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SOIL FACTORS INFLUENCING ATRAZINE SORPTION: IMPLICATIONS ON FATE

JEFFREY M. NOVAK*
Coastal Plains Soil, Water and Plant Research Center, Agricultural Research Service, U.S. Department of Agriculture, 2611 West Lucas Street, Florence, South Carolina 29501-1242

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Abstract—The effects of two soil properties—soil organic carbon (SOC) content and landscape position—and a management factor (tillage) from Iowa and South Carolina soils on the sorption of the herbicide atrazine (6-chloro-*N*-ethyl-*N*′-(1-methylethyl)-1,3,5-triazine-2,4-diamine) were evaluated to assess their influence on atrazine fate in the soil environment. In both Iowa and South Carolina, the magnitude of atrazine sorption was strongly and positively correlated with SOC, landscape position, and tillage. Landscape position was especially important for Iowa soils because SOC-enriched depressional areas (potholes) on the Wisconsin glacial surface could sorb more atrazine than soils in sloping positions. Our data suggest that herbicide management strategies such as application rates or herbicide selection will require some adjustments to account for the effects of SOC, landscape position, and tillage management on herbicide sorption in to augment effective weed control and prevent herbicide movement to groundwater.

Keywords—Soil organic carbon Landscape position Tillage Atrazine Sorption

INTRODUCTION

Herbicides applied to soil interact with both organic and inorganic particles. This interaction promotes the herbicide to partition between solid and liquid phases, subsequently influencing its short- and long-term behavior. Those in the liquid phase are readily available for weed uptake and leaching, whereas those sorbed to the organic and inorganic phases are slowly available for weed uptake because of strong binding to soil particles and slow desorption kinetic reactions [1]. It is desirable to have some herbicide in the liquid phase for immediate weed control and to have some sorbed for long-term weed control. The literature has extensively shown that the magnitude of herbicide sorption in soils is important because sorption regulates herbicide efficacy, bioavailability, and persistence [1–3].

For most agricultural soils in humid regions, soil organic carbon (SOC) is regarded as the dominant property influencing the magnitude of herbicide sorption [4]. It has been shown previously that soils with a high SOC content are capable of sorbing more herbicide, especially the triazines-type herbicides [2]. Because this relationship has an important effect on herbicide behavior, scientists are conducting research to evaluate how soil properties influence rates of SOC formation. Birkland [5] reported that topography will influence the accumulation of SOC by variations in decomposition rates of organic debris. For example, soils formed in level, floodplain areas of the coastal plain region of South Carolina are SOC enriched because of poor internal drainage when compared to the well-drained soils in sloping areas [6]. Additionally, researchers have been concerned with conservation tillage effects on SOC contents and herbicide sorption, as the U.S. Department of Agriculture (USDA) encourages conservation tillage of soil. A few studies have demonstrated that conservation tillage results in the buildup of SOC in the surface horizon [7,8] and increases herbicide sorption [8]. However, some studies [9,10] have reported contrary results in that conservation tillage actually increased herbicide leaching. The increased leaching was attributed to preferential herbicide transport through macropores, although tillage effects on herbicide sorption was not examined. Nevertheless, these studies demonstrate the concern for evaluating soil properties and management factors that influence the quantity of SOC and their effects on herbicide sorption.

Atrazine is the most heavily used herbicide in the United States with application amounts in 1995 estimated to be between 68 and 75 million pounds (active ingredients) [11]. Much research has been devoted to the movement and behavior of atrazine in soils because of the frequent detection in ground and surface waters around the United States [12–14].

The pesticide program at the Coastal Plains Research Center of the U.S. Department of Agriculture-Agricultural Research Service (USDA-ARS) has evaluated several soil properties and management factors that influence the quantity of SOC and the magnitude of herbicide sorption. Our objectives are to describe the effects of SOC and landscape position in Iowa glacial till soils on atrazine sorption coefficients (as K_d), to describe the influence of tillage on SOC contents and atrazine sorption coefficients in a coastal plain soil from South Carolina, and to evaluate the effects of these properties and factors on potential atrazine fate in the environment.

MATERIALS AND METHODS

Site description and soil analyses

Soils from Iowa were collected from a pothole field located on the Wisconsin glacial surface in the western part of the Walnut Creek watershed, Boone County, Iowa. Physical fea-

* (novak@florence.ars.usda.gov).

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tures of the site and chemical properties of the soil have been described elsewhere [15]. A 25 × 25-m grid pattern was established across the 6.25-ha field, which provided 121 main grid points to sample. In addition, secondary intersection points at 2-, 5-, and 10-m intervals were established to provide information on soil variability at distances of less than 25 m for this study [15]. In total, there were 121 main grid and 120 node points (total of 241 sampling points). Each grid point was surveyed using a rod and transit to determine elevations, and relative elevations were then calculated by subtracting the lowest point measured in the field. A landscape position class was determined for these points using an algorithm developed by Pennock et al. [16]. The algorithm was based on elevations above mean sea level, percentage slope, and calculated curvature for each grid point. Gradient scales were established for each grid point from the algorithm, and five landscape position classes (shoulder, foot slope, depressions, back slopes, and level uplands) were assigned to the points. Soil samples (0–15 cm deep) were collected at each grid point (n = 241), and the SOC contents were measured on air-dried, 2-mm sieved soil using a Carlo-Erba NA1500 NCS elemental analyzer (Haake Buchler, Paterson, NJ, USA).

Soils from South Carolina were collected from two different fields. The first field was used to evaluate the relationship between SOC content and atrazine sorption, and the second field was used to evaluate tillage and atrazine sorption. The first field is 5 ha in size and is located at the Coastal Plains Research Center in Florence, South Carolina. The soil series is a Norfolk loamy sand (fine-loamy, siliceous thermic Typic Kandiudult), which is typical of the coastal plain region of South Carolina. In March 1997, a total of 144 plots (approx. 15 × 20 m in area) were sampled using a 3-cm-diameter soil probe to collect approx. 300 g of 0- to 3-cm-deep soil (n = 144). The soils were air-dried, 2-mm sieved, and the SOC was measured using a LECO carbon analyzer (LECO, St. Joseph, MI, USA). The second field contains long-term (19 years) conservation and conventional tillage research plots and is located at the Clemson University, Pee Dee Research and Education Center, Darlington, South Carolina. The specific cropping and tillage management histories have been described previously [7,17]. A 5 × 8-m grid pattern was established over replicate conservation and conventional tillage plots that provided 40 sampling points per plot. In March 1996, approx. 200 g of soil were collected using a 3-cm soil probe from the 0- to 3- and 0- to 15-cm soil depths at each grid point. A total of 320 soil samples were collected, and SOC content was determined as described previously.

Atrazine sorption

Sorption of atrazine was determined with batch equilibration techniques using two different atrazine concentrations that reflect typical application rates for the two states. Soils from Iowa (4 g, 2-mm sieved) were equilibrated with 15 ml of solution containing 1.5 mg/L of atrazine dissolved in 0.01 M $CaCl_2$ for 72 h. Soils from South Carolina (5 g, 2-mm sieved) were equilibrated with 20 ml of solution containing 1.0 mg/L of atrazine dissolved in 0.005 M $CaCl_2$ for 72 h. In the initial and equilibrium solutions, atrazine was determined using a Waters High Performance Liquid Chromatography instrument (Waters, Milford, MA, USA). The difference between initial and equilibrium atrazine concentrations was attributed to sorption by soil. The sorption equilibrium partition coefficient K_d (L/kg) was calculated as K_d = X/C, where X = milligrams of atrazine per kilogram of soil and C = milligrams of atrazine per liter of equilibrium solution. Relationships between the SOC content and atrazine sorption K_d values were analyzed using linear regression analyses and effects of tillage versus the SOC, and atrazine K_d values were determined using a Mann–Whitney rank sum test (SigmaStat software, SPSS, Richmond, CA, USA).

Table 1. Mean ($\bar{x}$) and standard deviation (SD) for soil organic carbon (SOC) content and atrazine sorption coefficients (K_d) measured in soils collected in an Iowa pothole field and a field in South Carolina

		SOC (mg/kg)		Atrazine (L/kg)	
State	n	$\bar{x}$	SD	$\bar{x}$	SD
Iowa	241	27.6	10.9	4.95	2.23
South Carolina	144	10.3	2.9	1.84	0.62

RESULTS AND DISCUSSION

Soil organic carbon content

The relationship between SOC content and atrazine sorption was tested using soils from Iowa and South Carolina because of their large variation in SOC content (Table 1). Fenton [18] reported that Iowa glacial soils are SOC enriched because the soils formed under prairie vegetation and have soil properties (high cation exchange capacity and calcium saturation) that promote the accumulation of organic matter. On the other hand, coastal plain soils in South Carolina have a relatively lower SOC content because the native vegetation is forest [18]. Forest vegetation contributes less organic debris to the soil than prairie vegetation, and the warm temperatures promote rapid decomposition. As shown in Table 1, soils from Iowa are SOC enriched and have higher atrazine sorption coefficients than coastal plain soils from South Carolina. This trend corroborates the general principle that soils high in SOC sorb higher amounts of atrazine (2). This significant relationship ($p <$ 0.001) is supported by regression analyses that showed fairly high r^2 values of 0.56 and 0.67 for SOC versus atrazine K_d for soils from Iowa and South Carolina, respectively (Fig. 1).

Landscape position

The Des Moines lobe of the Wisconsin glacial surface in Iowa contains closed depressions that are referred to as potholes [19]. These potholes are scattered across the Wisconsin glacial surface of Iowa. Our study site contains two potholes that have the lowest relative elevations in the field (Fig. 2). Surface runoff accumulates in the potholes because they are closed depressions. Soils in the potholes have poor internal drainage and are SOC enriched relative to the surrounding sloping soils (Fig. 3). The poor internal drainage has slowed organic debris decomposition and contributed to the high SOC contents. Additionally, our study site is nearly surrounded by sloping soils that are well to moderately well drained. Water does not accumulate appreciably on these sloping soils, but it is redirected to drain into the SOC-enriched potholes. The highest atrazine K_d values (10–15) occur in the two depressional areas (Fig. 4). This is not surprising considering the significant relationship between SOC content and atrazine K_d values for the Iowa soils (Fig. 1).

Relative elevations for grid points in the Iowa pothole field were used to segregate these points into distinct landscape position classes to better understand the effects of landscape

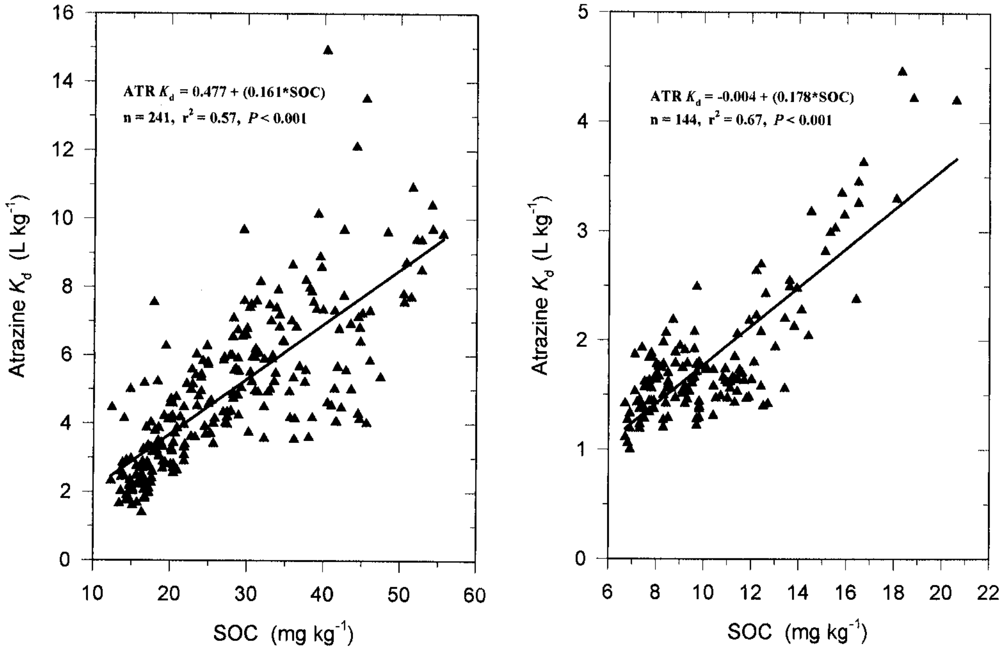

Fig. 1. Relationship between soil organic carbon (SOC) content and atrazine K_d values for soils from the Iowa pothole field (left) and from the South Carolina field (right).

position on SOC content and atrazine sorption. The mean SOC contents of the landscape position classes (Table 2) follow the same trend shown in Figures 2 and 3. Sloping soils (back slope and shoulder positions) have lower SOC contents relative to the level upland and depressional areas. Soils formed in sloping landscape positions typically have a higher degree of erosion of SOC-enriched sediments than depressional areas [5]. Soils in the depressional areas collect these sediments, contributing to their high SOC contents. The mean atrazine K_d values follow the same trend as found with the SOC contents.

The strong relationship between the SOC content and magnitude of atrazine sorption suggests that atrazine movement might be different between soils in these landscape positions. The higher amount of atrazine sorption in the SOC-enriched depressional areas of the Iowa pothole field might allow a greater opportunity for biodegradation to occur, provided that the microorganisms have physical or enzymatic access to the sorbed atrazine. On the other hand, sloping soils might be prone to atrazine leaching and runoff because of the lower sorptive capacity and surface movement of sorbed atrazine

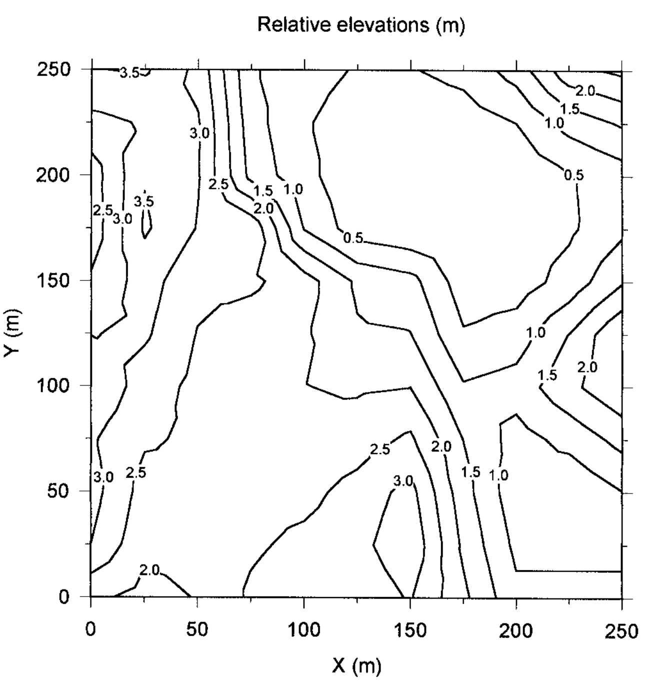

Fig. 2. Relative elevations for grid points in the Iowa pothole field (elevations corrected to lowest elevation measured in the field).

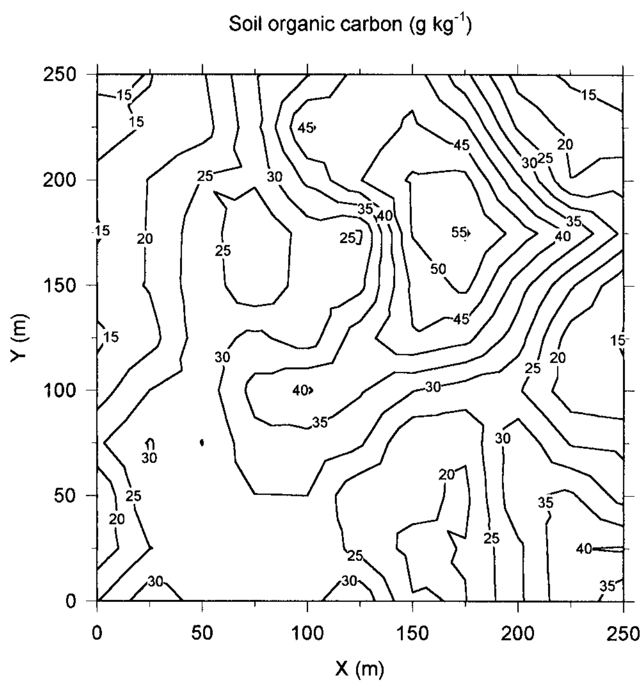

Fig. 3. Soil organic carbon contents measured in soils from the Iowa pothole field.

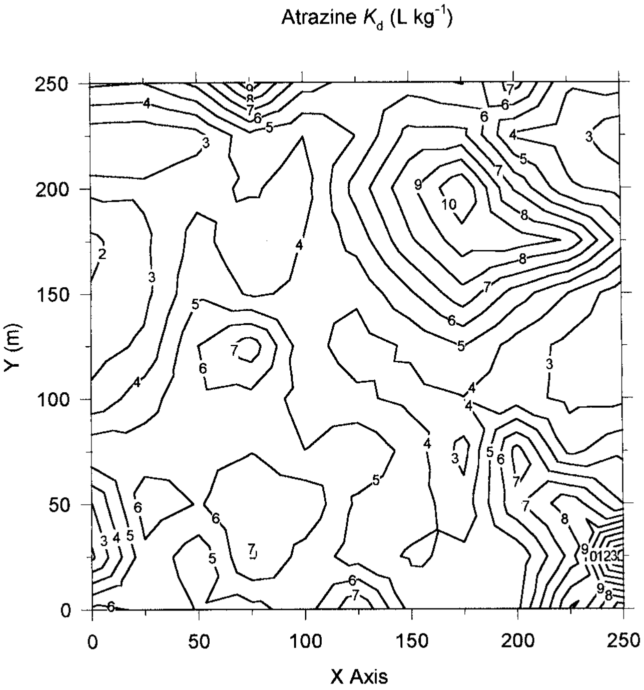

Fig. 4. Atrazine K_d values measured in soils from the Iowa pothole field.

with eroding sediments. These speculations have some merit, considering that Jaynes et al. [20] reported that atrazine was below 2 μg/L in tile drainage leaving the potholes from this field in 1992 and accounted for approx. 0.045% of the applied herbicide. In a similar study, Jayachandran et al. [21] reported that 40% of the samples collected from tile drains leaving a nearby field with sloping soils had atrazine concentrations that exceeded 3 μg/L. The total amount of atrazine leaving the field with sloping soils was estimated to be between 0.3 and 0.6% of the applied atrazine. These results indicate that as drainage water percolates through the profile to the tile drains, the larger sorptive capacity of soils in depressional areas tends to retard atrazine movement. In general, depressional areas can act as a sink and minimize atrazine leaching. However, significant atrazine losses from depressional areas by overland flow can

Table 2. Mean ($\bar{x}$) and standard deviation (SD) of soil organic carbon (SOC) content and atrazine sorption coefficients (K_d) from soils collected at grid points and grouped by landscape position class[a] in the Iowa pothole field

Landscape position class	n	SOC (mg/kg)		Atrazine K_d (L/kg)	
		$\bar{x}$	SD	$\bar{x}$	SD
Shoulder	40	16.9	2.3	2.78	0.97
Back slope	117	25.8	9.3	4.48	1.68
Foot slope	24	28.1	6.4	5.15	1.66
Level upland	29	31.3	3.8	6.13	1.05
Depression	31	45.5	6.2	8.30	2.50

[a] Landscape position class assignment determined using the algorithm developed by Pennock et al. [16].

occur if the pothole is drained by a riser. Atrazine sorbed to sediments or in the dissolved state will be transported to the risers with the surface drainage water and exit the depressional areas.

Conservation tillage

Farmers are encouraged to use conservation tillage to minimize soil erosion. This tillage management also improves water infiltration and maintains long-term soil productivity [22]. In conservation tillage systems, the soil is minimally disturbed, and the plant residue accumulates on the soil surface to form a surface layer enriched in SOC [7,8]. The mean SOC content at the 0- to 3- and 0- to 15-cm depths in soils under conservation tillage was significantly higher ($p < 0.001$) than soils under conventional tillage (Fig. 5). Significantly higher atrazine K_d values ($p < 0.001$) occurred in soils collected at the 0- to 3-cm soil depth under conservation tillage, although no significant differences occurred at the 0- to 15-cm soil depth ($p = 0.411$). Collecting surface soils to a deeper depth (0–15 cm) resulted in the inclusion of non-SOC-enriched soil from the lower part of the surface horizon and was sufficient to lower atrazine sorption.

We speculate that the higher amount of atrazine sorption in soils under conservation tillage will reduce leaching relative to soil under conventional tillage. In addition, microbial breakdown of atrazine might be higher in soils under conservation

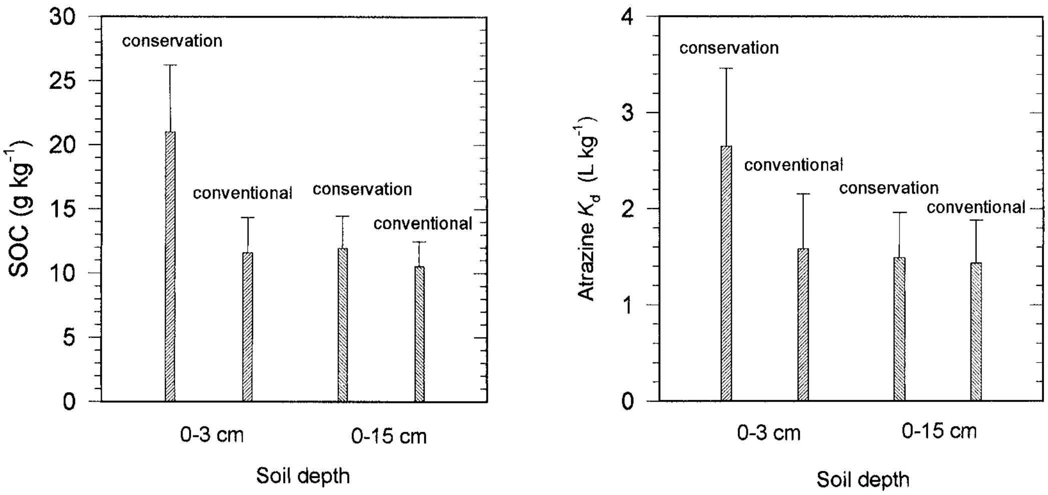

Fig. 5. Comparison of the effects of tillage (conservation vs conventional) at the 0- to 3- and 0- to 15-cm soil depths on the SOC content (left) and atrazine K_d values (right) measured in South Carolina long-term tillage plots (error bars represent one SD value).

tillage because microbial decomposition activity should be stimulated by the higher SOC contents.

CONCLUSIONS

Evaluation of a few relevant soil properties and a management factor on atrazine sorption revealed some interesting trends. Atrazine sorption was found to be strongly influenced by SOC content and landscape position in central Iowa glacial till soils. Atrazine sorption was also strongly correlated with the SOC content in a South Carolina coastal plain soil under conservation tillage. Atrazine losses by tile drainage from depressional areas (potholes) in Iowa are lower than soils in sloping positions, suggesting that depressions can reduce atrazine leaching. However, atrazine losses from depressional areas can be significant when the area is drained with risers. Effective herbicide management strategies might need to consider the effects of SOC, landscape position, and tillage on atrazine sorption. Applicators might need to adjust application rates and/or select another type of herbicide to account for these properties and factors for optimum weed control and to prevent herbicide leaching to groundwater.

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