was not an important factor in the amount of water flowing into the subsurface drainage system (Weed and Kanwar, 1996).

In the first 21 d, no-till columns tended to have more

alachlor leaching loss than chisel-plow columns. But the only significant tillage difference at a probability of 0.10 or less occurred during the rain on Day 21 (Fig. 5). In subsequent rainfalls, alachlor losses from both treatments were essentially the same. The total loss was small; leaching removed only 1.6% of the alachlor applied from no-till columns and 0.4% from chisel-plow columns. A 3-yr field study at the Nashua site found more herbicide leaching from no-till plots than from plots under other tillage treatments, including chisel plow. These losses, while significant, were small; only 0.0002 to 0.10% of the alachlor applied leached through 1.2 m of soil into the subsurface drainage system (Weed et al., 1995).

Alachlor dissipation in the soil columns (Fig. 6) was similar to dissipation in the field (Fig. 3 and 4), although the effect of tillage was less distinct in the laboratory experiment. The half-life was about 3 d, and the time to 90% dissipation was roughly 30 d. Most of the alachlor remained in the upper 10 cm of the columns. There was no peak in alachlor content in the lower 20 cm, unlike the 1993 field study. This suggests that water flow

Table 2. Environmental conditions in the first week after alachlor application.

Study	Temperature		Relative humidity	Solar radiation	Wind speed
	Air	Soil			
	°C		%	mm d ⁻¹	km d ⁻¹
1993 field	13	14	80	5.6	241
1994 field	19	18	65	8.8	177
Laboratory	21	21	25	1.0	345

through the soil matrix did not contribute much to alachlor leaching in this experiment.

Warm air and soil temperatures, low relative humidity, and continuous air flow during the first week of the laboratory study (Table 2) raised the driving force for water evaporation (Fig. 6) and thus for alachlor volatilization. Because the first rain occurred on Day 7, most of the alachlor remained on the surface of the soil columns and so was available for volatilization during a longer period than in the field studies. Spray-mist loss of alachlor during the laboratory experiment was not a factor, however, since the fan ventilation was not turned on until the solution had completely dried. As a result, most of the 1.6 kg ha⁻¹ of alachlor that dissipated by Day 7 apparently did so by volatilization. The overall rate of alachlor dissipation in this experiment is similar to that in the field experiments previously described, which implies that spray-mist loss may not have been a major factor in the field experiments, or that the initial volatilization in the laboratory was comparable to the combined spray-mist loss and initial volatilization in the field.

SUMMARY AND CONCLUSIONS

Regardless of tillage, the overall half-life was 3 d or less, and the time to 90% dissipation ranged from 17 to 30 d. The initial dissipation rate was apparently accelerated by spray-mist loss during application or by volatilization immediately after application. Future work on alachlor dissipation should better characterize the magnitudes of these losses. Alachlor dissipated slightly faster in no-till soil, although this effect also depended on weather that favored movement into and dissipation within the soil, rather than dissipation from the soil surface.

Most of the alachlor in the soil was found in the top 10 cm at all times. Alachlor leached through no-till soil more quickly and in larger amounts than through chisel-plow soil. These differences were often small and inconsistent, however, because the amount of leaching may have depended on whether it rained within 1 d after alachlor application.

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