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Soil characteristics and herbicide sorption coefficients in 140 soil profiles of two irregular undulating to hummocky terrains of western Canada

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ABSTRACT

Sensitive input parameters such as herbicide sorption coefficients are seldom quantified in sufficient spatial detail, leading to large uncertainties in pesticide fate model predictions at regional and national scales. This study examined the spatial variability of soil characteristics and herbicide sorption coefficients (K_d) in a total of 609 soil samples obtained from 140 soil profiles in two undulating to hummocky soil-landscapes of western Canada. In all soil horizons, K_d values were always the largest for glyphosate followed by atrazine then 2,4-D. In each soil-landscape, SOC, 2,4-D and atrazine K_d values (all strongly associated) numerically decreased with A > B > C mineral horizons, regardless of the segment of the slope in which the soil profile was located. SOC, 2,4-D K_d and atrazine K_d values were typically smaller in the eluvial A-horizons (Ae, Aej) than other A-horizons. In several landform elements, glyphosate K_d values were numerically greater in the B rather than the A or C mineral horizons. Glyphosate K_d values were particularly large in B-horizons with redoximorphic features such as in illuvial B-horizons enriched with clay (Btg, Btgj). When the soil properties and sorption values of similar horizons were compared across the soil-landscapes, SOC and 2,4-D K_d demonstrated greater coefficients of variation than atrazine K_d and glyphosate K_d. The strength of prediction equations for 2,4-D K_d and atrazine K_d were strong in each soil-landscape when all samples in the soil profile were included in the model. However, the strength of prediction equations by mineral horizon was generally weaker and in some cases not significant. The in-field variability of glyphosate K_d values could not be predicted from the measured soil properties data, or calculated digital terrain attributes. Terrain attributes also showed little to no correlation, or predictive strength for describing the variability of 2,4-D and atrazine sorption in the soil-landscapes.

1. Introduction

Pesticide sorption coefficients such as K_d values are among the most sensitive input parameters in pesticide fate models (Boesten and Van der Linden, 1991; Dubus et al., 2003; Farenhorst et al., 2008). K_d values of herbicides 2,4-D, alachlor, atrazine, glyphosate and mesotrione all vary across slope positions in surface soils of fields and watersheds (De Jonge and De Jonge, 1999; Dorado et al., 2003; Dyson et al., 2002; Farenhorst et al., 2008; Liu et al., 2002; Novak et al., 1997). It is therefore that digital terrain models have been shown to improve in some cases the predictions of herbicide fate parameters in surface soils of fields (Farenhorst et al., 2003). Few studies have focused on the spatial variability of K_d values in subsurface soils (Farenhorst et al., 2008; Gaultier et al., 2006).

The Prairie pothole region of Canada consists of 390,000 km^2 of undulating to hummocky agricultural landscapes with millions of wetlands (Wrubleski and Ross, 2011). These Prairie wetlands act as fresh water filtration systems and provide habitats for aquatic and terrestrial wildlife. Pesticides have been detected in Prairie wetlands (Messing et al., 2011), sometimes at levels violating the Canadian Aquatic Water Quality guidelines (Donald et al., 1999). Knowledge of the spatial variability of herbicide sorption parameters in terrains typical of the Prairie pothole region of Canada is important when pesticide fate models are used in assessing the impact of improved farm management practices on the risk of water contamination by pesticides (Cessna et al., 2010).

Approximately 94% of the agriculture applied pesticides in Canada are herbicides (Environment Canada, 2011). Three herbicides, 2,4-D (weak-acid), atrazine (weak-base) and glyphosate (zwitterion) with contrasting physicochemical characteristics were used in this study (Table 1).

Previous studies have demonstrated that sorption of 2,4-D and atrazine is largely controlled by soil organic carbon content (SOC) while soil pH has been shown to influence the sorption of all three herbicides (Calvet, 1989; De Jonge and De Jonge, 1999; Dorado et al., 2003;

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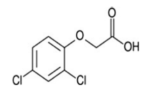
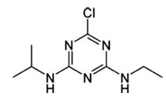
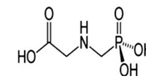
Table 1
Molecular structure and physicochemical properties of the herbicides used in the study (PPDB, 2009).

	2,4-D	Atrazine	Glyphosate
			
Molecular mass (g mol^{-1})	221.04	215.68	168.07
Solubility in water (mg L^{-1}) at 20 °C	23,180	35	10,500
log Kow at pH 7, 20 °C	−0.83	2.70	−3.20
pKa at 25 °C	2.87	1.70	(2, 2.6, 5.6, 10.6)*
Vapor pressure (mPa) at 25 °C	1.87×10^{-2}	3.9×10^{-2}	1.31×10^{-2}
Soil half-life (days) at 20 °C	14	66	49

Where: log Kow = log octanol water partitioning coefficient and pKa = dissociation constant.
* Sprankle et al. (1975).

Senesi, 1992; Sprankle et al., 1975). 2,4-D, atrazine and glyphosate are commonly detected in surface and ground water sources of North America (Donald et al., 2007; Humphries et al., 2005; Messing et al., 2011).

The objective of this study was to quantify the spatial variability of sorption parameters of 2,4-D, atrazine and glyphosate in 1 m deep soil profiles of irregular undulating to hummocky terrain landscapes, as influenced by soil depth and landform elements.

2. Materials and methods

2.1. Research site and soil sampling

Soil sampling was conducted at research sites representative of agricultural fields in the Prairie pothole region of Canada and classified as irregular undulating to hummocky terrain landforms (Pennock et al., 1987; Podolsky and Schindler, 1994). Two parallel fields (8-ha each) were selected at the Manitoba Zero Tillage Research Association Research Farm (MZTRA) (49° 53′N latitude, 99° 58′W longitude), located about 17 km north of Brandon in the Province of Manitoba and one field (20-ha) was selected at the St. Denis National Wildlife Research Area (SDNWA) (106° 5′N longitude, 52° 12′W latitude), located about 50 km East of Saskatoon in the Province of Saskatchewan. Both MZTRA (zero-tilled) and SDNWA (conventional-tilled) fields are in a grain and oilseed rotation and pesticides and synthetic fertilizers were used following typical farm practices (Xu et al., 2009). Conventional tillage, as the term is used here, refers to shallow surface disturbance and incorporation of a portion of the previous year's crop residues into surface soil.

The study design was set up such that the impact of landform elements on soil properties and herbicide sorption could be tested. Digital elevation models (grid size 5×5 m^2) and digital terrain modeling software (Pennock, 2003) were used to classify the MZTRA and SDNWA landscapes into convergent and divergent shoulders (CSH and DSH), convergent and divergent backslopes (CBS and DBS), convergent and divergent footslopes (CFS and DFS) and depression (DEP) landform elements. Within each landform element, 10 sampling points (latitude and longitude) were randomly selected to collect soil profiles to a depth of 1 m (truck mounted hydraulic probe with a 5 cm diameter). At each of the 70 sampling points, ten terrain attributes were also calculated (Pennock, 2003) to explore the association between terrain attributes and herbicide sorption in the A-horizon. These terrain attributes were elevation (Z, m), gradient (G, degree), aspect (A, degree), profile curvature (Profile, degree m^{-1}), plan curvature (Plan,

Table 2
Mean (coefficient of variance %) of K_d values and SOC by soil horizons and landform element down the soil profiles and along a catenary sequence in MZTRA and SDNWA.

	Landform elements							
	MZTRA				SDNWA			
Soil profiles	Shoulder	Backslopes	Footslopes	Depression	Shoulder	Backslopes	Footslopes	Depression
SOC	(Landscape range 0.42–5.81%)				(Landscape range 0.00–3.52%)			
A-horizon	3.30 (28)	3.45 (30)	3.17 (26)	4.04 (36)	1.92 (33)	2.11 (32)	2.14 (31)	2.07 (49)
B-horizon	1.54 (37)	1.40 (31)	1.29 (33)	1.26 (37)	0.80 (39)	0.58 (52)	0.58 (62)	0.41 (51)
C-horizon	1.05 (34)	0.93 (33)	0.91 (37)	0.72 (33)	0.25 (192)	0.33 (124)	0.27 (33)	0.29 (41)
Profile mean	1.97 (61)	1.99 (67)	1.95 (63)	2.11 (81)	0.86 (99)	1.01 (94)	1.00 (94)	1.26 (89)
2,4-D	(Landscape range 0.03–7.70 L kg^{-1})				(Landscape range 0.01–5.11 L kg^{-1})			
A-horizon	2.48 (38)	3.28 (47)	2.59 (40)	3.84 (47)	1.68 (25)	2.16 (34)	1.95 (45)	2.07 (53)
B-horizon	0.70 (80)	0.55 (65)	0.54 (67)	0.66 (109)	0.73 (100)	0.64 (33)	0.56 (116)	0.41 (68)
C-horizon	0.31 (94)	0.27 (78)	0.25 (56)	0.24 (54)	0.37 (100)	0.44 (75)	0.28 (54)	0.35 (69)
Profile mean	1.18 (101)	1.47 (116)	1.30 (101)	1.68 (118)	0.84 (77)	1.09 (85)	0.94 (103)	1.26 (92)
Glyphosate	(Landscape range 13.63–222.70 L kg^{-1})				(Landscape range 5.36–842.01 L kg^{-1})			
A-horizon	35.55 (35)	39.83 (91)	49.74 (62)	49.33 (47)	150.81 (140)	18.40 (91)	83.48 (140)	45.74 (140)
B-horizon	49.85 (34)	57.05 (46)	72.60 (60)	64.94 (47)	100.00 (129)	35.50 (57)	73.09 (69)	191.73 (108)
C-horizon	48.32 (36)	37.57 (27)	55.27 (42)	48.64 (39)	100.89 (74)	41.23 (74)	75.93 (72)	73.53 (83)
Profile mean	43.99 (38)	43.24 (63)	56.80 (58)	55.33 (47)	116.96 (120)	31.91 (81)	77.73 (103)	101.63 (146)
Atrazine	(Landscape range 1.01–52.49 L kg^{-1})				(Landscape range 0.08–9.12 L kg^{-1})			
A-horizon	13.64 (42)	15.76 (45)	14.70 (45)	25.98 (47)	4.00 (33)	4.37 (45)	4.31 (41)	4.72 (55)
B-horizon	4.51 (59)	3.45 (47)	3.76 (55)	3.87 (82)	1.43 (31)	1.21 (37)	1.05 (32)	1.02 (49)
C-horizon	2.71 (49)	2.46 (57)	2.12 (36)	1.73 (30)	0.76 (36)	0.79 (39)	0.69 (49)	0.94 (51)
Profile mean	7.05 (89)	7.71 (100)	7.81 (95)	11.17 (119)	1.90 (88)	2.13 (95)	2.04 (97)	2.94 (90)