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Characterization of Alachlor and Atrazine Desorption from Soils¹

SHARON A. CLAY and WILLIAM C. KOSKINEN²

Abstract. Herbicide desorption isotherms may be affected by the amount of nondesorbable herbicide present in soil. Nondesorbable alachlor (as determined after methanol extraction) generally increased on a Waukegan silt loam (Typic Hapludolls) and a Ves clay loam (Udic Haplustolls) during five 0.01 M CaCl₂ desorptions. Atrazine was totally extracted with methanol from the Waukegan soil after one desorption using 0.01 M CaCl₂. However, after five desorptions with 0.01 M CaCl₂ an average of 5.5 and 15.5% of the total recovered atrazine from two atrazine application rates was methanol nondesorbable from the Waukegan and Ves soils, respectively. Freundlich desorption isotherms adjusted for nondesorbable herbicide accounted for as much as 71% of the difference between adsorption and desorption isotherms. Only a portion of the hysteresis observed can be attributable to nondesorbable herbicide. Nomenclature: Alachlor, 2-chloro - *N* - (2,6-diethylphenyl) - *N* - (methoxymethyl)acetamide; atrazine, 6 - chloro-*N*-ethyl-*N'*-(1-methylethyl) - 1,3,5-triazine - 2,4-diamine.

Additional index words. Hysteresis, Freundlich isotherms, adsorption, nondesorbable herbicide, bound herbicide.

INTRODUCTION

Herbicide adsorption to and subsequent desorption from soil is often characterized in the laboratory using slurry experiments. The Freundlich equation is used frequently to describe the herbicide distribution between soil and solution for both adsorption and desorption. Herbicide desorption from soil, however, may not be predicted reliably from the Freundlich adsorption isotherm. Less herbicide desorbed from soil than predicted by the adsorption isotherm is often referred to as hysteresis. Hysteresis implies that a portion of the applied herbicide is very strongly or irreversibly bound to soil (2, 3, 7, 9, 14). However, experimental factors that can contribute to a hysteresis effect include nonattainment of equilibrium during adsorption or desorption processes, formation of herbicide precipitates, and loss of herbicide due to metabolism or experimental error.

Pesticide residues are considered bound when the chemical species cannot be extracted by methods commonly used for

residue analyses or after exhaustive extraction (6). Bound residues may be parent material or degradation products. Bound pesticide residues have accounted for 7 to 90% of the total applied pesticide, several days to several months after application (6). Approximately 60% of ¹⁴C-atrazine applied to an Ochrepts soil was nonextractable by methanol solution (4:1 methanol:water) 1 yr after atrazine application (11).

Kinetic parameters of binding and release of atrazine on "restricted" and "labile" soil sites of freshwater sediments have been reported (14). A nonlinear regression model predicts an increase in binding of atrazine to restricted sites with a concomitant decrease in binding to labile sites as adsorption time increases (14). Also, soil organic matter may provide restricted binding sites for herbicides. Bound ¹⁴C residues of prometryn [*N,N'*-bis(1-methylethyl) - 6 - methylthio-1,3,5-triazine-2,4-diamine] in an organic soil increased to 43% over a 150-day incubation (5).

Degradation or the formation of nonextractable herbicide residues during laboratory batch experiments may account for the irreversible binding of parent compound. Metolachlor [2-chloro-*N*-(2-ethyl-6-methylphenyl) - *N* - (2-methoxy-1-methylethyl)acetamide] adsorption was not completely reversible 3 days after application (8). The half-lives of metolachlor and alachlor, at 20 C and 80% soil moisture, were 16 and 11 days, respectively, in a clay loam soil (16). Beestman and Deming (1) reported an alachlor half-life of 8 days at 22 C in a silt soil.

Bound pesticide residues would affect the observed herbicide-soil equilibrium during desorption. Only a portion of the adsorbed herbicide would be available for desorption. Correcting the desorption isotherms for the amount of nondesorbable herbicide on the soil may result in desorption isotherms more similar to adsorption isotherms. The objectives of this study were to determine: a) if a portion of adsorbed atrazine and alachlor was nondesorbable from two Minnesota soils used extensively for corn (*Zea mays* L.) and soybeans [*Glycine max* (L.) Merr.] production, and b) the effects of correcting for the amount of nondesorbable herbicide on the desorption isotherms. This information may help describe a portion of hysteresis.

MATERIALS AND METHODS

Adsorption. Soil from a 0- to 15-cm depth of a Ves clay loam (fine-loamy, mixed, mesic Udic Haplustolls) and a Waukegan silt loam (fine-silty over sandy or sandy-skeletal, mixed, mesic Typic Hapludolls) was air dried and passed through a 2-mm sieve. Soil characteristics are presented in Table 1. Herbicide solutions were made in 0.01 M CaCl₂ and contained 107, 50, 28.1, or 12.1 μmol L⁻¹ alachlor or 59.3, 27.8, 18.1, or 6.2 μmol L⁻¹ atrazine. The alachlor solutions contained 0.8 kilobecquerel (kBq)³ of [ring uniformly labeled

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³Abbreviations: KBq, kilobecquerel; UL, uniformly labeled; GBq, gigabecquerel; MBq, megabecquerel; LSC, liquid scintillation counting; TLC, thin-layer chromatography; CEC, cation exchange capacity.

Table 1. Soil characteristics of Waukegan silt loam and Ves clay loam soils.

Parameter	Soil characteristics	
	Waukegan silt loam	Ves clay loam
Silt, %	60	30
Clay, %	23	27
Organic carbon ^a , g kg ⁻¹	26.4	27.7
CEC ^b , cmol kg ⁻¹	23	20
pH ^c	5.8	4.8

^aOrganic carbon determined by combustion.

^bDirect CEC determination using exchangeable NH₄ with KCl.

^cpH determined in soil: 0.01 M CaCl₂ (1:1 v/v).

(UL)-¹⁴C] alachlor (specific activity 1 gigabecquerel (GBq)³ mmol⁻¹) and the atrazine solutions contained approximately 0.8 kBq of [ring-UL-¹⁴C] atrazine (specific activity 129 megabecquerel (MBq)³ mmol⁻¹). A 10-ml aliquot of each solution was added to 10 g soil in a 25-ml glass centrifuge tube and the tube was sealed with a teflon-lined cap.

The tubes were shaken mechanically for 24 h. Time study results (not shown) indicated that 88% of the alachlor and 98% of the atrazine that was adsorbed in 24 h was adsorbed in the first 2 h. The change in the amount of alachlor and atrazine adsorbed between 24 and 48 h was less than 2% on each soil. Following equilibration, the suspensions were centrifuged for 30 min at 8000 rpm (ca. 8000 × g). A 4-ml aliquot of supernatant was removed. Fine sediments in the supernatant were not removed. Filtering through a 2-μm silver filter did not affect herbicide solution concentration in a previous study (4). The amount of ¹⁴C in supernatant was determined by liquid scintillation counting (LSC)³ for 10 min. The amount of herbicide in solution was then calculated.

The amount of herbicide adsorbed to the soil after equilibration was the difference between herbicide concentration in soil-free blanks and herbicide concentration in solution after equilibration with soil. Adsorption was determined on six soil samples for each initial herbicide solution concentration at 23 °C. Adsorption isotherms were calculated for each herbicide using the linearized form of the Freundlich equation $\log x/m = \log K_f + (1/n) \log C$, where x/m is μmol herbicide adsorbed per kg soil, C is μmol herbicide per L of supernatant solution after equilibration, and K_f and $1/n$ are empirical constants. Isotherm coefficients were calculated by the least squares technique on the mean of the replicates of the log-transformed equilibrium data. Statistical evaluation included Bartlett's test for homogeneity of variances, comparison of slopes and elevations of the regression lines, and calculation of the 95% confidence intervals for the intercept ($\log K_f$) and slope ($1/n$).

⁴Packard Instrument Co., 2200 Warrenville Rd., Downers Grove, IL 60515. Mention of a trade name does not imply an endorsement or recommendation by the USDA-ARS.

Desorption. Desorption studies were conducted by initially adsorbing herbicides to the Ves clay loam and Waukegan silt loam from 0.01 M CaCl₂ solutions containing 50 or 28.1 μmol L⁻¹ of alachlor with ¹⁴C-alachlor or 59.3 or 18.1 μmol L⁻¹ of atrazine with ¹⁴C-atrazine as described previously. A 4-ml aliquot was removed after the first 24-h equilibration period, the amount of ¹⁴C in the aliquot was determined by LSC techniques, and the concentration of herbicide in solution and adsorbed to soil was calculated.

Desorption of herbicides was accomplished by replacing a herbicide-containing 4-ml aliquot removed by pipetting from the tube with 4 ml of 0.01 M CaCl₂ (4). After solution replacement, tubes were vibrated to disperse the soil pellet, mechanically shaken for 24 h, and recentrifuged. The 24-h desorption process with 0.01 M CaCl₂ was repeated five times. Final ¹⁴C-activity ml⁻¹ supernatant after five 0.01 M CaCl₂ desorptions was approximately 500 disintegrations per minute (8.4×10^{-3} kBq) and the standard error between duplicate tubes averaged 2.1%.

The concentration of alachlor or atrazine present in the aqueous solution after each desorption step was determined as previously described. The amount of herbicide that remained adsorbed to the soil was calculated by difference. Desorption studies were done at 23 °C starting with six tubes for each herbicide concentration-soil combination.

At the end of 1, 3, and 5 days of desorption, a mass balance of initially added herbicide was determined for duplicate tubes containing each herbicide concentration-soil combination. The soil-alachlor solution was shaken for 24 h with 4 ml of methanol (solution mixture 2:3 methanol:0.01 M CaCl₂ v/v). The slurry was centrifuged and a 4-ml aliquot of the supernatant was removed. The soil was extracted a second time with 4 ml of methanol (final solution mixture 16:9 methanol: 0.01 M CaCl₂ v/v). Concentrations of ¹⁴C in the supernatant were determined by LSC techniques and the amount of alachlor calculated.

The soil-atrazine solution was shaken for 24 h with 4 ml methanol adjusted to pH 2 with HCl (4) (solution mixture 2:3 methanol:0.01 M CaCl₂ v/v). The slurry was centrifuged and a 4-ml aliquot of supernatant was removed. The soil was extracted a second time with 4 ml methanol adjusted to pH 2 (final solution mixture 16:9 methanol: 0.01 M CaCl₂ v/v). Concentration of ¹⁴C in the methanolic extracts was determined by LSC techniques and the amount of atrazine calculated.

The total recovery of ¹⁴C in the soil was determined by combustion. Approximately 0.5 g of soil was mixed with an equal volume of cellulose and combusted using a Packard 306 oxidizer⁴. The ¹⁴CO₂ evolved was trapped in Carbo-sorb⁴ and collected in a liquid scintillation vial. Permafluor V⁴ was then added and the radioactivity determined by LSC techniques.

Linearized desorption isotherms were calculated using the Freundlich equation for each herbicide-concentration-soil treatment. Calculations were done assuming total recovery and also correcting for nondesorbable herbicide.

Degradation. For each herbicide adsorption-desorption process, a portion of the supernatant containing ¹⁴C was spotted

Table 2. Adsorption isotherm, and nonadjusted and adjusted desorption isotherms of alachlor.

Soil	Isotherm	Initial conc. $\mu\text{mol L}^{-1}$	K_f^a $\mu\text{mol}^{1-1/n} \text{L}^{1/n} \text{kg}^{-1}$	$1/n^b$	r^2
Waukegan silt loam	Adsorption	...	3.7 (3.2– 4.3)	0.85 (0.01)	0.99
	Desorption:	50.0			
	Nonadjusted		13.0 (12.5–13.6)	0.38 (0.01)	0.98
	Adjusted ^c		9.7 (8.9–10.6)	0.48 (0.03)	0.97
	Desorption:	28.1			
	Nonadjusted		8.9 (8.5– 9.4)	0.40 (0.02)	0.96
Ves clay loam	Adsorption	...	5.3 (3.8– 7.3)	0.80 (0.02)	0.97
	Desorption:	50.0			
	Nonadjusted		16.7 (16.3–17.2)	0.37 (0.01)	0.98
	Adjusted ^c		14.0 (13.5–14.5)	0.46 (0.01)	0.99
	Desorption:	28.1			
	Nonadjusted		12.3 (11.9–12.6)	0.36 (0.01)	0.97
	Adjusted ^c		10.4 (9.6–11.2)	0.46 (0.02)	0.98

^aNumber in parentheses is confidence interval (CI) for K_f ; antilogs of $\log K_f - \text{CI} \log K_f$ and $\log K_f + \text{CI} \log K_f$.

^bNumber in parentheses is standard error of $1/n$.

^cDesorption isotherms adjusted for methanol nondesorbable alachlor.

Figure 1. Alachlor adsorption isotherm, and nonadjusted and adjusted desorption isotherms for a) Waukegan silt loam, and b) Ves clay loam.

on a silica gel thin-layer chromatography (TLC)³ plate. Plates containing alachlor were developed with butanol/acetic acid/water (6:2:3 v/v/v) to a height of 13 cm, and those with atrazine were developed with butanol/acetic acid/water (11:5:4 v/v/v) to a height of 14 cm to determine the amount of parent compound and degradation products present in solution. After development, TLC plates were scraped to determine areas of ¹⁴C activity. Standards of ¹⁴C-alachlor or ¹⁴C-atrazine in 0.01 M CaCl₂ were cochromatographed on the plate with the soil extracts. ¹⁴C-atrazine was hydrolyzed to ¹⁴C-hydroxyatrazine, which was used as an atrazine degradation product standard in TLC techniques.

Experimental methods for determination of atrazine mineralization have been presented in a previous publication (4). Ring mineralization of alachlor was monitored over an 8-day period in biometer flasks. A 10-ml aliquot of a 0.01 M CaCl₂ solution containing 39 $\mu\text{mol L}^{-1}$ alachlor and 2.16 kBq of ring-UL-¹⁴C-alachlor was placed into the flask along with 10 g of either Waukegan or Ves soil. A 10-ml aliquot of 0.5 M NaOH was added to the trap tube. The flasks were sealed and incubated at 23 C. A 5-ml aliquot of NaOH was removed at the end of 8 days. The concentration of ¹⁴CO₂ in the NaOH was determined by LSC methods. The alachlor mineralization study was run once using three replicates for each soil type.

RESULTS AND DISCUSSION

Adsorption. The Freundlich equation adequately described adsorption of both herbicides to both soils ($r^2 > 0.96$) (Tables 2 and 3 and Figures 1 and 2). More herbicide was adsorbed to

Table 3. Adsorption isotherm, and nonadjusted and adjusted desorption isotherms of atrazine.

Soil	Isotherm	Initial conc. $\mu\text{mol L}^{-1}$	K_f^b $\mu\text{mol}^{1-1/n} \text{ L}^{1/n} \text{ Kg}^{-1}$	$1/n$	r^2
Waukegan silt loam	Adsorption	. . .	3.6 (3.1– 4.2)	0.83 (0.01)	0.99
	Desorption:	59.3			
	Nonadjusted		13.3 (12.6–15.9)	0.37 (0.01)	0.96
	Adjusted ^c		10.4 (9.7–11.1)	0.46 (0.02)	0.98
	Desorption:	18.1			
	Nonadjusted		7.7 (7.0– 8.0)	0.39 (0.02)	0.92
Ves clay loam	Adsorption	. . .	5.6 (4.9– 6.4)	0.83 (0.01)	0.99
	Desorption:	59.3			
	Nonadjusted		15.0 (13.5–16.7)	0.45 (0.04)	0.86
	Adjusted ^c		9.2 (6.9–12.2)	0.64 (0.12)	0.82
	Desorption:	18.1			
	Nonadjusted		9.8 (8.6–11.1)	0.41 (0.05)	0.73
	Adjusted ^c		7.0 (5.0– 9.8)	0.72 (0.17)	0.75

^aNumber in parentheses is confidence interval (CI) for K_f ; the antilogs of $\log K_f - \text{CI } \log K_f$ and $\log K_f + \text{CI } \log K_f$.

^bNumber in parentheses is standard error of $1/n$.

^cDesorption isotherms adjusted for methanol nondesorbable atrazine.

the Ves clay loam than to the Waukegan silt loam, as evidenced by a higher K_f value for the Ves than Waukegan (Tables 2 and 3). The adsorption isotherms for both herbicides on both soils had a $1/n$ (slope) value less than 1. The slope of less than unity indicates that as the concentration of herbicide in solution increased, the percentage of soil-adsorbed herbicide decreased. Adsorption isotherms with slopes less than 1 have been previously reported for alachlor (10) and atrazine (4).

Desorption. Desorption of both herbicides from both soils with 0.01 M CaCl_2 was hysteretic. Nonadjusted desorption isotherms had slopes less than those for the adsorption isotherms (Tables 2 and 3 and Figures 1 and 2). Hysteresis has been described previously for atrazine (4, 13).

The observed hysteresis may have resulted from several factors. Degradation of the parent compound may have occurred during desorption. Ring mineralization of alachlor and atrazine over an 8-day period at 22 C measured in both soils was approximately 0.4%. While ring mineralization for both herbicides was minimal, alachlor or atrazine degradation products may have formed.

As the herbicide degrades, a new equilibrium is established with more parent compound being removed from solution and bound to soil. However, analysis of the alachlor-containing supernatant solutions by TLC indicated that greater than 88% of the ^{14}C in solution chromatographed with parent alachlor ($R_f = 0.75$). The remaining 12% of the ^{14}C in solution was distributed equally along the plate. Atrazine and hydroxyatrazine had R_f values of 0.65 and 0.40, respectively. Greater than 99% of the ^{14}C in atrazine-containing supernatants chromatographed with parent atrazine

Figure 2. Atrazine adsorption isotherm, and nonadjusted and adjusted desorption isotherms for a) Waukegan silt loam, and b) Ves clay loam.

Table 4. Alachlor recovered partitioned into 0.01 M CaCl₂-desorbable, methanol-desorbable, and nondesorbable fractions in two soil types after 1, 3, or 5 desorption steps.

Initial alachlor concentration	Soil	Desorption number	Alachlor recovered			
			Total	0.01 M CaCl ₂	Methanol	Nondesorbable ^a
			(% of applied)			
50.0 μmol L ⁻¹ :	Waukegan silt loam	1	99	20	77	2
		3	97	34	55	8
		5	83	43	40	0
	Ves clay loam	1	100	15	84	1
		3	93	26	63	4
		5	93	35	54	4
28.1 μmol L ⁻¹	Waukegan silt loam	1	103	20	83	0
		3	98	34	56	8
		5	98	42	46	10
	Ves clay loam	1	100	14	86	0
		3	96	24	66	6
		5	97	34	57	6

^a95% confidence interval for paired t-tests, 50.0 $\mu\text{mol L}^{-1}$ = 6; 28.1 $\mu\text{mol L}^{-1}$ = 3.

while less than 0.2% of the ¹⁴C chromatographed with hydroxyatrazine.

Changes in solution composition during desorption may have occurred. Soluble soil organic carbon decreased when 0.01 M CaCl₂ was used for desorption replacement solution (4). However, atrazine desorption from a Ves clay loam was the same if 0.01 M CaCl₂ or fresh soil extract was used in the desorption process (4). Ionic strength of the supernatant may have changed each day as a result of 0.01 M CaCl₂ replacement. However, the changes in electrolyte composition of the solutions and the subsequent effects on desorption were not studied in this experiment.

Also, the herbicides may have bound to restricted soil sites, as proposed by Wauchope and Myers (14), and not have been readily released into solution. Organic solvents such as methanol, toluene, and acetonitrile have been used to break bonds that water may not break (6, 12). Methanol-desorbable herbicide may be desorbable with water, however, only after a much longer time period.

A portion of the adsorbed alachlor and atrazine was nondesorbable with methanol (Tables 4 and 5). The amount of methanol-nondesorbable herbicide increased as the number of desorption equilibrations increased. Nondesorbable herbi-

Table 5. Atrazine recovered partitioned into 0.01 M CaCl₂-desorbable, methanol-desorbable, and nondesorbable fractions in two soil types after 1, 3, or 5 desorption steps.

Initial atrazine concentration	Soil	Desorption number	Atrazine recovered			
			Total	0.01 M CaCl ₂	Methanol	Nondesorbable ²
			(% of applied)			
59.3 μmol L ⁻¹ :	Waukegan silt loam	1	96	19	77	0
		3	100	31	69	0
		5	94	41	46	7
	Ves clay loam	1	100	15	81	4
		3	100	26	74	0
		5	96	35	48	13
18.1 μmol L ⁻¹ :	Waukegan silt loam	1	100	11	89	0
		3	99	22	77	0
		5	98	39	55	4
	Ves clay loam	1	97	16	79	2
		3	100	21	79	0
		5	98	26	54	18

^a95% confidence interval for paired t-tests, 59.3 $\mu\text{mol L}^{-1}$ = 2; 18.1 $\mu\text{mol L}^{-1}$ = 3.

Table 6. Hysteresis accounted for by adjusting desorption isotherms of alachlor and atrazine for the amount of nondesorbable herbicide on a Ves clay loam and Waukegan silt loam.

Soil	Hysteresis accounted for ^a by herbicide and original concentration			
	Alachlor		Atrazine	
	50.0	28.1	59.3	18.1
	————— (%) —————			
Waukegan silt loam	27	38	18	9
Ves clay loam	9	23	51	71

^a $[\mu\text{mol adsorbed (nonadjusted)} - \mu\text{mol adsorbed (adjusted)}] / [\mu\text{mol adsorbed (nonadjusted)} - \mu\text{mol adsorbed (predicted by adsorption isotherm)}]$.

cide may be parent compound or strongly bound metabolite.

The Waukegan silt loam treated with alachlor at 28 $\mu\text{mol L}^{-1}$ had more nondesorbable alachlor than the Ves clay loam with the same treatment after five desorption equilibrations (Table 4). The Waukegan silt loam had 10% of the total recovered alachlor nondesorbable while the Ves clay loam had 6% of the total recovered alachlor nondesorbable. The greater concentration of nondesorbable alachlor remaining on the Waukegan silt loam probably was due to the slightly higher cation exchange capacity (CEC)³ compared to the CEC of the Ves clay loam (Table 1) (10, 15).

In contrast, more atrazine was nondesorbable after 5 days from the Ves clay loam compared to the amount of nondesorbable atrazine on the Waukegan silt loam (Table 5). The amount of nondesorbable atrazine from the 59 $\mu\text{mol L}^{-1}$ treatment was 13% of the total recovered atrazine from the Ves clay loam compared to 7% of the total recovered atrazine from the Waukegan silt loam. The higher clay content and CEC and lower pH of the Ves clay loam, compared to the Waukegan silt loam (Table 1), may be factors that increased the amount of nondesorbable atrazine on the Ves clay loam. In most cases, as the initial concentration of herbicide decreased, the percentage of methanol nondesorbable herbicide increased (Tables 4 and 5). Increase in the percentage of nondesorbable herbicide at low initial concentrations may be explained by a higher percentage of herbicide adsorbed initially at low concentrations.

Adjusting the desorption isotherms for the amount of nondesorbable herbicide present in the soil after 1, 3, and 5 desorption steps influenced both the K_f and $1/n$ values compared to the nonadjusted desorption isotherms. The slopes for the adjusted isotherms were more similar to the adsorption isotherm slopes than the slopes of nonadjusted isotherms (Tables 2 and 3). The amount of hysteresis accounted for when desorption isotherms were adjusted for the methanol nondesorbable herbicide ranged from 9% for the high alachlor-Ves combination and low atrazine-Waukegan combination to 71% for the low atrazine-Ves combination (Table 6).

Methanol nondesorbable herbicide did not account for all observed hysteresis in this experiment. Other factors contrib-

ute to the amount of hysteresis. Loss of herbicide due to pipetting was measured by rinsing pipettes twice with methanol and ^{14}C in rinsate counted by LSC techniques. Pipetting losses ranged from 0.4 to 0.8% during the entire 0.01 M CaCl_2 and methanol desorption processes. Choice of organic solvent affected the amount of nondesorbable herbicide that remained on the soil. For example, alachlor desorption with toluene, in the same experimental procedure, was studied. Alachlor was totally desorbed after one desorption; however, after 5 desorption steps, toluene desorbed less alachlor (8 to 21% nondesorbable) than did methanol (6 to 10% nondesorbable). The amount of hysteresis accounted for with toluene-nondesorbable alachlor was greater than with methanol (authors' unpublished data). However, total recovery of alachlor with toluene extractions was approximately 80% after five desorptions, while total recovery of alachlor with methanol extractions total recovery was greater than 90% (Table 4). Poor mixing of the soil-0.01 M CaCl_2 solution with toluene may have resulted in lower recoveries.

In conclusion, a portion of the observed hysteresis with alachlor and atrazine on Ves clay loam and Waukegan silt loam could be a result of soil-bound nondesorbable parent herbicide or degradation products. The amount of nondesorbable herbicide and the amount of hysteresis accounted for in this study were dependent on the soil type, herbicide applied, solvent used for extraction, and the number of equilibration periods. The amount of nondesorbable herbicides may increase as the aging process of the herbicide in soil progresses over days, weeks, and months (6, 11, 14). However, the amount of nondesorbable herbicide may explain a portion of observed hysteresis during laboratory batch desorption experiments.

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