

## Spatial and Temporal Variability of Herbicides in a Claypan Soil Watershed

F. Ghidey,\* E. E. Alberts, and R. N. Lerch

### ABSTRACT

The spatial and temporal variability of herbicides during the growing season were studied on a 35-ha watershed located in the claypan soil region of north-central Missouri. Soil samples were collected from the 0- to 5-cm soil depth in 1993, and 0- to 5-, 5- to 10-, and 10- to 15-cm soil depths in 1995 and analyzed for atrazine (2-chloro-4-ethylamino-6-isopropylamino-s-triazine) and alachlor (2-chloro-N-(2,6-diethyl-N-(methoxymethyl) acetanilide) concentrations. The effects of rainfall, topography, soil pH, cation exchange capacity (CEC), and organic matter (OM) content on the spatial distribution of herbicides were evaluated. There was no spatial dependency between samples taken immediately after herbicide application; however, spatial dependency was observed in the following sampling periods. During the year, <2.5% of atrazine and 2.0% of alachlor applied to the soil was lost in runoff, and the movement of herbicides below the layer of application was also very low throughout the sampling period. Atrazine and alachlor concentrations in the soil decreased rapidly during the growing season. Concentrations measured 4 and 8 wk after application were <20 and 5% for atrazine, and <10 and 3% for alachlor, respectively, of those measured immediately after application. The study showed that the spatial and temporal variability of herbicide concentration was a function of the interaction between soil pH and the sorptive capacity of the soil (CEC and OM content). These findings are useful for site-specific crop management to increase the efficiency of herbicide application and also to reduce the loss of excess herbicides to surface runoff.

THE transport of nutrients, pesticides, and other agricultural chemicals in runoff affects the quality of surface water. Claypan soils occupy about 4 million ha in Missouri and Illinois and are primarily found within major land resource area (MLRA) 113. Claypan soils have a unique hydrology characterized by the impedance of vertical soil matrix water flow by a restrictive clay layer (Jamison et al., 1968). Runoff from claypan soil regions is relatively high during the seedbed preparation period when agricultural chemicals are applied (Ghidey and Alberts, 1996). As a result, regions with claypan soils have been identified as potentially vulnerable areas for pesticide and nutrient contamination of surface water. Surface and groundwater samples taken from sites across the Corn Belt by the U.S. Geological Survey (USGS) indicated that surface water is more strongly impacted by herbicides than groundwater (Thurman et al., 1992; Burkhart and Koplín, 1993). Blanchard et al. (1995) reported similar results from a study on claypan region soils.

Determining the variability of agricultural chemicals along with other soil properties is important to efficiently manage crop inputs (particularly fertilizers and herbicides), which helps reduce agricultural losses to runoff and

or leaching. It encourages the use of site-specific crop management, which improves production efficiency by adjusting crop inputs to the local soil conditions within a field (Birrell et al., 1993). A number of studies have been conducted to evaluate the spatial variability of soil properties (Cambardella et al., 1994; Sudduth et al., 1994; Lascano and Hatfield, 1992; Gajem et al., 1981) and pesticide distribution (Rao and Wagenet, 1985; Wood et al., 1987). Several researchers have found that the behavior of herbicides was related to soil properties such as OM content and soil pH (Wood et al., 1987; Kells et al., 1980; Best et al., 1975; Best and Weber, 1974; Corbin et al., 1971; Sheets, 1970; Weber, 1970). Sudduth et al. (1994) reported that there was significant variability in water holding capacity, soil nutrients, soil pH, top soil depth, crop growth, and yield within fields and plots located in claypan soil area. However, the spatial variability of herbicides and the effect of soil properties such as OM content, CEC, and soil pH on the variability of the herbicides within these fields and plots have not been studied.

Previous research and modeling efforts indicated that extraction and transport of chemicals to surface runoff during a rainfall event occur from the top (<2.0 cm) soil (Donigan et al., 1977; Frere et al., 1980; Ahuja and Lehman, 1983). Early models such as ARM (agricultural runoff management) and CREAMS (chemicals, runoff, and erosion from agricultural management systems) assumed the existence of a thin layer (<1.0 cm) where rainwater mixes completely and uniformly with the soil solution. Later, Ahuja and Lehman (1983) found that rainfall extracts chemicals from the soil surface by raindrop impact after the soil surface is saturated. They indicated that extraction occurs from depths as great as 2.0 cm, but the contribution decreases exponentially with depth. Because the main concern on claypan soils is surface water quality and since the transfer of chemicals to runoff is from the top layer, our study primarily focused on measuring the chemical concentration within the top 5 cm of the soil profile. Data collected from this study can be used in the future to evaluate water quality models that predict chemical transfer to runoff.

The objectives of this study were to: (i) study the spatial and temporal variations in atrazine and alachlor concentrations in a claypan soil; (ii) evaluate the effects of rainfall and topography on the spatial variability of herbicides; (iii) evaluate the correlation between soil pH, CEC, or organic matter content, and herbicide concentration in the soil; and (iv) determine the loss of herbicides due to runoff during the growing season.

F. Ghidey, Dep. of Biological and Agric. Engineering, Univ. of Missouri, Columbia, MO 65211; and E.E. Alberts and R.N. Lerch, USDA-ARS, Cropping Systems and Water Quality Research Unit, Columbia, MO 65211. Received 13 Nov. 1996. \*Corresponding author (fessehaie\_ghidey@muccmail.missouri.edu).

**Abbreviations:** ARM, Agricultural Runoff Management; CEC, cation exchange capacity; OM, organic matter; MLRA, major land resource area; USGS, U.S. Geological Survey; CREAMS, chemicals, runoff, and erosion from agricultural management systems; N-P, nitrogen-phosphorus; LOI, loss of weight on ignition; GC, gas chromatography; UAN, urea ammonium nitrate.

## MATERIALS AND METHODS

The study was conducted on a 35-ha area (Fig. 1) located in the Goodwater Creek watershed, a 7250-ha agricultural area in northeast Missouri. Predominant soils are Udollic Ochraqualfs, Albaquic Hapludalfs, and Vertic Ochraqualfs of the Mexico, Adco, and Leonard series, respectively. Claypan soils are considered poorly drained, partially because of an argillic claypan horizon located 15 to 30 cm below the surface. The clay content of the argillic horizon is generally greater than 50% and is primarily montmorillonite. The outlet of the watershed was instrumented with a concrete v-notch weir, water stage recorder, and a refrigerated pumping sampler to measure runoff and chemical concentrations in runoff. The sampler automatically starts collecting when flow over the weir is significant and continues to sample until the end of the runoff period. The samples were stored in a refrigerated cabinet until transported back to the laboratory for chemical and sediment analysis.

The area was divided into 36 equally spaced cells (80 m by 120 m), and soil samples were collected from each cell within the depths of 0 to 5 cm in 1993 and 0- to 5-, 5- to 10-, and 10- to 15-cm depths in 1995. Initial samples were collected 1 wk before field operation or chemical application to monitor any chemical residue remaining from previous years' application. Additional samples were collected 3 d, and 1, 2, 4, 8, and 27 wk after application in 1993, and 1, 4, 8, and 27 wk in 1995.

The study area was farmed using a high chemical input minimum-till corn (*Zea mays* L.)-soybean [*Glycine max* (L.)

Merr.] rotation agricultural farming system with the goals of maximizing grain yield and profit. The area was cropped to soybean in 1992, corn in 1993, and soybean in 1994. In 1995, due to high rainfall during the planting period, it was not possible to plant corn. Instead, the study area was cropped to grain sorghum [*Sorghum bicolor* (L.) Moench]. In 1993, 190 kg ha<sup>-1</sup> of N (as UAN), 2.24 kg ha<sup>-1</sup> of atrazine, and 2.8 kg ha<sup>-1</sup> of alachlor were applied to the soil. In 1994, because the study area was cropped to soybean, only alachlor was applied at the rate of 2.8 kg ha<sup>-1</sup>. In 1995, 123 kg ha<sup>-1</sup> of N (as UAN), 1.9 kg ha<sup>-1</sup> of atrazine, and 2.8 kg ha<sup>-1</sup> of alachlor were applied to the soil. The chemicals were broadcast and incorporated with field cultivator before planting.

Soil samples were collected using a 2.5-cm diameter probe. Eight subsamples were taken from the ridges and furrows of each cell and were mixed and wrapped in aluminum foil. Samples were frozen before being sent to the USDA-ARS National Soil Tilth Laboratory at Ames, IA, for analysis. Soil samples were extracted with 80% methanol-water for atrazine and alachlor using a robotic system. Atrazine and alachlor were isolated and concentrated from the extracts by solid phase extraction (C<sub>18</sub> cartridge), eluted with ethyl acetate, and analyzed with a HP 5890 capillary gas chromatograph using a nitrogen-phosphorous (N-P) detector. Extraction efficiencies for atrazine and alachlor were approximately 90 and 80%, respectively. Atrazine and alachlor concentrations were corrected for the recovery efficiencies.

Soil samples were also taken from each cell to determine soil pH, cation exchange capacity (CEC), and organic matter (OM) content. Soil samples taken from the study area in 1993 (Birrell et al., 1993), and in 1995 (Drummond et al., 1995) did not display significantly different spatial trends for the individual soil parameters. Hence, samples for pH, CEC, and OM content analysis were taken once from each cell 6 wk after planting in 1995. Soil organic matter content was determined by loss of weight on ignition (LOI) method.

During each runoff event, water samples were collected using an automatic flow-proportioning sampler. Analysis of atrazine and alachlor were described previously (W.W. Donald et al., 1997, unpublished; Lerch et al., 1995). Briefly, all samples were filtered through 0.4- $\mu$ m nylon filters. Clean-up and concentrations were performed on 100-mL samples by C<sub>18</sub> solid-phase extraction followed by quantitation using chromatography (GC) and N-P detection. Limits of quantitation were 0.14  $\mu$ g L<sup>-1</sup> for atrazine and 0.76  $\mu$ g L<sup>-1</sup> for alachlor.

Geostatistical Software (GS<sup>+</sup>, Gamma Design Software, St Plainwell, MI) was used to analyze the spatial distribution of the data. Semivariogram and kriging were applied to quantify the spatial variability of atrazine and alachlor concentrations in the soil profile.

## RESULTS AND DISCUSSION

### Rainfall Characteristics

Annual precipitation in 1993 and 1995 for the study area was 1340 and 1146 mm, respectively. The 53-yr mean annual precipitation measured near the area at Centralia, MO, was 900 mm. Annual surface runoff accounted for 40 and 33% of the annual precipitation in 1993 and 1995, respectively. Approximately 12% of the runoff in 1993 and 27% of the runoff in 1995 occurred during the 2-mo period following chemical application. This period is considered to be critical for chemical loss to surface runoff.

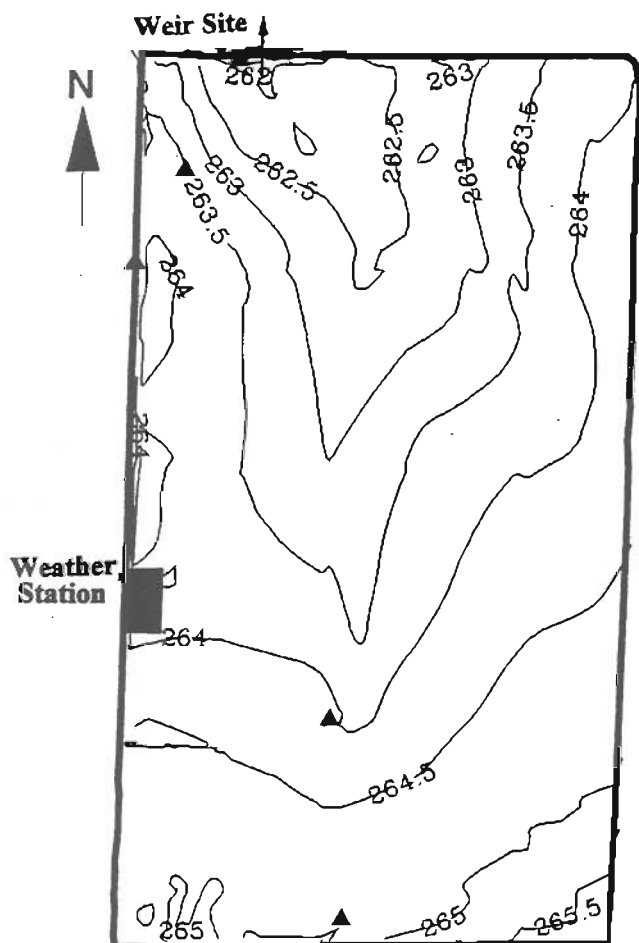


Fig. 1. Topographic map of the watershed. Contour elevation lines are shown in meters. (Drainage area = 35 ha).

### Herbicide Concentrations in Surface Runoff

Herbicide concentrations in surface runoff were measured throughout the year both in 1993 and 1995. Table 1 presents atrazine and alachlor concentrations in surface runoff during the critical period for chemical loss. For the runoff events before herbicide applications in 1993 and 1995, atrazine and alachlor concentrations in runoff were below the quantitation limits. In 1993, 3 d after chemical application, about 32.3 mm of rain and 1.8 mm of runoff were measured from the area, and the concentrations in runoff were very high (301 and 236  $\mu\text{g L}^{-1}$  for atrazine and alachlor, respectively). Two weeks later, about 13.6 mm of runoff was measured; the concentrations were still high but significantly lower than the previous event concentrations. In the following weeks, the herbicide concentrations in runoff became very low and were below the current drinking water standards (3  $\mu\text{g L}^{-1}$  for atrazine and 2  $\mu\text{g L}^{-1}$  for alachlor) within 8 wk for both atrazine and alachlor. Herbicide concentrations in runoff were below the quantitation limits for the events that occurred 15 and 8 wk after application for atrazine and alachlor, respectively. Throughout the year, about 19 and 7.0 g  $\text{ha}^{-1}$  of atrazine and alachlor were lost to runoff, representing 0.85 and 0.25% of the total applied, respectively. The first two events following application accounted for almost 90% of the annual atrazine and alachlor lost to surface runoff.

In 1995, approximately 40, 3, and 8 mm of runoff were measured from the drainage area 10, 11, and 13 d after chemical application, respectively (Table 1). Atrazine concentration was high in all the events (69, 92, and 51  $\mu\text{g L}^{-1}$  in the first, second, and third events, respectively). Alachlor concentration was also high in the first event (81  $\mu\text{g L}^{-1}$ ) and decreased in the following two events. The next runoff event occurred 8 wk after chemical application. Atrazine and alachlor concentrations for this event were very low. During the year, about 46 and 45 g  $\text{ha}^{-1}$  of atrazine and alachlor were lost to runoff, representing 2.42 and 1.61% of the total applied, respectively. The first event following application accounted for 60 and 70% of the annual atrazine and alachlor lost to surface runoff, respectively. The

**Table 1. Atrazine and alachlor concentrations in surface runoff.**

Date	Days after application	Rainfall	Runoff	Atrazine	Alachlor
		mm	mm	$\mu\text{g L}^{-1}$	$\mu\text{g L}^{-1}$
05-10-93	-4	23.9	7.0	<0.14†	<0.76†
05-17-93	3	32.3	1.8	300.90	235.50
06-06-93	23	38.4	13.6	81.60	21.80
06-24-93	41	29.2	2.5	16.60	3.70
07-07-93	54	38.4	18.0	2.90	2.70
07-13-94	60	28.5	6.7	1.30	<0.76
08-10-93	88	36.8	12.4	0.50	<0.76
09-02-93	111	50.6	25.1	<0.14	<0.76
05-17-95	-29	67.1	52.3	<0.14	<0.76
06-25-95	10	89.9	39.8	69.00	81.00
06-26-95	11	7.8	3.0	92.00	72.00
06-28-95	13	29.2	7.9	51.00	35.00
08-04-94	50	72.0	22.8	1.50	<0.76

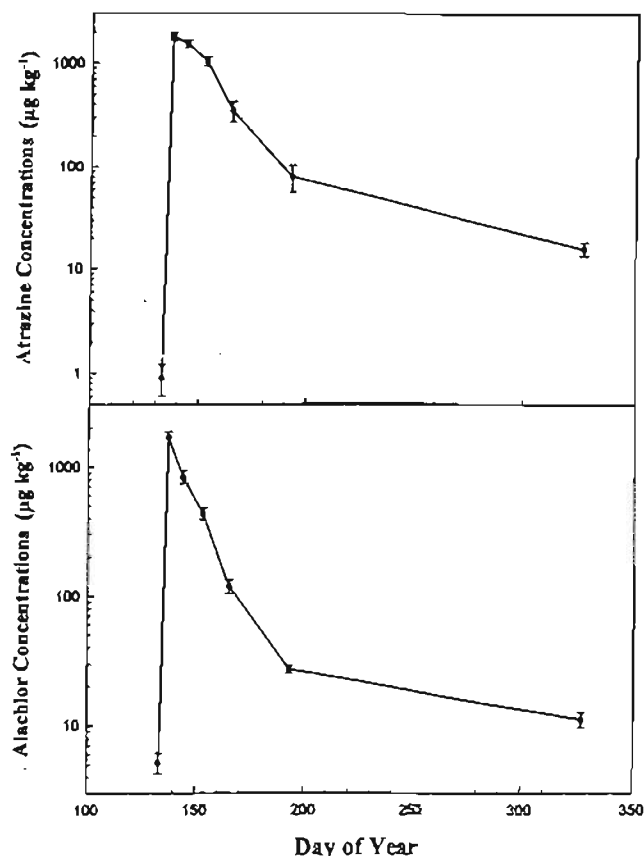
† Limits of quantitation for atrazine and alachlor in surface runoff are 0.14 and 0.76  $\mu\text{g kg}^{-1}$ , respectively.

results of the study showed that atrazine and alachlor concentrations in surface runoff water exceeded the current drinking water standards for the events that occurred within 8 wk following chemical application. However, transport of herbicides from the watershed by surface runoff was not a critical process to the temporal and spatial variability of herbicide concentrations observed.

### Temporal Variability of Herbicides in the Soil Profile

Mean atrazine and alachlor concentrations measured from the top 5.0 cm of the soil profile during the 1993 growing season are presented in Fig. 2. For the samples measured before herbicide application, atrazine was detected in 4 out of 36 samples with concentrations ranging from 6.0 to 7.0  $\mu\text{g kg}^{-1}$ . Alachlor was observed in half of the samples, and the concentrations ranged from 7 to 19  $\mu\text{g kg}^{-1}$ .

As mentioned previously, atrazine and alachlor were applied at the rate of 2.24 and 2.8  $\text{kg ha}^{-1}$ , respectively. Assuming herbicides were applied accurately and uniformly within a 5-cm depth throughout the field, the initial (on the day of application) atrazine and alachlor concentrations were approximately 3400 and 4200  $\mu\text{g kg}^{-1}$ . However, since no samples were collected on the day of application, the initial concentration values were not checked. For the samples taken 3 d after application,



**Fig. 2. Atrazine and alachlor concentrations in the 0- to 5-cm soil depth measured in 1993. Each point is a mean of 36 samples. The vertical bars are standard errors.**

the mean concentration values for atrazine and alachlor were 1608 and 1680  $\mu\text{g kg}^{-1}$ , representing 47 and 40% of the initial values, respectively. Although there might have been some losses due to chemical and biological processes, the percent atrazine and alachlor losses in the 3 d period (53% for atrazine and 60% for alachlor) seem to be high. Because of the size of the study area, it would be difficult to have accurate and uniform application; hence, the initial herbicide concentration values are believed to be much lower than the values computed from the application rates. In this study, herbicide concentrations measured 3 d after application were used as initial (or reference) values to compute the percent herbicide losses during the remaining sampling periods.

Atrazine and alachlor concentrations dissipated rapidly during the growing season. Atrazine concentrations measured at 1, 2, 4, 8, and 27 wk were 89, 60, 20, 5, and 1%, respectively, of those measured immediately 3 d after application. Alachlor concentrations, measured at 1, 2, 4, 8, and 27 wk were 49, 26, 7, 1.6, and 0.6%, respectively, of those measured 3 d after application. Alachlor dissipated much faster than atrazine. Half-life ( $t_{1/2}$ ) for alachlor dissipation was 9 d compared with 12 d for atrazine.

Mean atrazine and alachlor concentrations in the soil measured from three layers (0- to 5-, 5- to 10-, and 10- to 15-cm soil depths) in 1995 are shown in Fig. 3. For the samples collected 1 wk before herbicide application there were no significant differences in the mean atra-

zine and alachlor concentrations among the layers. The mean concentrations in each layer were  $<2.0 \mu\text{g kg}^{-1}$  for atrazine and  $<7.0 \mu\text{g kg}^{-1}$  for alachlor. Atrazine was detected in  $<15\%$  of the samples with concentrations ranging from 0.5 to 22.0  $\mu\text{g kg}^{-1}$ , whereas alachlor was observed in most of the samples with concentrations ranging from 5 to 30  $\mu\text{g kg}^{-1}$ . The second set of soil samples was taken 1 wk after herbicide application, and the mean concentrations at 0- to 5-cm depth were 1304  $\mu\text{g kg}^{-1}$  for atrazine and 1116  $\mu\text{g kg}^{-1}$  for alachlor. Mean atrazine and alachlor concentrations at 5- to 10-cm and 10- to 15-cm depths were  $<2.5$  and 1.5%, respectively, of those measured in the top layer. For the soil samples collected 4 wk following herbicide application, atrazine and alachlor concentrations in the top layer decreased to 12 and 8%, respectively, of the 1 wk values. At the 5- to 10-cm and 10- to 15-cm depths, atrazine concentrations slightly decreased compared with the previous sampling period while alachlor concentrations slightly increased; however, concentrations in the subsoil were still much lower than the concentration in the top layer. For the samples collected 8 wk after application, atrazine and alachlor concentrations in the top layer were 2.2 and 2.5%, respectively, of those measured 1 wk after application. Atrazine and alachlor concentrations in the subsoil were slightly lower than those measured in the previous sampling period and were still appreciably lower than the concentrations measured in the top layer. This portion of the study showed that temporal variations in atrazine and alachlor concentrations in the surface soil (0-5 cm) were not related to leaching. Blanchard et al. (1995) collected well water samples from the area and found that leaching of parent herbicide compounds had very little impact on groundwater quality. Thus, temporal changes in herbicide concentration were probably controlled by various chemical and biological processes.

### Spatial Variability of Herbicides

The spatial variability of atrazine and alachlor was analyzed using Geostatistics. The semivariograms of atrazine and alachlor concentration 3 d, 1 wk, and 8 wk following application measured in 1993 are shown in Fig. 4. There was no spatial dependency between the samples taken 3 d after application at 80-m sampling distance, despite the apparent lack of uniform application. No rainfall or runoff event occurred from the time of application until the first sampling period to affect the variability in agrichemicals within the study area. For the samples taken 1 wk after application, there was a spatial component to the variability. During this week, about 32.3 mm of rainfall and 1.8 mm of runoff were measured from the area. In all cases (as shown in Fig. 4), the variances were best fit by a simple spherical model, and the ranges of influence were 253 and 193 m for atrazine and alachlor concentrations, respectively. For samples taken 8 wk after applications the variability in atrazine and alachlor concentrations contained a spatial component as evidenced by the trend of increasing semivariance with increasing lag distance. However, in

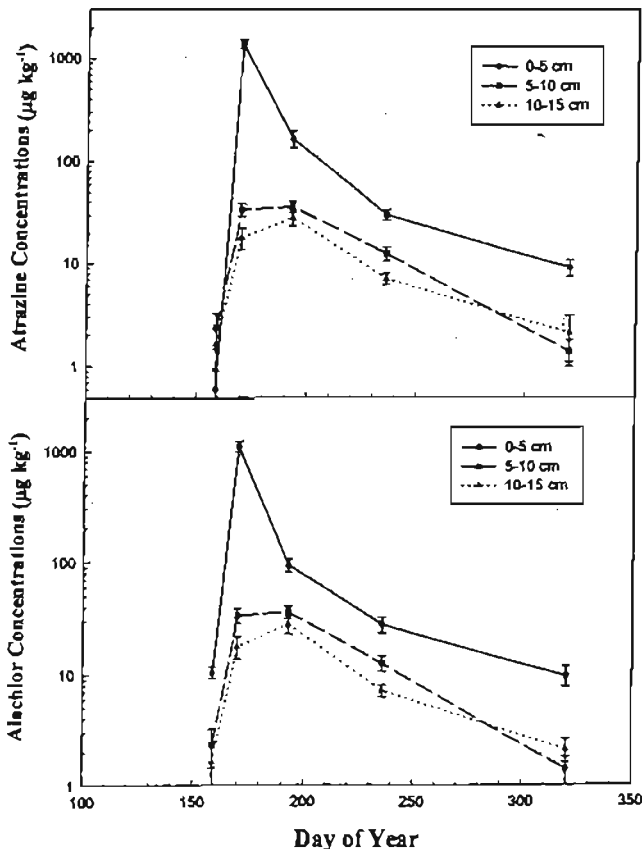


Fig. 3. Atrazine and alachlor concentrations in the 0- to 5-, 5- to 10-, and 10- to 15-cm soil depths measured in 1995. Each point is a mean of 36 samples. The vertical bars are standard errors.

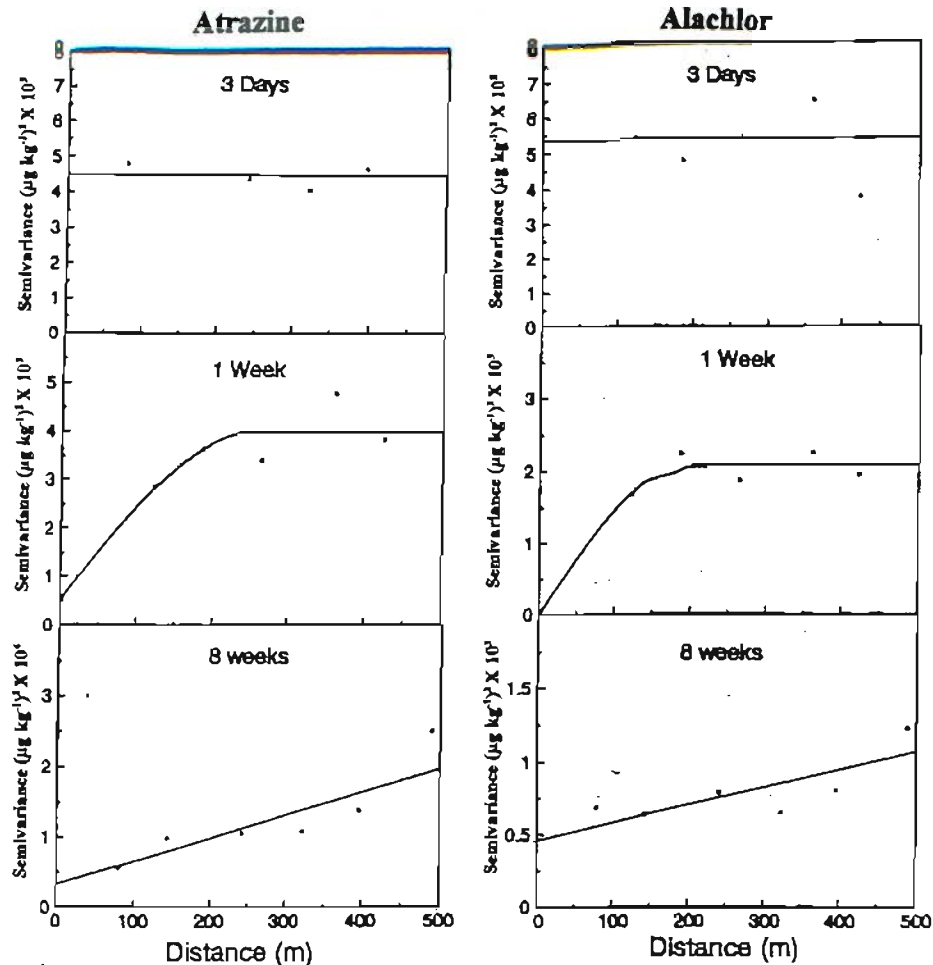


Fig. 4. Semivariograms of atrazine and alachlor concentrations (0- to 5-cm depth) measured 3 d, 1wk, and 8 wk after application in 1993.

all cases, a sill was not reached, and the range of spatial dependence was greater than the maximum distance (500 m). Similar spatial patterns were observed for the samples taken 2, 4, and 27 wk after application. In 1995, there was no spatial dependency between the samples 1 wk after application at 80-m sampling distance. For samples taken 4 and 8 wk after application, variability in atrazine and alachlor concentrations contained a spatial component; however, a sill was not reached.

The kriged maps for samples taken 1, 4, and 8 wk after application both in 1993 and 1995 are illustrated in Fig. 5 and 6. There was a special trend observed in the study area through the growing season. In general, atrazine and alachlor concentrations in the northern and southern portions of the watershed were higher than in the middle of the watershed. Several factors or a combination of these factors, including rainfall, topography, soil pH, CEC, and OM content were assumed to influence the spatial variability of the chemicals.

The effects of topography and rainfall on the spatial variability of chemical concentrations were clearly observed in the samples taken 1 wk after application in 1993 (Fig. 5). During this week, about 32.3 mm of rainfall and 1.8 mm of runoff were measured. Atrazine and alachlor concentrations were higher in the southern portion of the watershed (a relatively level area) than the

rest of the watershed. This could be due to a faster removal of chemicals by surface runoff from the relatively higher slope areas. In 1995, due to the continuous and large rainfall and runoff events that occurred a few days after chemical application, it was difficult to isolate the combined effect of rainfall and topography.

The correlation of soil pH and sorptive capacity (CEC and OM) with herbicide concentrations was also evaluated in this study (Table 2). Atrazine concentrations were not significantly correlated ( $p < 0.10$ ) with soil pH, OM content, or CEC for the samples collected immediately after application. For the samples collected 4, 8, and 27 wk after herbicide application atrazine concentrations in the soil were, in most cases, significantly correlated ( $p < 0.01, 0.05, \text{ and } 0.10$ ) with soil pH, OM content, or CEC. Atrazine concentration in the soil was highly correlated with soil pH followed by CEC and OM. Atrazine concentration was negatively correlated with soil pH and positively correlated with OM and CEC. Higher atrazine concentrations were found in areas of low soil pH and high OM content and CEC (Fig. 5, 6, and 7).

Alachlor concentration was significantly correlated with OM content ( $p < 0.05$ ) in 1993, and CEC ( $p < 0.10$ ) in 1995 for the samples collected immediately after application. Because alachlor dissipated faster than atra-

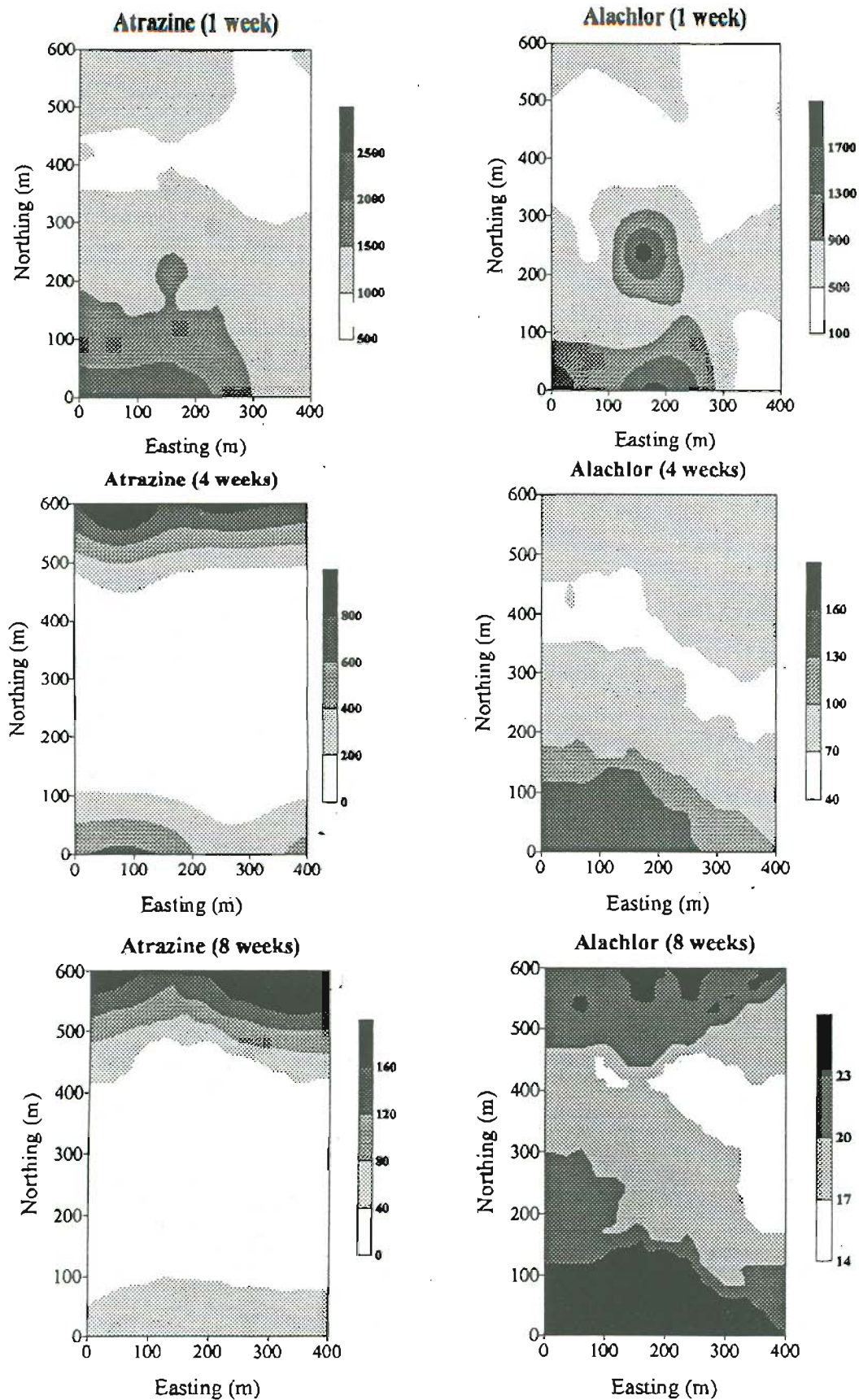


Fig. 5. Kriged atrazine and alachlor concentrations ( $\mu\text{g kg}^{-1}$ ) measured 1, 4, and 8 wk following application in 1993. Samples were collected from the 0- to 5-cm depth.

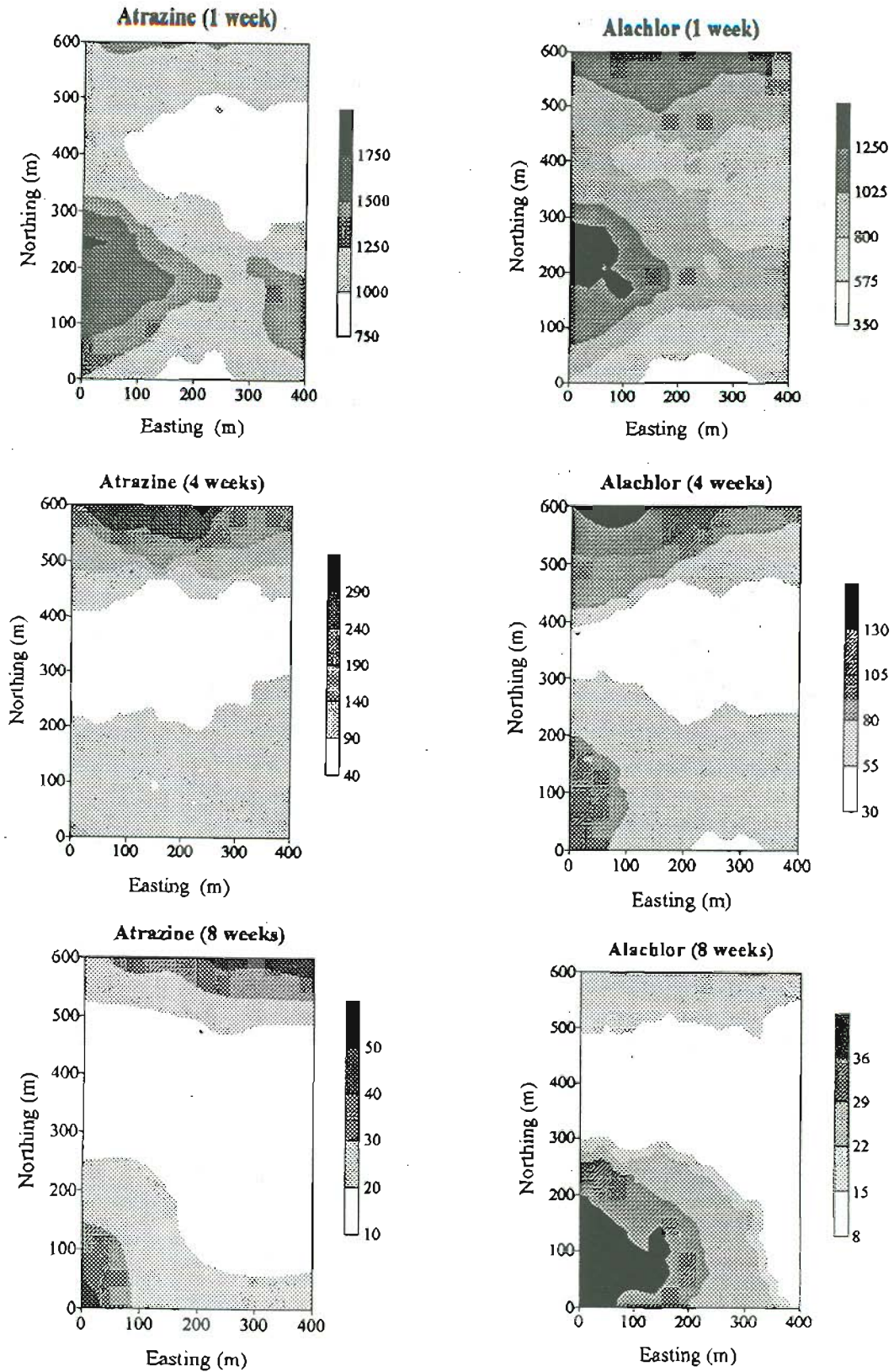


Fig. 6. Kriged atrazine and alachlor concentrations ( $\mu\text{g kg}^{-1}$ ) measured 1, 4, and 8 wk following application in 1995. Samples were collected from the 0- to 5-cm depth.

**Table 2. Coefficient of correlation ( $r$ ) between soil characteristics and herbicide concentrations in the soil measured 3 d and 4, 8, and 27 wk following application.**

Time after applic.	Soil parameter	Atrazine 1993	Atrazine 1995	Alachlor 1993	Alachlor 1995
3 d	pH	-0.19	-0.06	-0.25	-0.19
	CEC	0.15	0.20	0.11	0.29*
	OM	0.11	0.03	0.36**	0.08
4 wk	pH	-0.86***	-0.65***	-0.18	-0.52***
	CEC	0.56***	0.32*	0.16	0.39**
	OM	0.41**	0.14	0.41**	0.14
8 wk	pH	-0.79***	-0.65***	-0.38**	-0.20
	CEC	0.42***	0.46***	0.47***	0.49***
	OM	0.23	0.30*	0.53***	0.47***
27 wk	pH	-0.61***	-0.36**	-0.20	-0.21
	CEC	0.64***	0.47***	0.22	0.32*
	OM	0.24	0.40**	0.33**	0.48***

\*, \*\*, \*\*\*  $p < 0.10$ ,  $p < 0.05$ , and  $p < 0.01$ , respectively.

zine, the influence of OM content and CEC on alachlor activity was greater than atrazine during the 3-d or 1-wk period after application. For the samples collected at 4, 8, and 27 wk alachlor concentration was, in general, significantly correlated ( $p < 0.01$ , 0.05, and 0.10) with OM content, CEC, or soil pH. Alachlor concentration

was negatively correlated with soil pH; however, the correlations were lower when compared with those of atrazine. Alachlor soil concentrations showed the highest correlation with CEC followed by OM content and soil pH.

Several studies have indicated that the levels of soil acidity and OM content significantly effect atrazine activity and degradation in the soil (Wood et al., 1987; Kells et al., 1980; Best et al., 1975; Best and Weber, 1974; Weber, 1970). The researchers found that herbicides such as atrazine were adsorbed to a greater extent by acidic soils with high OM content than alkaline soils with low OM content. Plant uptake and leaching also decreased as soil pH decreased and OM increased (Best and Weber, 1974; Sheets, 1970). These studies showed that atrazine concentrations were higher in areas of lower soil pH and higher OM content because of high adsorption to soil and low plant uptake and leaching. Similarly, in this study, atrazine concentrations were controlled by the interaction between the sorptive capacity of the soil and soil pH. Atrazine and alachlor concentrations were higher in the northern and southern portion of the watershed than in the middle. The north-

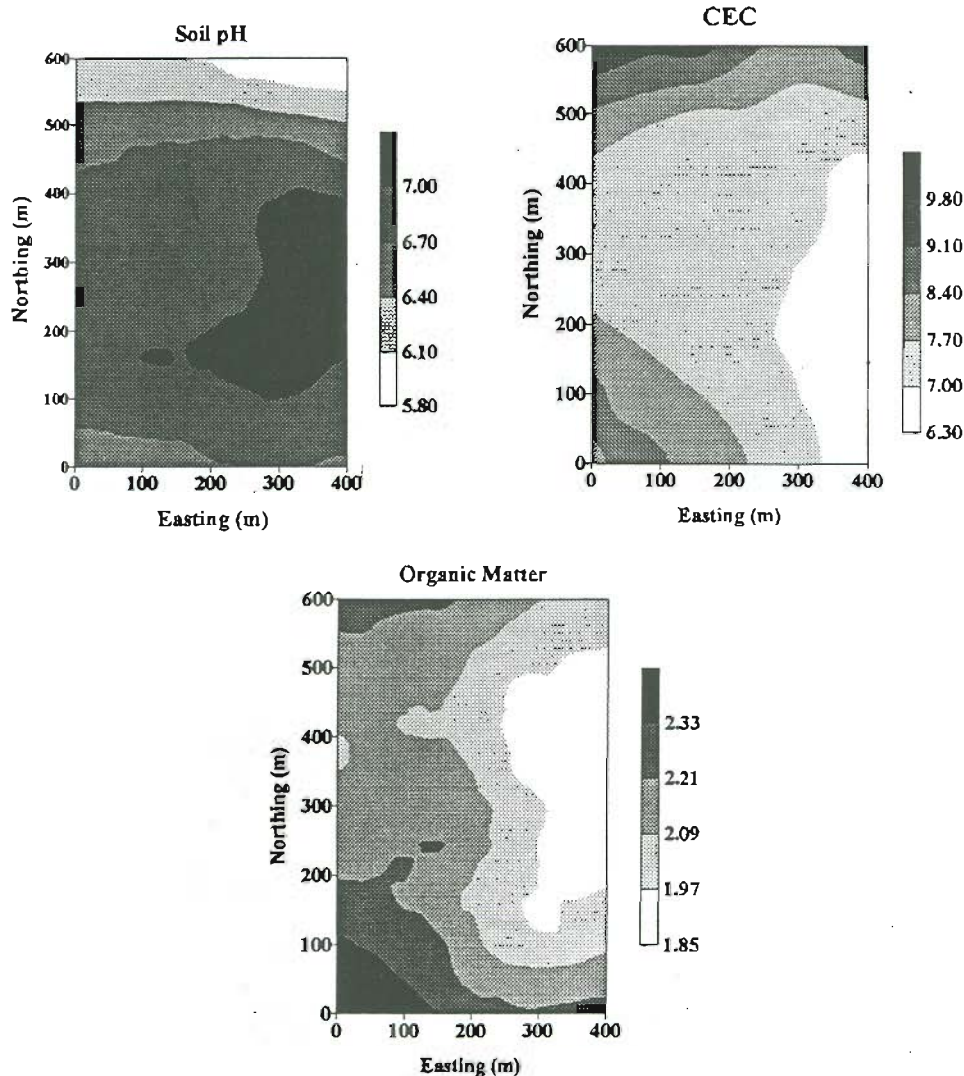


Fig. 7. Kriged soil pH, CEC, and organic matter content in the 0- to 5-cm soil depth for the watershed.



ern and southern portions of the watershed had higher sorptive capacity and lower soil pH which lead to increased atrazine sorption, and consequently higher atrazine concentration. Because alachlor has no pH-dependent functional groups affecting its sorption to soil, its spatial variability was generally more dependent on CEC and OM than soil pH.

## SUMMARY AND CONCLUSIONS

Atrazine and alachlor concentrations showed spatial dependency within the study area starting 1 wk after from the time of application. Throughout the study period, only a very small amount of atrazine and alachlor applied to the soil was lost to runoff and leaching. Therefore, herbicide losses due to some combination of runoff and leaching were not significant processes to the temporal or spatial dependence of herbicide concentrations. Herbicide concentrations in the soil dissipated rapidly during the growing season. In 1993, concentrations measured 4 and 8 wk after application were 20 and 5% for atrazine, and 7 and 2% for alachlor, respectively, of those measured immediately after application.

Herbicide concentrations in the watershed were significantly correlated with soil pH, CEC, and OM content. The spatial variability of observed soil concentrations starting 1 wk following application was largely controlled by soil pH and the sorptive capacity of the soil. Higher atrazine and alachlor concentrations were observed in areas of lower soil pH, higher OM content, and higher CEC.

These results have several implications for herbicide management. First, the spatial variability of herbicide concentrations, in combination with weed growth pattern, could serve as the basis for the variable rate herbicide application. Second, areas with low sorptive capacity and appreciable slope are most vulnerable to herbicide losses by surface runoff immediately following herbicide application. These areas, once identified, can be targeted for conservation efforts aimed at reducing surface runoff velocity and transport of herbicides. Overall, understanding the processes controlling spatial and temporal variability of herbicides at the field-size watershed scale are important to improving herbicide management in row crop settings.

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