

Adsorption and Desorption of Metolachlor and Metolachlor Metabolites in Vegetated Filter Strip and Cultivated Soil

L. J. Krutz,* S. A. Senseman, K. J. McInnes, D. W. Hoffman, and D. P. Tierney

ABSTRACT

Previous studies have indicated that dissolved-phase metolachlor [2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(methoxy-1-methylethyl)acetamide] transported in surface runoff is retained by vegetative filter strips to a greater degree than either metolachlor oxanilic acid [2-[(2-ethyl-6-methylphenyl)(2-methoxy-1-methylethyl)amino]-2-oxoacetic acid] (OA) or metolachlor ethanesulfonic acid [2-[(2-ethyl-6-methylphenyl)(2-methoxy-1-methylethyl-1)amino]-2-oxoethanesulfonic acid] (ESA), two primary metabolites of metolachlor. Adsorption-desorption of ESA and OA in vegetated filter strip soil (VFSS) has not been evaluated, yet these data are required to assess the mobility of these compounds in VFSS. The objective of this experiment was to compare metolachlor, ESA, and OA adsorption and desorption parameters between VFSS and cultivated soil (CS). Adsorption and desorption isotherms were determined using the batch equilibrium procedure. With the exception of a 1.7-fold increase in organic carbon content in the VFSS, the evaluated chemical and physical properties of the soils were similar. Sorption coefficients for metolachlor were 88% higher in VFSS than in CS. In contrast, sorption coefficients for ESA and OA were not different between soils. Relative to metolachlor, sorption coefficients for ESA and OA were at least 79% lower in both soils. Metolachlor desorption coefficients were 59% higher in the VFSS than in the CS. Desorption coefficients for ESA and OA were not different between soils. Relative to metolachlor, desorption coefficients for ESA and OA were at least 66% lower in both soils. These data indicate that the mobility of ESA and OA will be greater than metolachlor in both soils. However, higher organic carbon content in VFSS relative to CS may limit the subsequent transport of metolachlor from the vegetated filter strip.

METOLACHLOR IS USED for preemergence and post-emergence weed control in a variety of crops including corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), and soybean [*Glycine max* (L.) Merr.] (Ahrens, 1994). In soil, metolachlor is metabolized by microorganisms (Al-Khatib et al., 2002). The two primary metabolites of metolachlor are ESA and OA (Hostetler and Thurman, 2000; Phillips et al., 1999; Yokley et al., 2002) (Fig. 1). Metolachlor ethanesulfonic acid formation occurs through glutathione conjugation, a common detoxification process for several organisms (Aga et al., 1996; Field and Thurman, 1996). Pathway(s) describing the degradation of metolachlor to OA are unknown.

Surface runoff can transport metolachlor and metolachlor metabolites to surface water bodies including rivers, lakes, and streams (Aga and Thurman, 2001;

Kolpin et al., 2000; Lambropoulou et al., 2002; Lerch et al., 1998; Phillips et al., 1999; Senseman et al., 1997). Metolachlor metabolites frequently constitute a majority of metolachlor's measured concentration in hydrologic systems (Kolpin et al., 1996, 2000; Thurman et al., 1996). Therefore, means for limiting the transport of these compounds from application zones is desirable.

Vegetated filter strips are narrow strips of permanent vegetation planted adjacent to cropland with the intent to reduce herbicide transport from agricultural application zones. Vegetated filter strips increase the retention time of surface runoff and thus reduce herbicide losses by (i) facilitating the deposition of sediment-adsorbed compounds (Arora et al., 1996; Asmussen et al., 1977; Barfield et al., 1998; Patty et al., 1997; Rankins et al., 2001; Tingle et al., 1998); (ii) enhancing herbicide retention by increasing time available for infiltration (Arora et al., 1996; Asmussen et al., 1977; Barfield et al., 1998; Patty et al., 1997; Rankins et al., 2001; Schmitt et al., 1999); and (iii) sorbing dissolved-phase herbicides to the grass, grass thatch, and soil surface (Arora et al., 1996; Asmussen et al., 1977; Barfield et al., 1998; Krutz et al., 2004; Misra et al., 1996). However, the environmental fate of herbicides and their metabolites are rarely evaluated in VFSS.

By design, vegetated filter strips accumulate greater above- and belowground organic matter compared with adjacent cultivated soils (CS) (Benoit et al., 1999; Blanche et al., 2003; Rankins et al., 2002; Staddon et al., 2001). Organic matter significantly affects herbicide sorption. Greater metolachlor (Staddon et al., 2001), fluometuron (Rankins et al., 2002; Blanche et al., 2003), and isoproturon (Benoit et al., 1999) sorption has been reported for VFSS compared with CS. Similarly, greater atrazine (Dozier et al., 2002), metolachlor (Dozier et al., 2002), and fluometuron (Blanche et al., 2003) adsorption has been reported for bermudagrass (Dozier et al., 2002) and switchgrass (Blanche et al., 2003) thatch compared with CS (Dozier et al., 2002; Blanche et al., 2003) and VFSS (Blanche et al., 2003). In these experiments, metolachlor (Staddon et al., 2001), isoproturon (Benoit et al., 1999), and fluometuron (Rankins et al., 2002) desorption was greater for CS than VFSS.

In our previous work, vegetated filter strips retained dissolved-phase metolachlor transported by surface runoff to a greater extent than the metabolites (Krutz et al., 2004). The subsequent release of metolachlor, ESA, and OA from vegetated filter strips has not been evaluated. Staddon et al. (2001) concluded that enhanced metolachlor adsorption and lower desorption in VFSS compared with CS should limit further transport. How-

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Abbreviations: CS, cultivated soil; ESA, metolachlor ethanesulfonic acid; MET, metolachlor; OA, metolachlor oxanilic acid; OC, organic carbon; VFSS, vegetative filter strip soil.

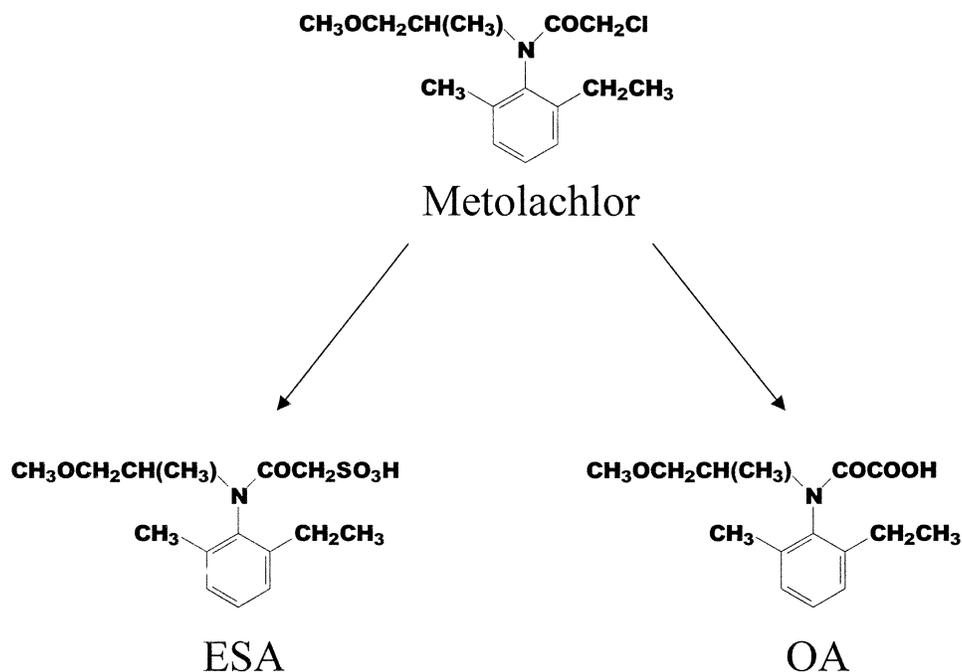


Fig. 1. Chemical structure of metolachlor, metolachlor ethanesulfonic acid (ESA), and metolachlor oxanilic acid (OA).

ever, ESA and OA adsorption-desorption data have not been published. Adsorption-desorption data for these metabolites are needed to assess their mobility in VFSS and CS. Therefore, an experiment was designed to compare metolachlor, ESA, and OA adsorption-desorption between VFSS and CS.

MATERIALS AND METHODS

Soil

The VFSS and CS were collected from 1.5-acre (0.6-ha) watersheds constructed by the USDA-ARS in 1937 at the Blackland Research Center in Temple, TX. The soil at the site is classified as a Houston Black clay (fine, smectitic, thermic Udic Haplusterts). Vegetated filter strips were established with a mixed stand of bermudagrass [*Cynodon dactylon* (L.) Pers.] and buffalograss [*Buchloe dactyloides* (Nutt.) Engelm] in 1991. Since that date, the cultivated fields directly adjacent to the vegetated filter strips have been in a corn-sorghum rotation. Soil samples were collected from the top 0- to 5-cm depth from the VFSS and CS. The soil samples were air-dried, passed through a 2-mm sieve to remove roots and verdure, and stored at $22 \pm 2^\circ\text{C}$ for less than 3 wk before initiating experiments. Particle size distribution was determined with the hydrometer method (Bouyoucos, 1953). Organic carbon content was measured by combustion in a medium-temperature induction furnace (Allison et al., 1965) and corrected for total inorganic carbon (Dremanis, 1962). Soil pH (1:1) was determined as described by Thomas (1996). Soil data are presented in Table 1.

Table 1. Properties of the Houston Black clay vegetative filter strip soil (VFSS) and cultivated soil (CS).

Soil	Sand	Silt	Clay	Organic carbon	CEC†	pH
VFSS	37.9	31.9	30.2	4.2	67.8	7.6
CS	36.8	29.5	33.7	2.5	62.5	7.6

† Cation exchange capacity.

Chemicals

Batch equilibrium experiments were conducted with a mixture of ¹⁴C-labeled and technical-grade chemicals supplied by Syngenta Crop Protection (Basel, Switzerland). Metolachlor's specific radioactivity was 4.96×10^8 kBq mol⁻¹ and radiochemical purity was 98.5%. Metolachlor ethanesulfonic acid's specific radioactivity and radiochemical purity were 4.46×10^8 kBq mol⁻¹ and 98.0%, respectively. Metolachlor oxanilic acid's specific radioactivity was 1.29×10^8 kBq mol⁻¹, and its radiochemical purity was 94.1%. The chemical purity for nonlabeled metolachlor, ESA, and OA was 98, 95.7, and 99.9%, respectively. All parent solutions were prepared in high performance liquid chromatography (HPLC)-grade methanol and diluted to 0.01, 0.05, 0.1, and 1.0 mg L⁻¹ batch solutions in 0.01 M CaCl₂. The batch equilibrium radioactivity range was 4.6 to 194.9 kBq L⁻¹.

Adsorption

Metolachlor, ESA, and OA adsorption isotherms were determined for VFSS and CS with the batch equilibration technique at $24 \pm 2^\circ\text{C}$. A 5-mL aliquot of each chemical solution was added to 1 g of soil in a 50-mL glass centrifuge tube resulting in a water to soil ratio of 5:1. Each concentration was replicated four times. Slurries were placed on a reciprocal shaker for 24 h and then centrifuged at $2000 \times g$ for 20 min at $24 \pm 2^\circ\text{C}$. Three milliliters of supernatant solution was removed from each tube. One milliliter of the equilibrium supernatant solution was mixed with 10 mL of Ecolite (+) liquid scintillation cocktail (ICN Biomedicals, Irvine, CA), and the ¹⁴C content was analyzed by liquid scintillation spectrometry (LSS). The amount of chemical adsorbed after each equilibration was calculated as the difference between the supernatant concentration and the amount of chemical initially added. Preliminary quality assurance data included adsorption to glass centrifuge tubes, compound solubility at test concentrations, appropriate soil to solution ratios, and equilibration time.

Desorption

Desorption isotherms were obtained from the adsorption samples in equilibrium with the largest initial concentration in solution. Three milliliters of supernatant solution was removed from the centrifuge tubes and replaced with an equal volume of 0.01 M CaCl₂ solution. Soil pellets were dispersed using a vortex shaker, and tubes were placed on a reciprocal shaker for 24 h at 24 ± 2°C. Tubes were then centrifuged for 20 min at 2000 × g. One milliliter of the desorption equilibrium supernatant solution was removed and mixed with 10 mL of Ecolite (+) liquid scintillation cocktail, and the ¹⁴C content was analyzed by LSS. The sorbed concentration was calculated as the difference between the supernatant concentration and the remaining total chemical content after subtracting the amount of chemical removed. The desorption procedure was repeated three times for a total of four 24-h desorption periods.

Coefficients were calculated using the linearized form of the Freundlich equation:

$$\log(S_{eq}) = \log(K_{feq}) + (1/n) \log(C_{eq}) \quad [1]$$

where S_{eq} is mg of test substance per kg of soil at equilibrium, C_{eq} is mg test substance per L of supernatant at equilibrium, and K_{feq} and $1/n$ are empirical constants. Hereafter, K_{fads} and $1/n_{ads}$ indicate adsorption while K_{fdes} and $1/n_{des}$ refer to desorption.

The adsorption distribution coefficient (K_d) was calculated:

$$K_d = S_{eq}/C_{eq} \quad [2]$$

Distribution coefficients were determined at each concentration and averaged across all equilibrium concentrations to obtain a single estimate of K_d . The adsorption coefficient was normalized to the organic carbon (OC) content of the soil (K_{oc}), and hysteresis (ω) was quantified as described by Ma et al. (1993):

$$K_{oc} = (K_d/\%OC) \times 100 \quad [3]$$

$$\omega = \{[(1/n_{ads})/(1/n_{des})] - 1\} \times 100 \quad [4]$$

Statistical Analysis

Regression analysis was performed on adsorption and desorption isotherms. The 95% confidence intervals were calculated for K_f and $1/n$ values. The terms K_d , K_{oc} , and ω were analyzed by analysis of variance (ANOVA) for a completely randomized design using SAS (SAS Institute, 1999) with treatments in a 3 × 2 factorial arrangement (compound × soil). Contrasts were not orthogonal, but were chosen for the objective of the study. To control experiment-wise error, significance of a contrast was evaluated only if the corresponding overall F test was significant ($P < 0.05$).

RESULTS AND DISCUSSION

Adsorption

Adsorption isotherms are presented in Fig. 2. The Freundlich equation adequately described metolachlor, ESA, and OA adsorption to VFSS and CS ($r^2 \geq 0.99$). Calculated K_{fads} values are presented in Table 2. The K_{fads} values for metolachlor were within the range of published results of 1.3 to 3.5 L kg⁻¹ (Ding et al., 2002), 4.8 to 26.7 L kg⁻¹ (Patakioutas and Albanis, 2002), 1.0 to 2.7 L kg⁻¹ (Seybold and Mersie, 1996), and 1.6 to 7.8 L kg⁻¹ (Zhu and Selim, 2000). The K_{fads} values reported for OA are 0.04 L kg⁻¹ for a Maryland sand and 0.171 for

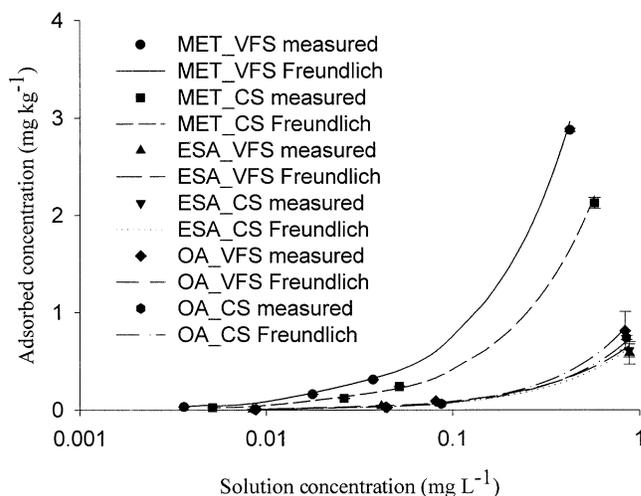


Fig. 2. Adsorption isotherms for metolachlor (MET), metolachlor ethanesulfonic acid (ESA), and metolachlor oxanilic acid (OA) in vegetative filter strip soil (VFSS) and cultivated soil (CS). Each point is the mean and standard deviation of four replications. The error bars do not appear when they are smaller than the symbol for the mean. Calculations are based on the Freundlich equation.

an Iowa sandy loam soil (USEPA, 1995). The K_{fads} values for ESA have not been published.

Based on 95% confidence intervals, K_{fads} values for metolachlor, ESA, and OA were not different between soils. The term K_{fads} is directly correlated with sorption affinity (Seybold and Mersie, 1996). Thus, these data indicate that metolachlor, ESA, and OA sorption is not enhanced in the VFSS. The K_{fads} values for ESA and OA were at least 71% lower than the values for metolachlor in both soils. Thus, the sorption of metolachlor is greater than the sorption of ESA and OA in both soils. Our sorption data for OA are consistent with the results presented by USEPA (1995) where they concluded that OA has the potential to be extremely mobile in the environment. In addition, our data indicate that the potential for ESA mobility is as great as that of OA.

The Freundlich adsorption constant, $1/n_{ads}$, is a measure of adsorption nonlinearity. When $n = 1$, adsorption is linearly proportional to the equilibrium solution concentration, and a distribution coefficient (K_d) is more appropriate for making comparisons among treatments (Seybold and Mersie, 1996). The $1/n_{ads}$ values ranged from 0.92 to 1.09, and the 95% confidence interval for all $1/n_{ads}$ values contained 1 (Table 2). Despite some nonlinearity in the adsorption isotherms due to higher

Table 2. Freundlich adsorption parameters for metolachlor (MET), metolachlor ethanesulfonic acid (ESA), and metolachlor oxanilic acid (OA) in vegetative filter strip soil (VFSS) and cultivated soil (CS).

Compound	Soil	K_{fads}	$1/n_{ads}$	r^2
		$g^{1-1/n} L^{1/n} kg^{-1}$		
MET	VFSS	6.61 (4.69–9.42)†	0.94 (0.85–1.03)	0.99
	CS	3.72 (2.86–4.82)	0.95 (0.87–1.02)	0.99
ESA	VFSS	0.74 (0.51–1.23)	0.92 (0.66–1.19)	0.99
	CS	0.72 (0.47–1.11)	0.99 (0.85–1.13)	0.99
OA	VFSS	1.02 (0.31–3.38)	1.09 (0.71–1.46)	0.99
	CS	0.83 (0.55–1.23)	1.03 (0.90–1.16)	0.99

† Numbers in parentheses are 95% confidence intervals.

Table 3. Average soil distribution coefficient (K_d) and soil adsorption coefficient normalized for organic carbon (K_{oc}) values for vegetative filter strip soil (VFSS) and cultivated soil (CS) and the compounds metolachlor (MET), metolachlor ethanesulfonic acid (ESA) and metolachlor oxanilic acid (OA).

Compound	Soil	K_d		K_{oc}	
		L kg ⁻¹			
Met	VFSS	8.26 (1.00)†		195.9 (23.79)	
	CS	4.39 (0.45)		173.7 (17.90)	
ESA	VFSS	0.92 (0.20)		21.89 (4.95)	
	CS	0.75 (0.09)		29.8 (3.57)	
OA	VFSS	0.84 (0.26)		20.1 (6.57)	
	CS	0.77 (0.09)		30.6 (3.87)	

† Numbers in parentheses are standard deviations.

adsorption at lower concentrations, K_d values were determined at each concentration and then averaged across all equilibrium concentrations to obtain a single estimate of K_d (Table 3) (Seybold and Mersie, 1996).

Our metolachlor K_d values are higher than published results of 1.0 to 2.5 L kg⁻¹ (Seybold and Mersie, 1996) and 1.6 to 2.3 L kg⁻¹ (Staddon et al., 2001). The K_d values for ESA and OA have not been published. The OC content of the VFSS and CS is at least three times higher than the OC reported by Seybold and Mersie (1996) and Staddon et al. (2001). Since metolachlor adsorption has been directly correlated with OC content (Braverman et al., 1986; Patakioutas and Albanis, 2002; Obrigawitch et al., 1981), the elevated K_d values for metolachlor in this experiment compared with published results are probably due to the greater OC content of the soils we evaluated.

The model F test indicated a significant difference in K_d values among compounds and soils (Table 4). Specifically, there was a compound by soil interaction (Table 4). Therefore, simple effects were evaluated (Table 5). The K_d values for metolachlor were 88% higher in VFSS than in CS. Conversely, K_d values for ESA and OA were not different between soils (Table 5). These data demonstrate the greater capacity of the VFSS to sorb metolachlor and the inability of the VFSS to increase ESA and OA sorption.

In this study, higher OC in the VFSS compared with CS probably contributed to enhanced metolachlor sorption (Benoit et al., 1999; Blanche et al., 2003; Rankins et al., 2002; Staddon et al., 2001). Greater herbicide sorption to VFSS than CS has been reported for several herbicides including metolachlor (Staddon et al., 2001), isoproturon (Benoit et al., 1999), and fluometuron

Table 4. P values for soil distribution coefficients (K_d), soil adsorption coefficients normalized for organic carbon (K_{oc}), and the measure of hysteresis (ω).

Comparison	P value		
	K_d	K_{oc}	ω
Model (F test)	0.0001	0.0001	0.0001
Compound	0.0001	0.0001	0.0001
Soil	0.0001	0.6421	0.1038
Compound \times soil	0.0001	0.0001	0.2314

(Blanche et al., 2003; Rankins et al., 2002). Since herbicide sorption is generally inversely correlated with mobility, greater metolachlor sorption to the VFSS should reduce its mobility (Mersie et al., 1999; Staddon et al., 2001). Conversely, since the K_d values for ESA and OA were not different between soils, it is unlikely that the mobility of ESA and OA will be reduced in the VFSS.

The K_d values for metolachlor were greater than the K_d values for ESA and OA in both soils (Table 5). Relative to metolachlor, K_d values for ESA and OA were at least 82% lower in both soils. These data indicate that ESA and OA will be more mobile in soil than metolachlor. This conclusion is supported by a large-scale surface and ground water monitoring study where 88 municipal wells and 12 streams in eastern Iowa were sampled for chloroacetanilide herbicides and their metabolites (Kalkhoff et al., 1998). In that study, the concentration and detection rate for ESA and OA exceeded that of metolachlor in both surface and ground water samples. Similarly, the concentration of ESA and OA in tile drains beneath CS in central New York were 10 to 1800 times higher than those for metolachlor (Phillips et al., 1999). Since ESA and OA are formed in surface soils, their detection in ground water and tile drain water indicates that these metabolites are leachable.

Values of K_d can vary drastically among soils due to the quantities and composition of soil components. Since OC is typically considered the primary soil component responsible for the sorption of nonionic herbicides (Shea, 1989), K_{oc} values are widely used to predict herbicide sorption. However, this normalization assumes that organic matter is the primary soil component controlling sorption, and that the sorption properties of organic matter are identical among soils. When these qualifications are not actualized, K_{oc} values can vary widely among soils (Torrents et al., 1997).

Values of K_{oc} are presented in Table 3. The K_{oc} values for metolachlor are within the range of published results

Table 5. P values for simple effects of compound and soil on the soil distribution coefficient (K_d) and soil adsorption coefficient normalized for organic carbon (K_{oc}) for vegetative filter strip soil (VFSS) and cultivated soil (CS) and the compounds metolachlor (MET), metolachlor ethanesulfonic acid (ESA), and metolachlor oxanilic acid (OA).

Parameter	P value					
	K_d			K_{oc}		
	VFSS vs. CS	MET vs. ESA	MET vs. OA	VFSS vs. CS	MET vs. ESA	MET vs. OA
MET	0.001			0.001		
ESA	0.312			0.083		
OA	0.673			0.021		
Soil						
VFSS		0.001	0.001		0.001	0.001
CS		0.001	0.001		0.001	0.001

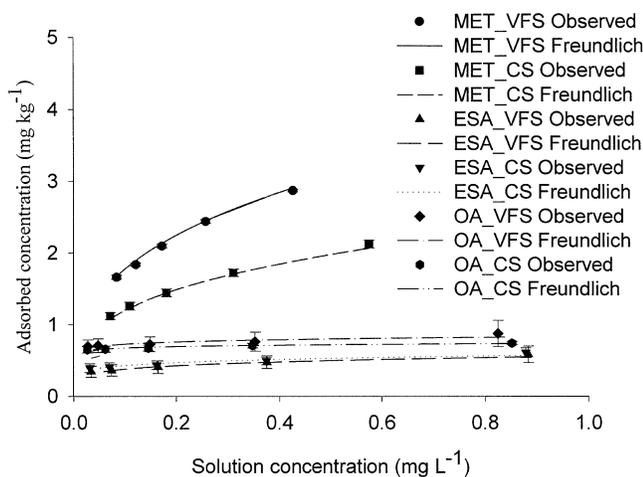


Fig. 3. Desorption isotherms for metolachlor (MET), metolachlor ethanesulfonic acid (ESA), and metolachlor oxanilic acid (OA) in vegetative filter strip soil (VFSS) and cultivated soil (CS). Each point is the mean and standard deviation of four replications. The error bars do not appear when they are smaller than the symbol for the mean. Calculations are based on the Freundlich equation.

of 162 to 190 L kg⁻¹ (Seybold and Mersie, 1996) and 506 L kg⁻¹ (Patakioutas and Albanis, 2002). The coefficient of variation (CV) for K_d and K_{oc} determined from the general linear model (GLM) was 17.8 and 16.2, respectively. The lower CV for K_{oc} indicates that the normalization procedure slightly reduced sorption variability.

The model *F* test indicated a significant difference in K_{oc} values among compounds and soils (Table 4). A compound by soil interaction was detected by the GLM (Table 4). Therefore, simple effects were evaluated (Table 5). The K_{oc} values for metolachlor were 13% higher in VFSS than in CS. Conversely, Staddon et al. (2001) reported higher K_{oc} values for metolachlor in VFSS than in CS. The K_{oc} values for OA were 34% lower in VFSS than in CS. Although not statistically significant ($P = 0.083$), a similar trend was noted for ESA. Higher K_{oc} values for metolachlor metabolites in CS compared with VFSS may indicate a higher affinity of these compounds for the organic matter of the CS. This can occur when there are differences in the physiochemical properties of the organic matter between soils (Kile et al., 1995; Rutheford et al., 1992; Seybold et al., 1994).

The K_{oc} values for metolachlor were greater than the K_{oc} values for ESA and OA in both soils (Table 5). Relative to metolachlor, K_{oc} values for ESA and OA were at least 83% lower in both soils. The water solubili-

ties of metolachlor and OA are 484 and 8500 g L⁻¹, respectively (Dennis Tierney, personnel communication, 2003). Metolachlor ethanesulfonic acid's water solubility is not available. In general, K_{oc} increased as water solubility decreased. This is a common trend for several herbicide classes (Shea, 1989; Mersie and Seybold, 1996).

Desorption

The desorption isotherms for metolachlor, ESA, and OA are presented in Fig. 3, and calculated K_{fdes} values and their associated 95% confidence intervals are presented in Table 6. Desorption isotherms for all compounds were adequately described by the Freundlich equation ($r^2 \geq 0.83$). The K_{fdes} values for metolachlor are within the range of published results of 1.3 to 6.5 L kg⁻¹ (Seybold and Mersie, 1996) and 5.9 to 51.6 L kg⁻¹ (Zhu and Selim, 2000). The K_{fdes} values for ESA and OA have not been published.

Large K_{fdes} values indicate that a small proportion of the chemical has desorbed into solution following successive desorption steps. The K_{fdes} value for metolachlor was 37% higher in VFSS compared with CS. Similarly, larger K_{fdes} values were reported for metolachlor (Staddon et al., 2001), isoproturon (Benoit et al., 1999), and fluometuron (Blanche et al., 2003; Rankins et al., 2002) in VFSS compared with CS. In these experiments, higher K_{fdes} values were attributed to the greater OC of the VFSS. Our data indicate that metolachlor is potentially less mobile in the VFSS compared with CS. This is consistent with the conclusions of Staddon et al. (2001). Conversely, the K_{fdes} values for ESA and OA were at least 66% lower than the values for metolachlor in both soils, and the K_{fdes} values for ESA and OA were not different between soils.

The Freundlich $1/n_{des}$ value describes nonlinearity in the desorption isotherm and is often used as an index of hysteresis (Ma et al., 1993). In this experiment, the $1/n_{des}$ values were smaller than the $1/n_{ads}$ values for all chemicals. The degree of hysteresis (ω) was quantified as described in Eq. [4] (Table 6). The model *F* test indicated a significant difference in ω values among compounds and soils (Table 4). Specifically, ω was different among compounds (Table 4). The ω value for metolachlor, ESA, and OA averaged across soils was 189, 582, and 2378, respectively. The value for metolachlor was not different than the value for ESA ($p = 0.23$). However, the ω value for metolachlor was lower than the value for OA ($p \geq 0.0001$). Since higher ω values indicate greater hysteresis, our data indicate that

Table 6. Freundlich desorption parameters and the measure of hysteresis (ω) for metolachlor (MET), metolachlor ethanesulfonic acid (ESA), and metolachlor oxanilic acid (OA) in vegetative filter strip soil (VFSS) and cultivated soil (CS).

Compound	Soil	K_{fdes} g ^{1-1/n} L ^{1/n} kg ⁻¹	$1/n_{des}$	r^2	ω
Met	VFSS	3.89 (3.63–4.07)†	0.34 (0.31–0.37)	0.99	173 (15.9)‡
	CS	2.45 (2.35–2.62)	0.31 (0.28–0.34)	0.99	205 (10.2)
ESA	VFSS	0.56 (0.50–0.64)	0.17 (0.11–0.23)	0.96	477 (54.4)
	CS	0.58 (0.49–0.68)	0.13 (0.06–0.20)	0.91	688 (60.0)
OA	VFSS	0.83 (0.75–0.93)	0.06 (0.01–0.11)	0.83	1835 (545.2)
	CS	0.74 (0.71–0.77)	0.04 (0.02–0.06)	0.95	2921 (1448.8)

† Numbers in parentheses indicate 95% confidence intervals.

‡ Numbers in parentheses indicate one standard deviation.

hysteresis decreases in the order of $OA > ESA = \text{metolachlor}$.

Adsorption-desorption hysteresis has been noted for several herbicides and herbicide metabolites (Clay and Koskinen, 1990; Seybold and Mersie, 1996; Mersie and Seybold, 1996) including metolachlor (Graham and Conn, 1992; Seybold and Mersie, 1996; Zhu and Selim, 2000). A definitive explanation for hysteresis does not exist in the literature but may include nonattainment of equilibrium, precipitate formation, changes in desorption solution composition, degradation, volatilization, and/or irreversible binding (Calvet, 1980).

CONCLUSIONS

Sorption and desorption parameters for metolachlor were higher in VFSS than in CS. Higher sorption and desorption partitioning coefficients for metolachlor in VFSS compared with CS is probably due to the greater OC content of the VFSS. Thus, our results corroborate previous studies that VFSS can increase metolachlor sorption relative to CS. Under the conditions in this study, we have further determined that the sorption and desorption coefficients for ESA and OA are not different between the evaluated soils. Thus, the higher OC content of the VFSS may not reduce the mobility of these metabolites. Due to the low sorption and desorption partitioning coefficients for ESA and OA relative to metolachlor, ESA and OA will probably be more mobile in the environment and pose a greater threat to both surface and ground water.

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