

Evaluating the use of digital terrain modelling for quantifying the spatial variability of 2,4-D sorption by soil within agricultural landscapes

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Farenhorst, A., Florinsky, I. V., Monreal C. M. and Muc, D. 2003. **Evaluating the use of digital terrain modelling for quantifying the spatial variability of 2,4-D sorption by soil within agricultural landscapes.** *Can. J. Soil Sci.* **83**: 557–564. The most sensitive input parameter in many herbicide fate and transport models is the sorption-partitioning coefficient (K_d), a measure of herbicide sorption by soil. Spatial analyses of K_d are traditionally performed using geostatistics, but this approach requires intensive soil sampling and herbicide analysis. This study examined the use of digital terrain modelling as an alternative tool for quantifying the distribution of herbicide sorption within agricultural fields. Soil samples from a conventional-till (CT) and zero-till (ZT) field were analysed for soil organic carbon (SOC), soil pH, clay content, and the 2,4-D ((2,4-dichlorophenoxy)acetic acid) soil-water partitioning coefficient. Digital terrain models were used to calculate topographical variables (elevation, slope gradient, slope aspect, horizontal curvature, vertical curvature, mean curvature, specific catchment area, topographic index and stream power index) for each sampling point. Results indicated that topographic variables were adequate predictors of all soil properties in ZT (R^2 ranging from 0.64 to 0.76), and of SOC in CT ($R^2 = 0.65$, $P < 0.001$). For CT, 2,4-D sorption by soil was very well predicted with soil properties alone ($R^2 = 0.82$, $P < 0.001$) and with soil properties in combination with topographic variables ($R^2 = 0.85$, $P < 0.001$), but was less predicted by topographic variables alone ($R^2 = 0.50$, $P < 0.001$). For ZT, the level of prediction of 2,4-D sorption by soil was weak with soil properties alone ($R^2 = 0.53$, $P < 0.001$) or when topographical variables alone ($R^2 = 0.56$, $P < 0.001$) were used, but a substantial increase in the level of prediction was achieved when both soil properties and topographic variables were used ($R^2 = 0.73$, $P < 0.001$). We conclude that digital terrain modelling, in combination with soil properties data, is an appropriate approach for predicting the spatial distribution of 2,4-D sorption within undulating-to-hummocky glacial till landscapes in western Canada.

Key words: herbicide sorption, topography, zero-tillage, conventional-tillage, digital terrain modelling.

Farenhorst, A., Florinsky, I. V., Monreal, C. M. et Muc, D. 2003. **Évaluation de l'utilisation de la modélisation numérique du terrain pour quantifier la variabilité de la sorption du 2,4-D par la terre dans les paysages agricoles.** *Can. J. Soil Sci.* **83**: 557–564. Pour beaucoup de modèles sur la dispersion et le transport des herbicides dans le sol le paramètre d'entrée le plus variable est le coefficient de distribution de la sorption (K_d). Les analyses de K_d sont généralement réalisées en utilisant des méthodes géostatistiques, mais cette approche requière d'intensifs échantillonnages de terre avec recherche d'herbicides. Notre étude se propose de vérifier l'utilité de la modélisation numérique du terrain comme un outil alternatif pour quantifier la distribution de la sorption des herbicides dans les terres agricoles. Des échantillons de terre, provenant d'un champ avec travail du sol traditionnel (TC) et d'un champ n'ayant subi aucun travail du sol nul (NT), ont été analysés pour déterminer leurs teneurs en carbone organique (SOC) et en argile, leur pH et le coefficient de distribution du 2,4-D ((2,4-dichlorophénoxy) acide acétique). La modélisation numérique du terrain a été utilisée pour calculer les variables topographiques (altitude, degré de la pente, aspect de la pente, la courbure horizontale, verticale, la principale courbure, l'aire de captage spécifique, l'index topographique et l'index de la puissance du flot) pour chaque point d'échantillonnage. Les résultats indiquaient que les variables topographiques se trouvaient être les paramètres adéquates pour chaque type de sol non travaillé (R^2 allant de 0.64 à 0.76), et des sols composés de carbone organique en TC ($R^2 = 0.65$, $P < 0.001$). Pour TC, la sorption du 2,4-D est très bien évaluée avec les propriétés seules du sol ($R^2 = 0.82$, $P < 0.001$); en combinant les propriétés des sols et les données topographiques ($R^2 = 0.85$, $P < 0.001$), mais les résultats n'utilisant seulement que les variables topographiques étaient moins prometteurs ($R^2 = 0.50$, $P < 0.001$). Pour NT, le niveau de prédiction de la sorption du 2,4-D par le sol était faible que ce soient, en utilisant seulement les propriétés du sol ($R^2 = 0.53$, $P < 0.001$) ou avec seulement les variables topographiques ($R^2 = 0.56$, $P < 0.001$) étaient utilisées, une augmentation substantielle a été atteint lorsque les variables de propriétés du sol et de la topographie étaient utilisées ($R^2 = 0.73$, $P < 0.001$). Nous pouvons conclure que l'utilisation de la modélisation numérique du terrain, combiné avec les données des propriétés du sol, est une approche appropriée pour prévoir la distribution spatiale du 2,4-D dans les terrains plus ou moins vallonnés de l'ouest canadien.

Mots clés: Sorption d'herbicides, topographie, travail du sol nul, travail du sol classique, modélisation numérique du terrain

Abbreviations: A, slope aspect; CA, catchment area; CT, conventional till; DEMs, digital elevation models; DTMs, digital terrain models; G, slope gradient; GPS, global positioning system; H, mean curvature; K_d , sorption-partitioning coefficient; k_h , horizontal curvature; k_v , vertical curvature; SI, stream power index; SOC, soil organic carbon; TI, topographic index; ZT, zero-till

Table 1. Definitions, formulae and physical interpretations of some topographic variables [after Florinsky et al. (2002)].

Variable	Definition and formula	Interpretation
Elevation (z) (m)	Elevation above sea level at a given point on the land surface	Elevation
Slope gradient (G) ($^\circ$)	An angle between a tangent plane and a horizontal one at a given point on the landsurface: z $G = \arctan \sqrt{p^2 + q^2}$	Velocity of substance flows
Slope aspect (A) ($^\circ$)	An angle clockwise from north to a projection of an external normal vector to a horizontal plane at a given point on the landsurface: z $A = \arctan \left(\frac{q}{p} \right)$	Direction of substance flows
Vertical curvature (k_v) (m^{-1})	A curvature of a normal section of the landsurface by a plane, including gravity acceleration vector at a given point: z $k_v = -\frac{p^2 r + 2pqs + q^2 t}{(p^2 + q^2) \sqrt{(1 + p^2 + q^2)^3}}$	Relative deceleration of substance flows
Horizontal curvature (k_h) (m^{-1})	A curvature of a normal section of the landsurface. This section is orthogonal to the section of vertical curvature at a given point on the land surface: z $k_h = \frac{q^2 r - 2pqs + p^2 t}{(p^2 + q^2) \sqrt{1 + p^2 + q^2}}$	Convergence of substance flows
Mean curvature (H) (m^{-1})	$H = (k_h + k_v)/2$	Flow convergence and relative deceleration with equal weights
Specific catchment area (CA) (m^2m^{-1})	A ratio of an area of an exclusive figure formed on the one hand by a contour intercept with a given point on the landsurface and, on the other by flow lines coming from the upslope to the ends of this contour intercept, to length of this intercept	Contributing area
Topographic index (TI)	$TI = \ln(CA/G)$	Extent of flow accumulation
Stream power index (SI)	$SI = CA \times G$	Extent of potential flow erosion

r, t, s, p and q are partial derivatives of the function $z = f(x, y)$: $r = \frac{\delta^2 z}{\delta x^2}, t = \frac{\delta^2 z}{\delta y^2}, s = \frac{\delta^2 z}{\delta x \delta y}, p = \frac{\delta z}{\delta x}$ and $q = \frac{\delta z}{\delta y}$. Moving the 3×3 elevation submatrix along a regular DEM, we can calculate values of r, t, s, p and q for all points of the DEM, except boundary points (Evans 1980; Moore et al. 1993; Shary 1995).

The most sensitive input parameter in many herbicide fate and transport models is the soil-water partitioning coefficient, a measure of herbicide sorption by soil. Herbicide sorption has been shown to influence herbicide volatilization, degradation and leaching rates, and herbicide uptake by plants and soil fauna (Walker 1972; Baker et al. 1996; Barriuso et al. 1997). Since herbicide models increasingly incorporate spatial variability (Troiano et al. 1999; Wu and Workman 1999), it is essential to evaluate the distribution of herbicide sorption within landscapes. With increasing technology and capability of precision farming, understanding herbicide sorption by soil at the large-scale may lead to a reduction in herbicide movement off-site and the amount of herbicide needed (Khakural et al. 1994).

Evaluating soil-water partitioning coefficients at the large-scale has been done for the herbicides atrazine (Novak et al. 1997), imazethapyr (Oliveira et al. 1999), metolachlor

(Wood et al. 1987), and 2,4-D (Farenhorst et al. 2001). Spatial analyses of soil-water partitioning coefficients are traditionally performed using kriging, but this approach requires intensive soil sampling and herbicide analysis (Novak et al. 1997). For example, Webster and Oliver (1992) demonstrated that for soil and environmental surveys, a variogram is reliable only when it is based on at least 100 data points. Given the limited amount of resources available for some studies, it becomes important to develop new techniques for describing the distribution of herbicide sorption in agricultural fields.

Soil properties, such as soil organic carbon content, are highly correlated with herbicide sorption by soil (Farenhorst et al. 2001; Coquet and Barriuso 2002). Soil properties vary predictably within the landscape due to the influence of topography on hydrologic and pedogenic processes (Gerrard 1981). As such, information on soil series or landscape posi-

tion is useful for quantifying the spatial distribution of herbicide sorption within agricultural fields (Novak et al. 1997).

A modern approach for quantitative morphometric characterization of landscapes is digital terrain modelling. Digital terrain models (DTMs) are digital representations of a topographic surface, such as digital elevation models (DEMs) and digital models of the variables listed in Table 1. DTMs have been used to solve a wide range of geoscientific problems, as topographic variables can be used to quantify landscape biophysical processes and soil properties (Moore et al. 1991; Shary et al. 1991; Florinsk 1998; Pike 2000). It has been shown that the strongest dependence of soil properties on topography arises within the surface layer to a depth of 30 cm (Florinsky et al. 2002). This is also the soil layer in which most herbicides remain.

The herbicide 2,4-D [(2,4-dichlorophenoxy)acetic acid] is registered in Canada for the post-emergent control of broadleaf weeds, particularly in cereal crops. The herbicide was first introduced in Manitoba in 1946, and has since become one of the most widely used pesticides in this province. It is also the most frequently detected pesticide in Southern Manitoba river waters (Johnson et al. 1995; Rawn et al. 1999).

Previously, we found a strong correlation between soil properties and 2,4-D sorption by soil (Farenhorst et al. 2001). In this study, we determine the possibilities and limitations of digital terrain modelling for quantifying the spatial variability of 2,4-D sorption in an agricultural prairie landscape.

MATERIAL AND METHODS

Chemicals and Analytical Methods

[U-ring- ^{14}C]2,4-D (99% radiochemical purity; sp. act. 10 mCi mmol $^{-1}$; American Radiolabeled Chemicals Inc., St. Louis, MO) was used to determine the extent of herbicide sorption by soil. Herbicide stock solutions for experiments were prepared by mixing [U-ring- ^{14}C]2,4-D with analytical-grade 2,4-D (95% purity, Sigma Chemical Co., St. Louis, MO) in 0.01 M CaCl $_2$. The amount of radioactivity in herbicide solutions and samples from experiments was determined by Liquid Scintillation Counting (LS 7500 Beckman Instruments, Fullerton, CA) using 10 ml of Scintisafe scintillation cocktail (Fairlawn, NJ).

Study Site

The study site (3408 m by 821 m) was located 3 km north-west of Minnedosa, MB, Canada, and is representative of a broad region of undulating-to-hummocky glacial till landscapes in western Canada (Clayton et al. 1977). Soils were characterized as Black Chernozems (Soil Classification Working Group, 1998). Site characteristics were described in detail in earlier studies (Bergstrom et al. 2001a,b).

Land management practices varied with the northern-half of the study site being CT, and the southern-half of the study site being in ZT (Fig. 1). The ZT area had not been cultivated since 1977. Although agronomic practices were not necessarily identical for both fields from 1977 to present, the difference in tillage practices was the most important management contrast.

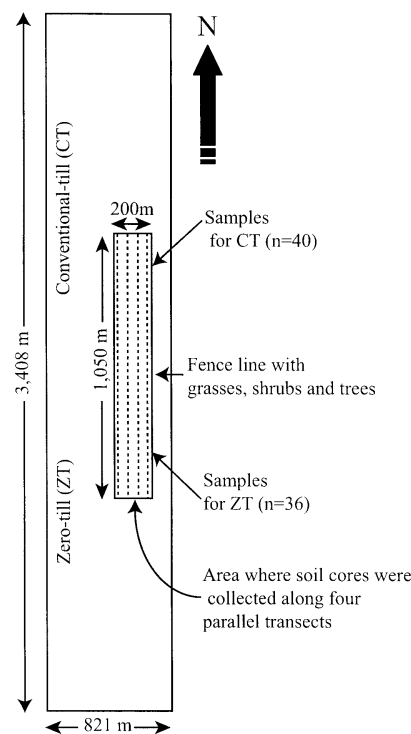


Fig. 1. Schematic of the study area and soil sampling location.

The Newdale and Varcoe soil series were the most important soil series in both ZT and CT fields. The Newdale soil series (Orthic Black Chernozem) occurred on well-drained crests and midslopes, while the Varcoe soil series (Gleyed Rego Black Chernozem) was indicative of imperfectly drained lower to toe slope positions. Elevation above sea level ranged from 568 m to 586 m (ZT) and from 575 m to 588 m (CT).

Soil Sampling and Laboratory Analysis

This study used soil samples that were collected in October 1998 for research on carbon sequestration (Bergstrom et al. 2001a,b). Soil cores (5 cm diameter, 1.5 m length) were collected at approximately 50-m intervals along four parallel transects (1000 m long, each 50 m apart) running north to south and spanning both fields (Fig. 1). Within the sampling plot, the maximum elevation difference within each field was 9 and 8 m for ZT and CT, respectively.

Forty soil cores were collected from CT, but only 36 cores from ZT because four sampling locations were inaccessible due to saturated soil moisture conditions. Sampling points were georeferenced using a Trimble global positioning system (GPS) (Cansel, Winnipeg, Manitoba). The GPS receivers used for the survey were single-frequency Trimble 4600LS Surveyors mounted on all-terrain vehicles; data were collected kinematically. Vertical and horizontal accuracy of the DEM was 0.05 m and 0.03 m, respectively. Further details about the soil sampling protocol can be obtained from Bergstrom et al. (2001a).

Although all soil horizons were sampled, this study used only the surface soil layer, which was collected from 0 to 8 cm in the ZT field and from 0 to 15 cm in the CT field. For comparison of the surface layer between fields, Bergstrom et al. (2001a,b) argued that the soil characteristics of the Ap horizon in the CT field were uniform throughout the 15 cm depth due to tillage. Therefore, soil characteristics measured for the entire Ap horizon in the CT field, represented the surface layer (0–8 cm) as well.

For each of the soil samples, SOC, soil pH and soil texture were determined, as described in Bergstrom et al. (2001a,b). The sorption of 2,4-D by soil was quantified by batch-equilibrium procedures, as described in Farenhorst et al. (2001). The soil-water partitioning coefficient, Kd (g kg⁻¹), was calculated as: $Kd = C_s/C_e$, where C_s = the amount of 2,4-D sorbed per amount of soil at equilibrium (g kg⁻¹), C_e = the 2,4-D concentration of the equilibrium solution (g L⁻¹).

Digital Terrain Modelling

An irregular DEM of the study site (3408 m by 821 m) was constructed based on 12 687 points using the GPS described above. The irregular DEM was converted into a regular DEM by the Delaunay triangulation and a piecewise smooth interpolation (Watson 1992). The grid interval of the regular DEM (20 m) corresponded to typical sizes of microtopographic elements within the site. Digital models of slope gradient (G), slope aspect (A), horizontal (k_h), vertical (k_v) and mean (H) curvatures (Table 1) were calculated according to Evans (1980). Digital models of specific catchment area (CA), topographic index (TI) and stream power index (SI) were calculated according to Martz and De Jong (1988) (Table 1). The grid interval of all derived DTMs was 20 m. Subsequently, the Delaunay triangulation and a piecewise smooth interpolation of these DTMs were used to determine values of elevation (z), and G , A , k_h , k_v , H , CA , TI , and SI at each of the 76 sampling points. Digital terrain modelling was carried out by LandLord software (Florinsky et al. 1995).

Statistical Analyses and Data Extrapolation

Statistical analyses were conducted independently for ZT (36 data points) and CT (40 data points). Data were tested for normality using the Kolmogorov-Smirnov test. Pearson correlation coefficients were calculated for both ZT and CT fields to assess the relation between soil properties (i.e., SOC, soil clay content, and soil pH) and Kd, between topographic variables and soil properties, and between topographic variables and Kd. Stepwise multiple linear regression (Aivazyan et al. 1985) was utilized to select which combinations of topographical variables should be used for predicting the spatial variability of soil organic carbon content, soil pH, and soil clay content within both the ZT and CT fields. Similar regression analyses were carried out to select the best combinations of soil properties, and the best combinations of topographical variables (alone or in combination with measured soil properties), for predicting Kd. All statistical analyses were carried out by Statgraphics Plus 3.0 software (Statistical Graphics Corp.).

Regression equations describing the dependency of Kd on topographic variables were used to predict the spatial distri-

Table 2. Pearson correlation coefficients between the soil-water partitioning coefficient (Kd) and soil properties

Variables	Soil organic carbon	Soil pH	Soil clay content
Zero-till field (Kd)	0.63****	- ^z	0.61****
Conventional-till field (Kd)	0.89****	-	-

^zCorrelation coefficient not significant at the 10% level.

**** Significant at $P < 0.001$.

bution of Kd within the entire study site. Predictions of Kd were done for both the northern- and southern-half of the study site using the DTM-based regression equations developed for CT and ZT fields, respectively. In total, Kd was calculated for 5940 points, utilizing a square-spaced grid interval of 20 m. For both the CT and ZT fields, predictive maps of Kd were produced by LandLord software (Florinsky et al. 1995).

RESULTS AND DISCUSSION

Relation between Soil Properties and Herbicide Sorption by Soil

SOC was $2.31\% \pm 0.86$ for CT compared with $3.13\% \pm 0.60$ for ZT. SOC ranged from 0.78 to 4.68% in CT, but only from 1.78 to 4.46% in ZT. Soil pH ranged from 6.0 to 8.0 (ZT) and from 6.6 to 8.1 (CT), with average values of 7.2 ± 0.5 (ZT) and 7.4 ± 0.4 (CT). Clay content was less variable in CT ($18.42\% \pm 4.61$) than in ZT ($20.85\% \pm 8.30$), and ranged from 8 to 31% and from 12 to 46% for CT and ZT, respectively. The amount of herbicide sorbed by soil was on average similar for ZT ($0.56 \text{ L kg}^{-1} \pm 0.25$) and CT ($0.51 \text{ L kg}^{-1} \pm 0.19$), and ranged from 0.12 to 1.33 L kg^{-1} (ZT), and from 0.11 to 0.97 L kg^{-1} (CT). The 2,4-D soil-water partitioning coefficients obtained in this study are comparable to those obtained by Mallawantantri and Mulla (1992) and Stephens et al. (2002) for soils with similar organic carbon contents.

For both ZT and CT fields, SOC was an important soil characteristic influencing the sorption of 2,4-D by soil (Table 2). The positive correlation between SOC and Kd was stronger for CT ($r = 0.89$, $P < 0.001$) than for ZT ($r = 0.63$, $P < 0.001$). Other studies have shown that soil organic matter is an important factor in the sorption of 2,4-D by soil and sediment (Khan 1973; Reddy and Gambrell 1987; Stephens et al. 2002).

Kd was not significantly correlated with any other soil property, except with clay content in the ZT field (Table 2). Given that 2,4-D is a weakly acidic herbicide, soil pH may have an influence on the amount of 2,4-D sorbed by soil (Reddy and Cambrell 1987). In this study, soil pH was not an influential factor because the soil pH was well above the pKa of 2,4-D (2.8) and the range of soil pH was narrow for both CT (soil pH 6.6 to 8.1) and ZT (soil pH 6.0 to 8.0). Sorption of 2,4-D by clay is influenced by the clay mineral type and soil pH (Hermosin and Cornejo 1993). When in the anionic form (soil pH > pKa), 2,4-D is repelled by negatively charged clay minerals (Weber et al. 1965), therefore the positive correlation between clay content and Kd in this study was unexpected. Other studies have found that 2,4-D was not correlated with clay content in Canadian prairie soils (Grover 1973).

Table 3. Pearson correlation coefficients between topographic variables, soil properties and the soil-water partitioning coefficient (Kd)

Variables ^z	<i>z</i>	<i>G</i>	<i>A</i>	<i>k_h</i>	<i>k_v</i>	<i>H</i>	<i>CA</i>	<i>TI</i>	<i>SI</i>
<i>Zero-till field</i>									
Soil organic C content	-0.66****	-0.39**	-	-	-	-	0.36*	-	-
Soil pH	-0.76****	-	-	-	-	-	-	0.37*	-
Soil clay content	-0.48****	-0.36*	-0.38*	-	-	-	0.55****	0.36*	-
Kd	-y	-	-	-	-	-	0.43**	-	-
<i>Conventional-till field</i>									
Soil organic C content	-0.67****	-0.36**	-	-	-0.60****	-0.53****	0.58****	0.69****	0.59****
Soil pH	-	-	-	-	-	-	-	-	-
Soil clay content	-	-	-	-	-	-	-	-	-
Kd	-0.52****	-	0.30*	-	-0.61****	-0.56****	0.45****	0.55****	0.53****

^zAbbreviations are *z* = elevation, *G* = slope gradient, *A* = slope aspect, *k_h* = horizontal curvature, *k_v* = vertical curvature, *H* = mean curvature, *CA* = specific catchment area, *TI* = topographic index, and *SI* = stream power index.

^yCorrelation coefficient not significant at the 10% level.

*, **, ***, **** Significant at *P* < 0.1, *P* < 0.05, *P* < 0.01, and *P* < 0.001, respectively.

Multiple linear regression for CT showed a very good prediction of Kd with SOC ($0.20\text{SOC} + 5.86 \times 10^{-2}$; $R^2 = 0.79$; $P < 0.001$). Inclusion of soil pH ($R^2 = 0.80$; $P < 0.001$) or clay ($R^2 = 0.81$; $P < 0.001$), or both ($R^2 = 0.82$; $P < 0.001$), did not improve the model for predicting Kd. For ZT, SOC was a poor predictor of Kd when used alone ($R^2 = 0.35$; $P < 0.001$), and in combination with clay content ($R^2 = 0.47$; $P < 0.001$). Including all soil properties provided the best prediction of Kd for ZT ($0.23\text{SOC} - 0.16 \text{pH} + 0.01\text{Clay}$; $R^2 = 0.53$; $P < 0.001$) but the level of prediction was weak.

Relation between Topographic Variables and Soil Properties

Soil organic carbon was significantly correlated with all topographic variables in CT, except *A* and *k_h* (Table 3). A correlation between topographic variables and SOC has been reported previously and can be explained by the physical interpretation of topographic variables (Table 1) (Florinsky et al. 2002). Fewer topographical variables were significantly correlated with SOC in ZT, with *z* being the only topographic variable that was significant at *P* < 0.001. The correlation between *z* and SOC was strong, regardless of the tillage system (Table 3). The correlation between topographic variables and either soil pH or clay content was not significant in CT. For ZT, there was a better correlation between topographic variables and either soil pH or clay content, but only a few topographic variables were significant at *P* < 0.001.

Topographic variables explained 65% (CT) and 76% (ZT) of the spatial variability of SOC within the landscape. Topographic variables were adequate to good predictors of SOC, but the prediction equations were different for CT ($-0.18z - 0.31G + 8.96 \times 10^{-4}A + 0.19SI + 108.76$; $R^2 = 0.65$; $P < 0.001$) than for ZT ($-0.12z - 0.34G - 1.14 \times 10^{-3}A - 1.74k_v + 3.77 \times 10^{-4}CA - 0.29TI + 75.76$; $R^2 = 0.76$; $P < 0.001$). For ZT, DTMs also showed adequate results for predicting soil pH ($R^2 = 0.64$; $P < 0.001$) and clay content ($R^2 = 0.66$; $P < 0.001$). However, topographic variables could not be used to predict soil pH ($R^2 = 0.15$) and clay content ($R^2 = 0.14$) in CT.

The R^2 values of regression equations describing the relation between topographic variables and soil properties have been shown to vary from 0.39 to 0.82 in other landscapes (Pennock et al. 1987; Moore et al. 1993; Gessler et al. 1995; Florinsky and Arlashina 1998). Digital terrain modelling may be a good approach for predicting a wide range of soil properties at the landscape-scale; however, for some temporally dynamic variables such as soil moisture and nutrients, different regression equations were obtained depending on the season (Florinsky et al. 2002). Also, in this study, digital terrain modelling was a good approach for predicting soil pH and clay content in ZT but not in CT. Furthermore, the different results for ZT and CT indicated that the regression equations developed for SOC are field-specific.

Relation between Topographic Variables and Herbicide Sorption by Soil

The correlation between topographic variables and Kd was not significant for any topographic variable in ZT, except *CA* ($r = 0.43$; $P < 0.05$) (Table 3). For CT, Kd was significantly correlated with all topographic variables, except *G* and *k_h* (Table 3). Although this agrees with the CT results obtained for SOC, the correlation coefficients between topographic variables and Kd were generally weaker than the correlation coefficients between topographic variables and SOC.

Topographic variables were weak predictors of Kd, and the prediction equations were different for ZT ($-1.82 \times 10^{-2}z + 0.29G - 7.63 \times 10^{-4}A - 1.90kh + 2.97 \times 10^{-4}CA - 0.19S + 11.51 I$; $R^2 = 0.56$; $P < 0.001$) than for CT ($-1.97 \times 10^{-2}z + 3.80 \times 10^{-4}A - 0.81kv + 2.10 \times 10^{-2}TI + 11.72$; $R = 0.50$; $P < 0.001$). These prediction equations can be used for describing the distribution of herbicide sorption within the entire study site, but this extrapolation is questionable as only 50% (CT) and 56% (ZT) of the spatial variability of herbicide sorption within the landscape was explained by topographic data. Also, for ZT, Kd values ranged from 0.12 to 1.33 L kg⁻¹ in the sampling-plot area, but predictions for the entire study site showed relatively large Kd values, up to 10 L kg⁻¹

for some locations (data not shown). This added another uncertainty to the extrapolation because with linear regression analysis, the associated error in making predictions beyond the range of measured observations is very large (Little and Hills 1978).

For ZT, both topographic variables ($R^2 = 0.56$; $P < 0.001$) and soil properties data ($R^2 = 0.53$; $P < 0.001$) were weak predictors of Kd. Since topographic data are more readily acquired than data on SOC, soil pH and clay content, DTM was the preferred method for estimating the distribution of Kd within this field. More importantly, a substantial increase in the level of prediction was achieved when data on soil properties and topographic data were combined ($2.18 \times 10^{-2}z + 0.27G - 1.68k_v + 1.72 \times 10^{-4}CA - 0.13SI + 0.21 \text{ SOC} + 0.01\text{Clay} - 12.80$; $R^2 = 0.73$; $P < 0.001$), suggesting that DTM is a useful addition or component of a model predicting herbicide sorption distribution within zero-till fields. For CT, the use of SOC alone ($R^2 = 0.79$; $P < 0.001$) produced better results in predicting Kd than regression analysis with topographic variables ($R^2 = 0.50$; $P < 0.001$). Also, for CT, using both soil properties and topographic data ($R^2 = 0.85$; $P < 0.001$) did not improve prediction of Kd, relative to the use of soil properties data alone ($R^2 = 0.82$; $P < 0.001$).

Possibilities and Limitations of Digital Terrain Modelling for Predicting Herbicide Sorption

Previous studies have indicated that topographical variables can be used to explain the spatial distribution of soil properties within landscapes (Odeh et al. 1991; Moore et al. 1993; Florinsky and Kuryakova 2000; Florinsky et al. 2002). An important finding of this study was the substantial increase in the level of Kd prediction obtained for ZT when both soil and topographic data were used, relative to the soil properties only. It is possible that the use of topographic variables helped to explain the distribution of soil organic matter quality within the ZT field. Previous studies have shown that the type of organic matter has a large influence on the strength of 2,4-D sorption by soil (Benoit et al. 1996). Soil organic matter characteristics are influenced by tillage practices and slope position (Wander and Yang 2000; Yang and Kay 2001), but the relation between soil organic matter and topography is poorly understood, particularly with respect to the chemical nature of soil organic constituents and their sorption capacity for herbicides.

One of the most difficult aspects of relating our results to other agricultural fields is the fact that the DTM-prediction equations appear to be site-specific. Unless additional studies are conducted to understand how prediction equations vary from site to site, the equations developed for this study cannot be used for predicting Kd in other areas. Also, this study was limited to 2,4-D, and other herbicides should be considered in future studies.

It is understood that varying the rate of herbicide applications in accordance with soil-sorption capacity would have to ensure equivalent weed control effectiveness, relative to conventional herbicide applications. Site-specific herbicide applications may be considered for environmental reasons when relatively mobile herbicides are applied to sensitive landscapes. Reducing the risks of environmental contamina-

tion is essential, particularly for controversial herbicides such as 2,4-D, whose usage has been linked to increased occurrence of Non-Hodgkin's Lymphoma among rural populations (Hoar et al. 1990) and to increased development of canine malignant lymphoma (Hayes et al. 1995). Environmental contamination may result from the off-site movement of 2,4-D by such processes as runoff and leaching (Wauchope 1978; Lavy et al. 1996). These processes are, in turn, influenced by the strength of 2,4-D sorption by soil.

CONCLUSION

Digital terrain modelling was an adequate approach for predicting the distribution of SOC, soil pH and clay content in a ZT field. Topographic variables could also be used to predict the spatial variability of SOC within an adjacent CT field, but not for predicting soil pH and clay content. For ZT, regression analysis with either soil properties data or topographic variables showed weak results in predicting the distribution of 2,4-D sorption within the field, but a substantial increase in the level of prediction was achieved when data on soil properties and topographic data were combined. For CT, soil properties data alone, and soil properties data in combination with topographic variables, produced good results in predicting 2,4-D sorption across the landscape but the use of topographic variables alone showed only weak results. We conclude that digital terrain modelling, in addition to soil properties data, is a good approach for predicting the spatial variability of 2,4-D sorption within undulating-to-hummocky terrain landscapes.

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