Topographic influence on the variability of soil properties within an undulating Manitoba landscape

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Manning, G., Fuller, L. G., Eilers, R. G. and Florinsky, I. 2001. **Topographic influence on the variability of soil properties within an undulating Manitoba landscape.** Can. J. Soil Sci. **81**: 439–447. As soil properties influence productivity, it is of interest to characterize their distribution for the purpose of intensified agricultural management in variable landscapes. Soil properties (soil organic C content, soil pH, A horizon thickness, solum thickness and depth to carbonates) were studied in 10 intensively sampled transects in a gently undulating glacial till landscape near Miniota, Manitoba. Using a landform description model, the study site was delineated into upper, mid and lower elevation **landform element complexes** (**LEC**) The program used a digital elevation model created from relative elevation data collected on a 10-m grid. Sample points were also stratified by soil series; Newdale (Orthic Black Chernozem), Varcoe (Gleyed Rego Black Chernozem) and Angusville (Gleyed Eluviated Black Chernozem) soils of the Newdale association were identified. Landform element complexes were ranked lower > mid > upper with respect to convergent landscape character. The eluviated Angusville profiles occurred under more convergent landscape character than the Newdale or Varcoe series. There was a consistent rank of lower > mid > upper with respect to depth to carbonates, A horizon thickness, solum thickness and soil organic C content. Relative ranking of the pH in the Ap horizon was the opposite. In all cases, the lower LEC emerged as most clearly distinct. There was substantial variability in soil profile development, and, therefore, soil series membership, within individual LEC. This indicated that the scale at which LEC are delineated is broader than that at which soil series variability occurs. Nonetheless, LEC were useful in capturing gross variability in soil properties within the landscape at a scale that would allow unique agricultural management practices.

Key words: Soil-landscape, solum thickness, depth to carbonates, organic carbon, soil pH

Manning, G., Fuller, L. G., Eilers, R. G. et Florinsky, I. 2001. **Incidence du relief sur la variabilité des propriétés pédologiques d’un terrain ondulé au Manitoba**. Can. J. Soil Sci. **81**: 439–447. Puisque les propriétés du sol agissent sur la productivité, en établir la distribution concourrait à une gestion plus intensive des terres arables sur différents terrains. Les auteurs ont étudié les propriétés du sol (teneur en carbone organique, pH, épaisseur de l’horizon A, épaisseur du solum et profondeur des carbonates) échantillonné à de nombreux endroits le long de dix transects, sur un terrain ondulé de till glaciaire près de Miniota, au Manitoba. Le site examiné a été subdivisé en complexes d’éléments topographiques (CET) de haute, de moyenne et de faible altitude grâce à un modèle de description du relief. Le logiciel faisait appel à un système de modélisation numérique des hauteurs reposant sur les relevés altimétriques obtenus de 10 m en 10 m. Les points d’échantillonnage ont également été stratifiés d’après la série de sols. Ainsi, les auteurs ont identifié les sols Newdale (tchernoziom noir orthique), Varcoe (tchernoziom noir régosolique gleyifié) et Angusville (tchernoziom noir éluvié gleyifié) de l’association Newdale. Les CET ont été classés faible > moyenne > haute (altitude) en fonction de leurs paramètres topographiques convergents. Le profil Angusville éluvié se retrouve dans des terrains aux paramètres topographiques plus convergents que les sols de la série Newdale ou Varcoe. Les sols suivent toujours l’ordre faible > moyenne > haute pour la profondeur des carbonates, l’épaisseur de l’horizon A, l’épaisseur du solum et la teneur en carbone organique. En revanche, le pH suit le sens opposé dans l’horizon Ap. Le CET de faible altitude est toujours le plus distinct. Le développement du profil du sol, donc l’appartenance à une série de sols, varie considérablement dans un CET donné. On en conclut que les CET sont délimités à une plus grande échelle que celle à laquelle les séries de sol varient. Les CET permettent néanmoins de saisir les variations grossières des propriétés pédologiques dans un relief particulier à une échelle qui autorise l’adoption de pratiques agronomiques précises.

Mots clés: Pédopaysage, épaisseur du solum, profondeur des carbonates, carbone organique, pH du sol

Characteristic, predictable soil-slope associations occur in gently rolling to hummocky landscapes of the Prairie Ecozone of Western Canada as a result of the influence of topography on pedogenesis. At the landscape scale, soils develop that are taxonomically and functionally distinct mainly due to varying intensities of accumulation and net downward flux of water, controlled by convergent and divergent landscape character. As a result, soil properties may be predicted as a function of topography, through mathematical models (Troeh 1964), or characterized within discrete, three-dimensional hillslope elements or complexes (Pennock et al. 1987, 1994). The distribution of physical and chemical soil properties are of interest because of their direct and indirect influences on productivity, which has implications for site-specific fertility management. Soil organic C, an indicator of historical production and mineralization of biomass in a given location, influences both fertility (Gregorich and Anderson 1985) and moisture retention (Gollany et al. 1992). The overall amount and concentration of soil organic C generally increases with convergent landscape character, due to erosion and differences in net mineralization. A horizon thickness, reflective of the balance between C addition and mineralization, is also a function of local moisture regime and thus coincides with soil organic C accumulation. Depth to carbonates and solum thickness at a given point are predominantly controlled by downward penetration of moisture into the soil profile (Pennock and de Jong 1990). Soil pH is reduced in more strongly leached surface horizons, as the infiltration of water into the soil moderates base concentrations in the soil profile due to leaching.

Due to the systematic, qualitatively predictable influences of the landscape on pedogenic development, broadly applicable landform segmentation procedures provide a useful means of capturing pedogenic variability in soil-landscapes. However, it remains important to validate such delineations with local information. Landform segmentation has been developed by Pennock et al. (1987) and MacMillan and Pettapiece (1997) that uses topographic derivatives from digital elevation data for the description of terrain orientation, shape and scale. Discrete LEC of similar convergent or divergent character are delineated, with consideration given to the landscape context in which they occur. These LEC have not previously been evaluated for their utility in capturing variability in soil properties in Manitoba soil-landscapes. The purpose of this study was to characterize the distribution of soil properties within these LEC in an undulating glacial till landscape.

MATERIALS AND METHODS

Site Characteristics

The study site, representative of a broad region of medium to moderately-fine textured glacial till landscapes in the Black soil zone, was located near Miniota, Manitoba. The surface form of the landscape was undulating with slope gradients not exceeding 3°. Prior to 1976, the site was in a cereal-fallow rotation. Subsequently, the site was continuously cropped under minimum tillage until 1988 when a zero-till system was established along with a more consistent cereal-broadleaf rotation.

A 1:5000 soil survey was conducted on the entire quarter section by the staff of Land Resource Unit of Agriculture and Agri-Food Canada, resulting in the differentiation of soil series of the Newdale association. Typical subgroups were identified and related to defined soil series (Fitzmaurice et al. 1999). The majority of soils in the site were Black Chernozems. Hydrologically, the area is considered to be a regional recharge site. Soils in the mid and upper portions of the landscape were predominantly well-drained Orthic Black Chernozems, described by the Newdale soil series. There were also minor occurrences of Regosolic and Calcareous soils, and on more convex surfaces, slightly eroded Orthic soils. Imperfectly drained soils in lower slope positions were of a typically higher moisture regime. Characterized by more strongly leached and eluviated horizons, these profiles were classified Gleyed Eluviated Black Chernozems (Angusville soil series). Minor areas of imperfectly drained Gleyed Carbonated Rego Black Chernozems, identified by the Varcoe soil series, occurred near the toe slopes in close association with Angusville soils.

Mean annual temperature at the site is 2.5°C (Environment Canada 1991), with a mean annual frost-free period of 120 d (Environment Canada 1982). Mean annual precipitation is 460 mm with 298 mm occurring from 1 May to 1 September (Environment Canada 1991). This information is based on data from a nearby climatic center at Virden, Manitoba.

Experimental Design

The site consisted of 10 parallel adjacent transects 450 m in length that were separated by 11 m. These transects crossed a variable landscape with 21 sampling points in each transect, for a total of 210 sampling points in a site area of 5.6 ha (Fig. 1). Sampling points along each transect were separated by 30 m except where additional sample points were required to capture topographic variations. In order to capture these topographic variations, sample points were separated by 15 m. The site encompassed classic crest, midslope and depression toposequence components, extending from one crest to another via an open depression bisecting the site at right angles.

Sampling Activities

Topographic characterization was performed on the site and surrounding area on a 10-m grid. The *X* and *Y* coordinates were chained in and marked so that elevations (*Z* coordinate) could be determined. A rod and level were utilized within the site boundaries to collect elevation data at each grid point intersection and at each of the 210 sampling points. This information was then used to create a digital elevation model. The remainder of the field was surveyed kinematically with GPS, using Trimble 4600 LS receivers.

A truck-mounted hydraulic coring device was used to collect intact soil cores in polyethylene sleeves at each of the 210 points, to the minimum depth of the underlying parent material. Each soil profile was characterized according to criteria outlined by the Expert Committee on Soil Survey (1983). The occurrence of each genetic horizon and its thickness, the depth to parent material, A horizon thickness, solum thickness and depth to carbonates were recorded. Individual genetic soil horizons were air-dried and weighed, and all A horizons were ground (<2 mm) for subsequent analyses.

Soil organic C was determined on A horizon samples by dry combustion of 0.12 g of oven-dried soil with a Leco model CHN 600 C and N determinator (Nelson and Sommers 1982). Inorganic C was removed by amending the samples with 6 N HCl (Tiessen et al. 1983). Prior to analysis, samples were rinsed clean of residual chlorine with deionized water and suction filtration, oven dried at 110°C, and stored in a desiccator. Soil organic C within the A hori-

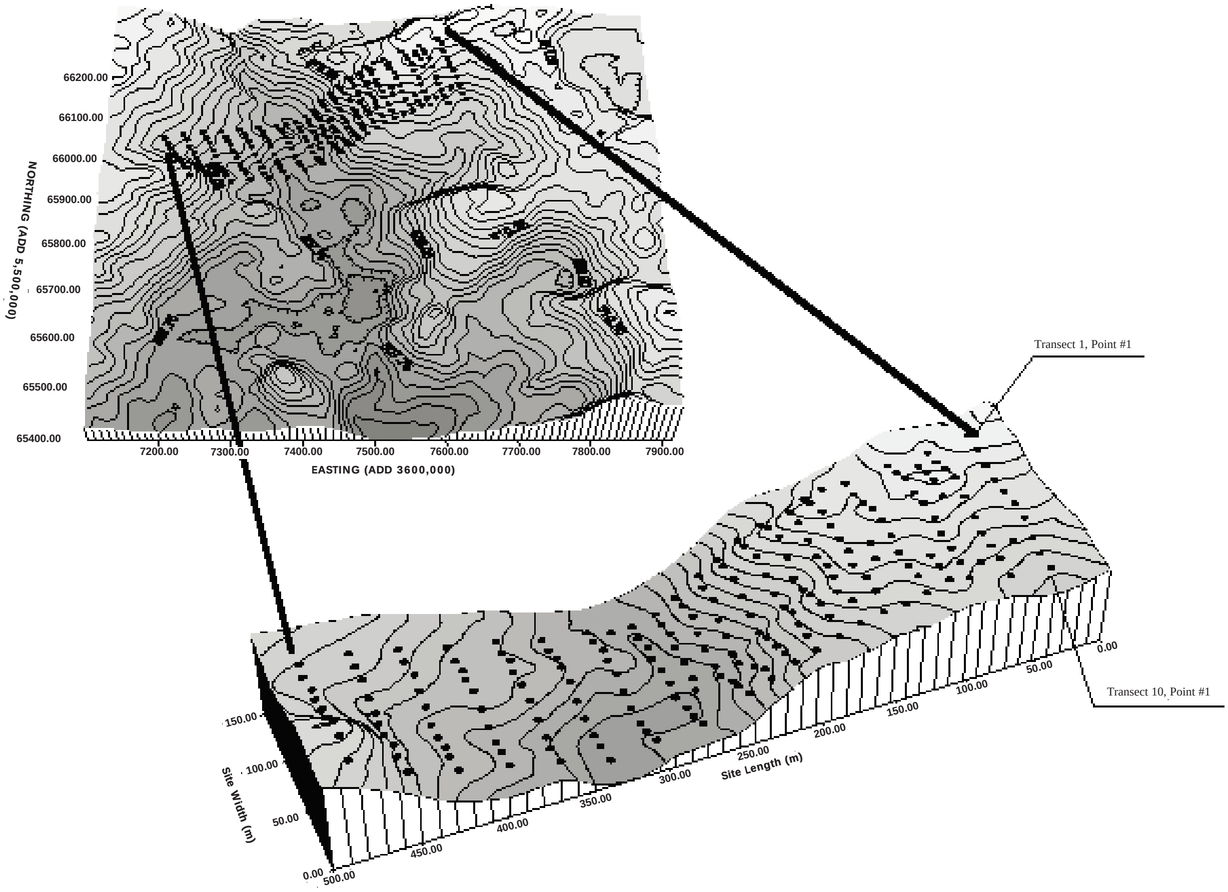

Fig. 1. Study site location, surface morphology and sampling point locations.

zon was expressed as mass per unit area (Mg ha^{-1}) using concentration (wt/wt) expressed on an oven-dry basis, multiplied by the bulk density and horizon thickness of each horizon obtained from the sample cores.

A 1:2 soil to $CaCl_2$ suspension was used to determine A horizon pH (Hendershot and Lalande 1993).

Landform Segmentation

The Landform Description Program from Landmapper Environmental Solutions (MacMillan and Pettapiece 1997; MacMillan et al. 2000) was used to delineate four discrete LEC using the site elevation data, corresponding to upper, mid, lower-mid and lower LEC. These LEC were superimposed on the existing design, and sampling points were assigned accordingly. The lower-mid LEC accounted for less than 5% of the sampling points, so these points were amalgamated with the lower and mid LEC. There were a total of 35, 126 and 49 sampling points in the remaining upper, mid and lower LEC, which accounted for 19, 54 and 27% of the surveyed site area, respectively. Topographic descriptors, including relative elevation, plan and profile curvature, slope gradient, and global and local catchment were calculated for each of the sampling points using algorithms presented by Pennock et al. (1987). Relative elevation is the elevation of a given point relative to the lowest point in the site. Gradient is the maximum rate of change of elevation at each grid point, in degrees. Plan curvature is the rate of change of aspect along a contour line in degrees/meter, where aspect is the azimuthal bearing of the gradient. Profile curvature is the rate of change of gradient in degrees/meter.

Global catchment measures the total catchment contributing runoff to a specific location, allowing for “spill-over” of water from depressions. Local catchment is the total catchment contributing runoff to a given point without “spill-over”. Global and local catchments were expressed as the number of 100 m^2 cells contributing runoff to a given point. Surfer^{TM} gridding and contouring software (Golden Software, Boulder, CO) was used to generate contour maps of elevation data, topographic descriptors and soil morphological variables.

Statistical Analysis

Some of the soil properties observed were not normally distributed. Rather than transforming the data, distribution-free, rank-based non-parametric tests were enlisted. Spearman correlations were calculated between all variables. Tests for statistically significant differences among

Table 1. Descriptive statistics of topographic descriptors summarized across all sampling points, and stratified by landform element complex and by soil series

	Topographic attribute					
	E (m)	G (°)	Kv (°/m)	Kh (°/m)	Cg ($m^2 \times 100$)	Cl ($m^2 \times 100$)
Overall (n = 210)						
Median	1.9	1.0	0.0	0.3	1.0	1.0
Mean	2.0	1.1	0.0	–0.2	13.2	10.8
Std. dev.	1.1	0.6	0.1	8.5	36.5	30.3
Minimum	0.1	0.0	–0.2	–102.3	0.0	0.0
Maximum	4.2	2.7	0.2	24.2	309.0	253.0
Upper (n = 35)						
Median	3.6	0.7	0.1	2.4	0.0	0.0
Mean	3.5	0.9	0.0	0.8	1.8	1.2
Std. dev.	0.4	0.5	0.1	7.6	4.9	2.9
Minimum	2.5	0.1	–0.1	–30.9	0.0	0.0
Maximum	4.2	2.2	0.2	14.1	24.0	13.0
Mid (n = 126)						
Median	1.9	1.2	0.0	0.4	1.0	1.0
Mean	2.0	1.3	0.0	0.5	5.8	4.7
Std. dev.	0.8	0.6	0.0	3.7	14.1	12.1
Minimum	0.7	0.1	–0.1	–9.7	0.0	0.0
Maximum	3.8	2.7	0.1	24.2	97.0	97.0
Lower (n = 49)						
Median	0.6	0.9	0.0	–1.3	4.0	4.0
Mean	0.8	0.8	0.0	–2.9	40.3	33.2
Std. dev.	0.8	0.4	0.1	15.0	65.4	54.2
Minimum	0.1	0.0	–0.2	–102.3	0.0	0.0
Maximum	3.0	1.6	0.1	15.3	309.0	253.0
Newdale (n = 151)						
Median	2.2	1.1	0.0	0.7	1.0	1.0
Mean	2.2	1.2	0.0	1.0	5.9	4.7
Std. dev.	1.0	0.6	0.0	3.9	17.3	14.7
Minimum	0.3	0.1	-0.1	–11.4	0.0	0.0
Maximum	4.2	2.7	0.2	24.2	128.0	108.0
Varcoe (n = 21)						
Median	0.7	1.1	0.0	0.9	1.0	1.0
Mean	0.6	1.1	0.0	1.6	15.3	12.1
Std. dev.	0.3	0.5	0.0	4.1	33.9	26.8
Minimum	0.2	0.3	–0.1	–3.6	0.0	0.0
Maximum	1.2	1.9	0.1	15.3	129.0	100.0
Angusville (n = 38)						
Median	1.9	0.5	0.0	–2.8	8.5	8.5
Mean	1.7	0.7	0.0	–6.3	41.0	33.9
Std. dev.	1.3	0.4	0.1	16.9	68.3	56.9
Minimum	0.1	0.0	–0.2	–102.3	0.0	0.0
Maximum	3.9	2.0	0.1	3.1	309.0	253.0

E = relative elevation; G = slope gradient; Kv = profile curvature; Kh = plan curvature; Cg = global catchment; Cl = local catchment.

LEC populations were performed using the Kruskal-Wallis test with a multiple-comparison procedure described by Daniel (1990). Statistical significance for multiple comparisons was set at $\alpha = 0.20$. There is greater error variability at the landscape scale, such that a lower significance level of $\alpha = 0.20$ has been justified by other researchers (Pennock et al. 1994; Jowkin and Schoenau 1998). Significance for correlations was defined as $P < 0.05$.

RESULTS AND DISCUSSION

Topographic Descriptors

The site was gently undulating, with a maximum of 4.2 m of relief and slope gradient that did not exceed 3° (Table 1). With the exception of slope gradient, topographic descriptors indicated that convergent landscape character increased in the order upper < mid < lower. Slope gradient is inversely related to convergent character. Overall, slope gradients were low, but were greatest in the mid LEC. The upper and lower were comprised of more level topography. Negative values for profile curvature and plan curvature indicate convergence of flow. With respect to plan curvature, the upper was most divergent (+2.4), the mid was slightly divergent, but more linear in character (+0.4), and the lower was most convergent (–1.1). Little difference was apparent in median profile curvature values, but minima and maxima suggested that negative curvature was more prevalent moving from the upper to the lower. The rank of convergent character with respect to both global catchment and local catchment indices was lower > mid > upper.

The LEC were expected to differ with respect to these topographic descriptors, as these descriptors are used, in

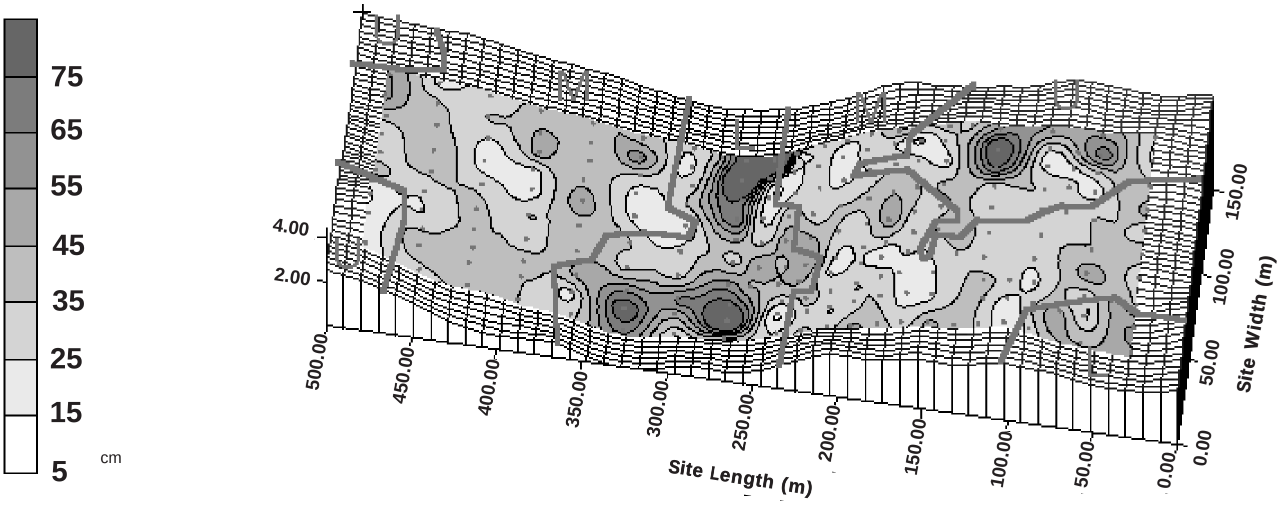

Fig. 2. Spatial distribution of solum depth (cm) across the study site, where upper, mid and lower elevation LEC are demarcated by "U", "M" and "L", respectively.

part, in their derivation (Table 1). However, among soil series, only the Angusville series was distinct with respect to most topographic descriptors. These soils had the lowest median slope gradient, the most negative median plan curvature, and most notably, the largest median values of global catchment and local catchment. The greater convergent character evident in the Angusville soils was consistent with greater pedogenic development in these profiles. The only obvious distinction between the Newdale and Varcoe series was that of relative elevation, which indicated that Varcoe series tended to occur in lower, more convergent areas in the landscape (0.7 m), and Newdale soils occurred in higher, more divergent areas (2.2 m), closer to the overall site median of 1.9 m. Angusville soils had a median relative elevation of 1.9 m, as they occurred in all three LEC.

Soil Profile Properties in Relation to Landform Element Complexes

The thickness of the A horizon, solum thickness (Fig. 2) and depth to carbonates increased moving from the upper to the lower, coinciding with the extent of convergent character in the landscape. This was similar to the findings of Pennock et al. (1987), who observed that convergent footslopes were most distinct in terms of A horizon thickness and depth to carbonates, and had the greatest number of gleyed and eluviated horizons. Over all LEC, total A horizon thickness, solum thickness and depth to carbonates ranged from 7 to 60 cm, 9 to 140 cm, and 0 to 140 cm, respectively (Table 2). Median A horizon thickness, solum thickness, and depth to carbonates values were 16, 29 and 26 cm in the upper, 18, 34 and 32 cm in the mid, and 26, 45 and 44 cm in the lower LEC, where the most strongly eluviated profiles occurred. The lower LEC emerged as statistically distinct for these attributes. Values were comparable to the averages for A horizon thickness and depth to carbonates in the Black soil zone obtained by Pennock and de Jong (1990), when the upper, mid and lower complexes were considered analogous to shoulder, backslope and footslope element groups, respectively.

As profile characteristics of A horizon thickness, solum thickness and depth to carbonates largely differ between individual soil series, the complement of soil series within each LEC was an important determinant of the values observed within LEC. While the upper and mid were dominated by the Newdale series, the lower LEC was comprised of nearly equal amounts of all three series (Table 3). Varcoe soils accounted for 10% of the soil profiles in the site, 70% of which occurred in the lower LEC. These soils measured 20, 23 and 19 cm for A horizon thickness, solum thickness and depth to carbonates, respectively (Table 2). The respective median values for the Angusville soils were 32, 59 and 61 cm for A horizon thickness, solum thickness and depth to carbonates, respectively, over all LEC. The Angusville series comprised 18% of all sample points, 18 of which occurred in the lower, 15 in the mid and 5 in the upper. The presence of Angusville soils (Eluviated Black Chernozem) within the upper LEC may seem contradictory; however, these soils in the upper LEC were located in higher elevation depressions that acted as water collection points high in the landscape thus facilitating the eluviation processes necessary for the development of this soil series. Median values for the well-drained Newdale soils, most of which occurred in the mid LEC, were 16, 30, and 29 cm for A horizon thickness, solum thickness and depth to carbonates, respectively, over all LEC. The progression from well to imperfectly drained, from Newdale to Varcoe and Angusville, was reflected in the increased A horizon thickness (Newdale < Varcoe < Angusville). The weak leaching regime resulted in the absence of B horizon development and shallow carbonates in the Varcoe soils, a strong leaching regime resulted in the occurrence of greater solum thickness and depth to carbonates in the Angusville soils, and intermediate to these

Table 2. Descriptive statistics of soil attributes summarized across all sampling points, and stratified by landform element complex and by soil series

	A horizon thickness (cm)	Solum thickness (cm)	Depth to Carbonates (cm)	Ap pH	Organic Carbon (Mg ha^{-1})
Overall (n *= 210)*					
Median	19	34	32	6.3	47.3
Mean	21	37	35	6.3	53.9
Std. dev.	9	18	21	0.4	30.3
Minimum	7	9	0	5.2	6.0
Maximum	60	140	140	7.3	180
Upper (n *= 35)*					
Median	16*a*	29*a*	26*a*	6.2*a*	35.1*a*
Mean	18	34	32	6.2	40.1
Std. dev.	7	20	25	0.4	20.3
Minimum	7	9	0	5.6	6.0
Maximum	45	99	112	7.0	79.9
Mid (n *= 126)*					
Median	18*a*	33*a*	32*a*	6.3*a*	45.2*b*
Mean	19	34	32	6.3	47.9
Std. dev.	7	12	14	0.4	20.9
Minimum	8	13	0	5.2	12.4
Maximum	37	80	80	7.2	109
Lower (n *= 49)*					
Median	28*b*	45*b*	45*b*	6.5*b*	68.1*c*
Mean	28	48	46	6.5	79.3
Std. dev.	12	25	30	0.3	41.1
Minimum	9	9	0	5.9	16.8
Maximum	60	140	140	7.3	181
Newdale (n *= 151)*					
Median	16	30	29	6.3	40.5
Mean	18	32	30	6.3	44.5
Std. dev.	6	11	13	0.4	20.6
Minimum	7	9	0	5.2	6.0
Maximum	37	68	68	7.2	109
Varcoe (n *= 21)*					
Median	20	23	19	6.7	49.3
Mean	22	25	16	6.7	62.3
Std. dev.	8	10	10	0.2	37.7
Minimum	9	9	0	6.4	16.8
Maximum	42	46	42	7.3	150
Angusville (n *= 38)*					
Median	32	58	61	6.2	83.2
Mean	33	63	67	6.2	86.5
Std. dev.	10	21	23	0.3	35.0
Minimum	19	35	37	5.6	30.2
Maximum	60	140	140	6.7	181

a–c Median values followed by the same letter were not significantly different among landforms at $\alpha = 0.20$ (Kruskal-Wallis multiple comparison procedure).

Table 3. The number of soil series encountered at sample points among upper, mid, and lower LEC

LEC	Newdale	Varcoe	Angusville	Total no.
Upper	30	0	5	35
Mid	105	6	15	126
Lower	16	15	18	49
Total no.	151	21	49	210

two extremes were the Newdale soils. The general transition from shallow and eroded Orthic profiles in the more divergent upper to a greater number of Eluviated profiles in the more convergent lower LEC was consistent with the observations of King et al. (1983).

Correlations with individual topographic descriptors supported the premise that pedogenic development was proportional to the extent of convergent landscape character. This is typical of regional recharge landscapes where net downward migration of the local water table over time within convergent portions of the landscape facilitates soil development processes that favor solum deepening. Over all LEC, within individual LEC, and within individual soil series, A horizon thickness, solum thickness, and depth to carbonates were generally inversely related to relative elevation, slope gradient, plan curvature, and profile curvature and positively related to global catchment and local catchment (Table 4).

Topography alone is not sufficient to mechanistically model the occurrence of any given soil profile attribute. Hydrologic processes are largely responsible for pedogenic development, but other formative controllers may mask them. Pennock et al. (1987) noted that sedimentological influences were extremely important, as a sandy “lense”

Table 4. Spearman correlations among topographic descriptors and soil profile attributes stratified by landform element complexes ($P < 0.05$)

	Relative elevation (m)	Gradient (°)	Profile curvature (°/m)	Plan curvature (°/m)	Global catchment ($m^2 \times 100$)	Local catchment ($m^2 \times 100$)	A horizon thickness (cm)	Solum thickness (cm)	Depth to carbonates (cm)	Ap pH	Organic C (Mg ha^{-1})
Overall (n = 210)											
A horizon thickness (cm)	–0.35	–0.26	–0.41	–0.44	0.42	0.44	1.00				
Solum thickness (cm)	–0.19	–0.30	–0.46	–0.57	0.51	0.52	0.70	1.00			
Depth to carbonates (cm)	NS	–0.30	–0.44	–0.56	0.53	0.53	0.60	0.89	1.00		
Ap pH	–0.36	NS	NS	NS	NS	NS	0.14	–0.16	–0.24	1.00	
Organic C (Mg ha^{-1})	–0.44	–0.33	–0.44	–0.45	0.43	0.45	0.92	0.66	0.59	0.22	1.00
Upper (n = 35)											
A horizon thickness (cm)	NS	NS	NS	–0.55	NS	NS	1.00				
Solum thickness (cm)	NS	–0.47	–0.52	–0.71	0.43	0.43	0.60	1.00			
Depth to carbonates (cm)	NS	–0.55	–0.55	–0.64	0.44	0.44	0.53	0.88	1.00		
Ap pH	NS	0.42	0.44	0.55	–0.56	–0.55	NS	–0.60	–0.59	1.00	
Organic C (Mg ha^{-1})	NS	NS	–0.39	–0.60	NS	0.33	0.85	0.63	0.70	NS	1.00
Mid (n = 126)											
A horizon thickness (cm)	–0.25	–0.21	–0.22	–0.32	0.28	0.30	1.00				
Solum thickness (cm)	NS	–0.24	–0.29	–0.44	0.33	0.34	0.68	1.00			
Depth to carbonates (cm)	NS	–0.26	–0.27	–0.44	0.39	0.39	0.59	0.87	1.00		
Ap pH	–0.23	–0.21	NS	NS	NS	NS	0.21	NS	NS	1.00	
Organic C (Mg ha^{-1})	–0.35	–0.31	–0.22	–0.30	0.26	0.27	0.90	0.60	0.53	0.35	1.00
Lower (n = 49)											
A horizon thickness (cm)	–0.49	–0.38	–0.61	–0.52	0.53	0.54	1.00				
Solum thickness (cm)	–0.34	–0.35	–0.55	–0.61	0.68	0.67	0.75	1.00			
Depth to carbonates (cm)	–0.29	–0.34	–0.52	–0.61	0.68	0.67	0.70	0.96	1.00		
Ap pH	–0.40	NS	NS	NS	NS	NS	NS	–0.38	–0.46	1.00	
Organic C (Mg ha^{-1})	–0.57	–0.39	–0.55	–0.54	0.51	0.53	0.93	0.71	0.64	NS	1.00

may increase solum thickness regardless of topographic position. Even the stratigraphy of “simple” glacial till soils may have pockets of textural discontinuities. Within the study site, parent material texture ranged from a clay-loam texture to sandy-loam, with the occurrence of gravel beneath some points in the lower LEC. Occurrence of eluvial horizons in the mid LEC often occurred at or near sample points, where soil texture was notably coarser, and were generally associated with the lower elevation portions of the mid LEC.

Hydrologic influences themselves are not predictable by surface morphology alone. The occurrence of the Varcoe series was a result of groundwater fluctuations and a lower net downward flux, adjacent to the Angusville soils. While their occurrence may be qualitatively predictable, their extent is really quite dependent on the extent of flow convergence and hydraulic conductivity of the underlying material in a given landscape.

Soil Organic Carbon

The amount of organic C contained within A horizons varied from 6 to 180 Mg ha^{-1} within the site. Measures of organic C increased with convergent character in the landscape; relative rank of the LEC was lower > mid > upper (Table 2). Median values were 35, 45, and 64 Mg ha^{-1} for the upper, mid and lower LEC, respectively. All differences were statistically significant among LEC. The differences in soil organic C content among LEC are attributable to differences in the balance between humus synthesis and C mineralization, along with erosional and depositional influences. As soil organic C is strongly related to mineralizable N and available water holding capacity (Goovaerts and Chiang 1993), the observed differences among LEC may well have implications for productivity. It is reasonable to expect that the lower LEC would be the most productive for a crop deficient in moisture or mineral N.

Organic C content also differed among soil series, most likely due to a combination of differences in the extent of organic matter addition, erosional and depositional influences, and net mineralization. Median values were 41, 49, and 83 Mg ha^{-1} for Newdale, Varcoe and Angusville soils, respectively (Table 2). The much higher amount of organic C in the Angusville series was likely due to greater vegetation biomass production under moister convergent conditions. Also, as these soils occurred in the most convergent portions of the landscape, they would have been most likely to receive deposition of eroded soil derived from soils located on more divergent topography.

Correlations with topographic descriptors also indicated a tendency for organic C content to increase with convergent landscape character, across all LEC, within individual LEC and individual soil series (Tables 4 and 5). While not significant in every instance, relationships were consistent in direction within individual LEC and soil series. Variation in solum thickness, A horizon thickness and organic C accumulation tend to coincide (Gregorich and Anderson 1985), and as expected, solum thickness and depth to carbonates were significantly and positively correlated with organic C content indicating organic C was proportional to the extent of pedogenic development.

Surface Soil pH

Surface soil pH (Ap pH) ranged from 5.2 to 7.3 over all LEC, a range that was not limiting to production. Median

Table 5. Spearman correlations among topographic descriptors and soil profile attributes stratified by soil series ($P < 0.05$)

	Relative elevation (m)	Gradient (°)	Profile curvature (°m)	Plan curvature (°/m)	Global catchment ($m^2 \times 100$)	Local catchment ($m^2 \times 100$)	A horizon thickness (cm)	Solum thickness (cm)	Depth to carbonates (cm)	Ap pH	Organic C (Mg ha^{-1})
Newdale (n = *151)*											
A horizon thickness (cm)	–0.30	NS	–0.25	–0.31	0.29	0.32	1.00				
Solum thickness (cm)	–0.29	NS	–0.37	–0.51	0.45	0.45	0.61	1.00			
Depth to carbonates (cm)	–0.29	NS	–0.39	–0.49	0.50	0.49	0.49	0.83	1.00		
Ap pH	–0.19	–0.20	NS	NS	NS	NS	0.22	NS	NS	1.00	
Organic C (Mg ha^{-1})	–0.41	NS	–0.32	–0.37	0.35	0.37	0.89	0.59	0.54	0.28	1.00
Varcoe (n = *21)*											
A horizon thickness (cm)	–0.55	NS	–0.45	NS	0.48	0.48	1.00				
Solum thickness (cm)	–0.67	NS	–0.50	NS	0.44	0.44	0.63	1.00			
Depth to carbonates (cm)	NS	NS	NS	NS	0.52	0.52	0.60	0.63	1.00		
Ap pH	NS	NS	NS	NS	NS	NS	NS	NS	NS	1.00	
Organic C (Mg ha^{-1})	NS	NS	NS	–0.51	0.49	0.49	0.92	0.62	0.63	NS	1.00
Angusville (n = *38)*											
A horizon thickness (cm)	–0.64	NS	–0.49	NS	NS	NS	1.00				
Solum thickness (cm)	–0.39	–0.50	–0.38	NS	NS	NS	0.74	1.00			
Depth to carbonates (cm)	–0.33	–0.50	–0.40	NS	NS	NS	0.71	0.95	1.00		
Ap pH	–0.60	NS	NS	NS	NS	NS	0.44	NS	NS	1.00	
Organic C (Mg ha^{-1})	–0.70	–0.42	–0.38	NS	0.37	0.35	0.81	0.68	0.60	0.54	1.00

values of 6.2, 6.3 and 6.6 were observed for upper, mid and lower LEC, respectively, where only the lower LEC was statistically distinct. Ap pH is generally expected to be more basic in the thin surface soils in upper slope positions (Miller et al. 1988). The more basic pH in the more convergent lower LEC suggested Ap pH has been altered by cultivation or by hydrologic reversal. Knuteson et al. (1989) observed the deposition of soil and the precipitation of carbonates on the soil surface of microdepressions, carried by runoff from precipitation events. As Ap pH values coincided with the hydrologic progression from well to imperfectly drained, it is possible that since cultivation, eluvial soils now receive bases from below via capillary action, from a shallower, less dynamic water table. Correlations indicated that while Ap pH increased with convergent character across the entire landscape, Ap pH values tended to be lower in more strongly leached soil horizons, most notably within the upper and lower LEC.

Pedogenic variability within individual LEC likely contributed to the unexpected pH observations. For example, inclusion of Varcoe soils in the lower LEC raised the median pH observed in this LEC. Median pH values of 6.3, 6.7 and 6.2 were observed in the Newdale, Varcoe and Angusville soil series, respectively. The relative ranking of these values was consistent with the extent of soil profile development. The Angusville profiles exhibited properties indicative of leaching as suggested by greater depth to carbonates. The Varcoe soils, characterized by the lowest net downward flux of soil moisture of the three profiles (as evidenced by presence of carbonates within the solum), had the highest surface soil pH. Regardless, significant correlations within individual soil series indicated that as convergent landscape character and profile development increased, Ap pH tended to decrease. This confirmed that while pH decreased with the extent of profile leaching within individual LECs, controls at a broader scale resulted in more basic pH in the most convergent lower LEC.

CONCLUSIONS

Differences in convergent and divergent character were apparent among LECs described using the digital terrain model of MacMillan and Pettapiece (1997). Accordingly, these LECs were useful in accounting for gross variability in various pedogenic properties. Within the LECs, organic C content, A horizon thickness, depth to carbonates and solum thickness were related to indices of convergence. Within the upper and the lower LECs, Ap pH was inversely related to certain indices of convergence, depth to carbonates and solum thickness. The LECs were delineated at a scale broader than that at which soil series variability occurred. Nonetheless, division of the site by LEC provided a practical means of capturing gross variability in the soil attributes measured, despite such variation in pedogenic character observed within LECs. Overriding practical considerations include scale of measurement, the influence of pedogenic controls other than water fluxes controlled by the land surface, and agricultural “manageability”. As a result, the LECs warrant further investigation as a means of capturing systematic variability in temporal yield determinants and productivity.

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