Soil moisture and nutrient variation within an undulating Manitoba landscape

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Manning, G., Fuller, L. G., Eilers, R. G. and Florinsky, I. 2001. **Soil moisture and nutrient variation within an undulating Manitoba landscape**. Can. J. Soil Sci. **81**: 449–458. The use of discrete management units for variable-rate N fertilization requires that factors influencing grain yield response to N fertilizer are adequately characterized by delineating landscapes into such management units. The objective of this study was to compare the use of topographically derived **landform element complexes** (**LEC**) and the use of individual soil series as management units. Soil volumetric moisture content, nitrate-N, exchangeable ammonium-N, extractable phosphorus, exchangeable potassium, and sulphate-sulphur were studied in 10 intensively sampled transects in an undulating glacial till landscape near Miniota, Manitoba. The study site was delineated into upper, mid and lower LEC using a digital elevation model derived from relative elevation data. The LEC were useful in capturing gross variability at a manageable landscape scale. Among LEC there was a general trend of lower > mid > upper for median values of soil moisture, nitrate, phosphate, potassium and sulphate, as these attributes generally increased with convergent landscape character. Differences among LEC were often statistically significant, and relative distributions exhibited temporal persistence. The site was also stratified by soil series, including Newdale, Varcoe and Angusville soils (Black Chernozems), which were identified by examination of individual soil cores at each sample point. Stratifying the site into management units using soil genetic information, which is reflective of historical moisture conditions and biomass production, was expected to be superior. There was little advantage, however, in using soil series rather than LEC. Spatial distributions of the most agronomically relevant attributes (soil moisture and nitrate) were expressed at a landscape scale broader than that at which soil series occurred within the site. While there were important differences among soil series with respect to nutrients such as phosphate and sulphate, the site was better stratified by LEC with respect to soil moisture and nitrate.

Key words: Soil-landscape, soil series, soil moisture, soil residual nitrate, extractable phosphorus

Manning, G., Fuller, L. G., Eilers, R. G. et Florinsky, I. 2001. **Variation de la concentration d'éléments nutritifs et d'eau dans le sol d'un terrain ondulé au Manitoba**. Can. J. Soil Sci. **81**: 449–458. Pour fertiliser le sol avec une quantité variable d'engrais azoté, il est essentiel de bien caractériser les facteurs qui affectent la réaction du rendement grainier à l'engrais en divisant le terrain en unités agronomiques. L'étude devait comparer l'utilité de complexes d'éléments topographiques (CET) et de séries de sols comme unités agronomiques. Les auteurs ont déterminé la quantité d'eau, de N sous forme de nitrates ou d'ammonium échangeable, de phosphore extractible, de potassium échangeable et de soufre-sulfate dans un grand nombre d'échantillons prélevés le long de dix transects, sur un terrain de till glaciaire, près de Miniota, au Manitoba. Le site a été subdivisé en CET de haute, de moyenne et de faible altitude grâce à un système de modélisation numérique des hauteurs, à partir de la hauteur relative. Les CET permettent de saisir les variations grossières à une échelle topographique commode. Avec les CET, la valeur médiane de la concentration d'eau, de nitrate, de phosphate, de potassium et de sulfate suit habituellement l'ordre faible > moyenne > haute (altitude), car ces attributs augmentent généralement avec la convergence des paramètres topographiques. Les écarts entre CET sont souvent statistiquement significatifs et leur distribution relative indique une persistance dans le temps. Les auteurs ont aussi stratifié le site par série de sols, notamment en fonction des sols Newdale, Varcoe et Angusville (tchernozioms noirs), lesquels ont été identifiés par analyse de carottes prélevées à chaque point d'échantillonnage. On estime qu'on obtiendra de meilleurs résultats si on stratifie le site en unités agronomiques à partir de données sur la pédogenèse reflétant l'historique de la teneur en eau du sol et de la production de biomasse. Préférer les séries de sols aux CET présente cependant peu d'avantages. La répartition des attributs agronomiques les plus utiles (teneur en eau et nitrates) dans l'espace s'effectue à une échelle topographique supérieure à celle des séries de sols. Bien que la concentration d'éléments nutritifs comme les phosphates et les sulfates varie sensiblement d'une série de sols à l'autre, les CET permettent une meilleure stratification du site pour la teneur en eau et les nitrates.

Mots clés: Pédopaysage, séries de sols, teneur en eau du sol, nitrates résiduels dans le sol, phosphore extractible

Moisture is the single most limiting factor to crop production in the semi-arid climate of Western Canada (Grant and Flaten 1998). Nitrogen is the most limiting element to cereal grain production on the majority of soils of the world (Olson et al. 1976). Differential distribution of moisture and residual N in the soil-landscape is, therefore, extremely important to potential productivity and yield response to N fertilizer. It should be possible to develop N recommendations for the most commonly encountered moisture regime in the landscape, if there is sufficient temporal stability in moisture supply and soil N supply.

In a pedogenic context, moisture and nitrogen are relatively dynamic, in the sense that they are not stable spatially or temporally (within or among growing seasons).

However, their distribution is influenced by systematic variation in relatively more static, predictable soil-landscape attributes. Distribution of soil moisture in the landscape is largely due to variation in surface curvature (Sinai et al. 1981), and as a result soil moisture is generally greater at landscape positions with more strongly convergent character (Hanna et al. 1982). Such landscape differences in available soil moisture may be accentuated or attenuated by differential distribution of soil organic carbon, soil textural characteristics, evapotranspirative demand and the amount, type and timing of precipitation.

Soil fertility includes the plant-available sources of inorganic, residual nutrients in the profile, and organic nutrients, which are potentially mineralizable in the growing season. Explanation of systematic differences in plant-available N as a function of landscape requires integration of soil properties, N-cycling, previous management and cropping effects (Fiez et al. 1994). As a result, complex patterns of net supply and crop uptake may preclude accurate prediction of soil residual nitrate levels, the most agronomically important form of mineral N, in the soil profile. Spring residual nitrate concentrations may be spatially random (Mulla 1993), greater in convergent areas (Malo and Worcester 1975), or greater in divergent areas (Farrell et al. 1996). Nonetheless, total N concentration and mineralization often increases with organic matter and convergent landscape character (Fiez et al. 1994).

Topography is often used for the creation of discrete management units for variable rate N application due to its well-known influence on the spatial distribution of soil moisture and N fertility. Manning et al. (2001) established that LEC created by MacMillan and Pettapiece (1997) (MacMillan et al. 2000) were useful in capturing topographic and resultant pedogenic variability in the soil-landscape. However, management units based on the occurrence of individual soil series may be equally useful. Soil genetic data provide a history of hydrologic conditions and, therefore, historical productive potential, and hence may be useful to predict the utility of additional N fertilizer at any given location. For the purpose of variable rate N application, it is important to find an appropriate means of partitioning the landscape into management units that are useful in capturing variability in properties directly affecting crop yield in Manitoba landscapes.

The objective of this study was to determine whether land management units could be delineated using either (1) topographic attributes and an existing landform segmentation model (MacMillan and Pettapiece 1997; MacMillan et al. 2000), or (2) soil series distribution within the landscape, as the basis for delineating management units. Soil moisture and soil nutrient variation within and among soil series and landform element complexes delineated using the model of MacMillan et al. (2000) were used to assess the validity of segmenting the landscape into meaningful management units.

MATERIALS AND METHODS

Site Characteristics

Established in spring 1997, the study site was an undulating glacial till landscape near Miniota, MB. The site was representative of a broad region of glacial till landscapes in the Black soil zone. The site consisted of 10 adjacent 11-m × 450-m transects over a variable landscape with 21 sampling points in each of these transects, for a total site area of 5.6 ha. Within transects, there was a maximum of 30 m separation between sampling points. There was a total of 4.2 m relief within the plot area, and slopes did not exceed 3°. The site encompassed classic crest, midslope and depression elements, extending from one crest to another via an open depression bisecting the site at right angles. The study site encompassed Newdale (Orthic Black Chernozem), Angusville (Gleyed Eluviated Black Chernozem) and Varcoe (Gleyed Rego Black Chernozem) soil series of the Newdale association (Fitzmaurice et al. 1999). Site pedogenic characteristics and sample point locations were described in detail in a previous manuscript (Manning et al. 2001).

Formal topographic characterization was performed on the site and surrounding area by collecting elevation data on a 10-m grid, in order to develop a site **Digital Elevation Model** (**DEM**) for use in the Landform Description Program. Four discrete LEC were delineated, corresponding to upper, mid, lower-mid and lower. These LEC were superimposed on the existing design, and sample points were assigned accordingly. Due to low areal percentage, points in the lower-mid were amalgamated with the lower and mid LEC.

N Fertilizer Application and Site Management

Experimental design was best described as a duplicated field-scale strip trial. For 1997 and 1998, there were 5 different N fertilizer treatments in the 10 transects, replicated twice. There were 0, 45, 90 and 135 kg ha^{-1} uniform rate transects, along with two variable-rate transects. In all cases, nitrogen fertilizer was surface broadcast as ammonium nitrate (34-0-0) after seeding. All N-fertilizer rates were predetermined and were not adjusted to reflect residual soil test levels. In 1997 and 1998, treatments were identical and were superimposed on the same locations. Treatments were designed to impose a range of available N concentrations across a representative cross-section of the regional soil-landscape, such that the same range was received by each of the localized LEC and soil series within. Within the variable rate transects there were six 22 kg ha^{-1} N treatments, omitted from further comparison due to lack of representation among LEC and soil series. The variable rate transects provided additional data at various rates of applied N for comparison of N-related attributes among LEC and soil series. Sample point allocation to each of the treatments, LEC and soil series is presented in Table 1.

Canadian Western Red Spring wheat was air-drilled into the mature zero-till seedbed in both 1997 (10 May, cv. Roblin) and 1998 (4 May, cv. Teal) on a 25-cm row spacing at a seeding rate of 128 kg ha^{-1} at a depth of 2.5 cm. The 10-m air drill was equipped with low disturbance 1.9-cm openers. Seed-placed phosphorus (12-51-0) was applied with the seed at a uniform rate across the site at a rate of 70 kg ha^{-1} of monoammonium phosphate, adding 8.4 kg N ha^{-1} to the applied N listed for all treatments.

Table 1. Sample point allocation (*n*) by LEC, soil series and N fertilizer treatment

	N fertilizer rate (kg ha^{-1})			
LEC/Soil series	0	45	90	135
Upper	9	12	7	4
Mid	25	36	34	29
Lower	8	14	17	9
Newdale	31	43	37	34
Varcoe	2	8	6	5
Angsville	9	11	15	3

Field-scale pesticide applications were at manufacturers' recommended rates. Glyphosate, 2,4-D and triallate were applied in fall 1996. In 1997, thifensulfuron, tribenuron methyl, MCPA and clopyralid were applied post-emergence, and glyphosate was applied pre-harvest. In 1998 dichlorprop, 2,4-D ester and imazamethabenz were applied post-emergence. Propiconazole fungicide was used to reduce foliar diseases.

Sample Collection

Soil attributes were measured at each of the 210 sample points over the 1997 and 1998 growing seasons. There were three primary intervals for data collection: early in the season, prior to seeding (ES), mid-season near anthesis (MS), and harvest or post-harvest (H). All soil samples were collected in 30-cm increments to 120 cm. Early-season soil sampling for nitrate, ammonium, phosphate, potassium and sulphate was performed using soil augers. Each of these four depths was subsampled for volumetric soil moisture determination. Mid-season soil sampling for soil moisture was performed using hand-held soil probes. Harvest sampling for nitrate and ammonium, sub-sampled for soil moisture, was performed on 2 September 1998, within a week of harvest. Again, all points were sampled to 120 cm in 30-cm increments using a soil auger. Timing and amounts of growing season precipitation were monitored locally.

Soil Nutrient and Soil Moisture Determination

Soil samples were refrigerated for transport and frozen for storage. Spring 1997 and 1998 macronutrients were analyzed by Norwest Labs (Winnipeg, Manitoba). Air-dried soils were ground to pass through a 2-mm sieve. Nitrate + nitrite nitrogen were extracted using a 0.001 M $CaCl_2$ solution and analyzed by automated colorimetry. Detection limit for the process is 0.1 ppm (MSS 4.35 APHA). Ammonium was extracted by a 1 M KCl solution and analyzed by phenate automated colorimetry, with a detection limit of 0.005 ppm (ASOA No. 9). Extractable phosphate and exchangeable potassium were extracted using acetic fluoride (Modified Kelowna method). Phosphate was analyzed by automated molybdate colorimetry, with a detection limit of 1 ppm (ASSW 26:178; APHA 4500-P:E; Ashworth and Mrazek 1995). Potassium was analyzed by flame photometry, with a detection limit of 10 ppm (ASSW 26:178; APHA 3500-K:D; Ashworth and Mrazek 1995). Sulphate was extracted with 0.001 M $CaCl_2$ solution and analyzed for sulphate by methyl thymol blue automated colorimetry, with a detection limit of 1 ppm (APHA 4500-SO_4:F). Estimated plant-available N supply was calculated as the sum of spring residual nitrate-N to a depth of 90 cm plus applied fertilizer N in each treatment.

Fall 1998 nitrate and ammonium were extracted from soil using a 10:1 2 M KCl to soil extraction ratio using 50 mL of KCl and 5 g of air-dried soil. The samples were shaken for 30 min, filtered through Whatman #42 filter paper and subsequently analyzed colorimetrically with a Technicon Autoanalyzer II System (Labtronics Inc., Tarrytown, NY). Extraction and analysis followed the methodology outlined by Maynard and Kalra (1993).

Volumetric soil moisture was determined by heating 20 to 30 g of moist soil at 105°C for 24 h (Topp 1993). Bulk density measurements used in conversion of nutrient and moisture concentration to area basis were obtained on an oven dry basis, using the 3.7-cm soil cores obtained in September 1997 by the method of Blake (1965). Composite bulk density values for each 30-cm increment were calculated using bulk densities for each genetic profile member, averaged across the entire site.

Values obtained for Harvest volumetric soil moisture in 1997 must be interpreted with caution. Gravimetric soil moisture from 0 to 60 cm was measured after the samples had been frozen for 3 mo. It is possible that the samples were subject to sublimation while in storage. Samples were not obtained for 60 to 120 cm, but rather values from spring of 1998 for 60 to 120 cm were used. This was done in order to express Harvest soil moisture as an estimate to 120 cm. It was reasoned that recharge from precipitation in the fall of 1997 and over winter would have been limited (in September and October 1997, a total of 4.1 cm of rainfall was received). Also, familiar patterns of relative moisture distribution were observed for the 0- to 30-cm and 30- to 60-cm increments (not shown). Among LEC, ranking was consistent with other times at which soil moisture was assessed, and the lower LEC was statistically distinct for both the 0- to 30-cm and 30- to 60-cm increments.

Grain and Straw Total N Determination

To estimate net mineralization, knowledge of crop N removal was required. Grain and straw yields were obtained from hand-harvested 1- and 2-m^2 quadrats in 1997 and 1998, respectively. Grain and straw total N was determined on 70 to 100 mg of ground plant material (< 2 mm) with a Leco FP 428 and CHN-600 (Leco Corporation, St. Joseph, MI) by combustion nitrogen analysis, on an oven-dry basis (Williams et al. 1998).

Statistical Methods

Tests for significant differences among median values of LEC and soil series populations were performed using the Kruskal-Wallis test, with a multiple-comparison technique 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 level of significance is justified (Pennock et al. 1994; Jowkin and Schoenau 1998).

Table 2. Descriptive statistics, volumetric soil moisture (cm) to a depth of 120 cm, across and within LEC and soil series at six sampling times in 1997 and 1998

	Volumetric soil moisture content to 120 cm (cm)									
	ES[z] 97	MS[y] 97	H[x] 97	ES 98	MS 98	H 98				
N rate (kg ha^{-1})			All			All	0	45	90	135
					Overall (n = *210)*					
Median	27.9	26.1	21.8	24.9	35.5	28.9	31.3	29.1	28.2	27.1
Minimum	13.5	13.3	10.1	12.9	24.9	15.0	15.0	16.7	22.8	22.0
Maximum	42.2	35.5	31.0	37.1	48.5	41.2	35.6	41.2	34.1	32.6
					Upper (n = *35)*					
Median	27.2*a*	25.0*a*	21.3*a*	24.0*a*	34.9*a*	28.2*a*	32.0*a*	28.3*a*	26.9*a*	24.7*a*
Minimum	13.5	13.3	10.1	12.9	30.0	15.0	15.0	16.7	23.4	23.3
Maximum	34.2	31.1	26.5	30.5	44.1	35.0	35.0	31.2	28.2	26.1
					Mid (n = *126)*					
Median	27.7*a*	25.6*a*	21.4	24.6*a*	35.4*a*	28.6*a*	30.9*a*	29.1*a*	27.7*a*	27.4*a*
Minimum	18.0	13.6	13.6	16.9	24.9	20.4	23.7	21.5	22.8	24.0
Maximum	38.5	33.1	31.0	35.5	45.8	35.6	35.6	34.8	32.5	32.6
					Lower (n = *49)*					
Median	31.8*b*	28.5*b*	24.7*b*	28.6*b*	37.2*b*	30.7*b*	31.3*a*	32.8*b*	30.4*b*	27.9*a*
Minimum	20.6	19.5	16.7	19.2	25.4	22.0	23.7	27.5	25.9	22.0
Maximum	42.2	35.5	30.5	37.1	48.5	41.2	34.9	41.2	34.1	31.0
					*Newdale (*n = *151)*					
Median	27.7*a*	25.6*a*	21.5*a*	24.5*a*	35.1*a*	28.5*a*	30.9*a*	28.7*a*	27.3*a*	27.2*ab*
Minimum	13.5	13.3	10.1	12.9	24.9	15.0	15.0	16.7	22.8	22.0
Maximum	42.2	33.8	31.0	37.1	48.5	35.6	35.6	34.8	32.7	32.6
					Varcoe (n = *21)*					
Median	31.9*c*	29.0*c*	25.2*c*	28.6*c*	37.2*b*	31.3*b*	33.4*a*	33.0*b*	30.9*b*	30.7*b*
Minimum	26.1	22.7	17.2	19.6	32.0	27.1	32.1	29.0	28.1	30.5
Maximum	39.7	35.5	29.1	35.3	45.8	41.2	34.7	41.2	32.7	31.0
					*Angusville (*n = *38)*					
Median	28.1*b*	26.8*b*	22.4*b*	25.5*b*	36.4*b*	28.9*a*	32.0*a*	29.0*a*	28.4*a*	25.1*a*
Minimum	21.9	20.6	16.8	18.0	30.8	24.0	25.4	25.9	24.5	24.0
Maximum	37.4	34.0	29.3	33.8	48.4	35.5	35.5	33.9	34.1	26.2

[z]ES = early-season sampling.
[y]MS = mid-season sampling.
[x]H = harvest sampling.
a, b Median values followed by the same letter were not significantly different when compared among LECs or among soil series at $\alpha = 0.20$ (Kruskal-Wallis multiple comparison procedure).

RESULTS AND DISCUSSION

Soil Moisture

Overall, volumetric soil moisture to 120 cm varied widely between seasons and LEC, ranging from 10.1 to 48.5 cm (Table 2). Relative distribution was consistent among LEC, with a trend of lower > mid > upper in both 1997 and 1998. Differences among the upper and mid were generally negligible, and in all instances, only the lower LEC emerged as statistically distinct. The characteristic increase in volumetric soil moisture to 120 cm with increasing convergent character in the landscape was consistent with the findings of Jowkin and Schoenau (1998). Differences among LEC were likely accentuated by variable distribution of soil organic carbon, which was observed to be significantly greater in the lower LEC in a previous study (Manning et al. 2001).

Soil moisture was greatest in the Varcoe soil series and least in the Newdale series at each of the six sampling times. Differences among soil series were most often statistically significant. Median soil moisture levels in the relatively more arid Newdale series were comparable to those of the upper LEC at each sampling time, and the median values of soil moisture in the Varcoe soils were very similar to that of the lower LEC, reflecting the distribution of these soils among the LEC. The most strongly leached Angusville soils were expected to have the highest soil moisture content. Several of these profiles, however, occurred in the relatively more arid upper and mid LEC where local topography and textural variations resulted in “pockets” of eluviated soil (Manning et al. 2001). Ultimately, the control of the distribution of soil moisture was expressed at a broader landscape scale, despite significant differences between soil series. When soil series were compared within the lower LEC alone, there was essentially no difference in moisture content between the Varcoe and Angusville soil series. While not observed in this study, it is conceivable that total soil moisture content could reflect hydrologic conditions responsible for the genetic differences in the Varcoe and Angusville series, even within the lower LEC. Less net downward water flux in the Varcoe soils relative to the Angusville soils may result in greater moisture retention.

The greatest differences in soil moisture values among LEC and among soil series were observed at early season sampling in 1997 and 1998. Absolute differences between median volumetric soil moisture values between the upper and lower LEC were 4.6, 3.5 and 3.4 cm in 1997, and 4.6, 2.3 and 2.5 cm in 1998, at early season, mid-season and harvest sampling times, respectively. Respective differences between median volumetric soil moisture values for Newdale and Varcoe soils were 4.2, 3.4 and 3.7 cm in 1997, and 4.1, 2.1 and 2.8 in 1998 for the early season, mid-season and harvest sampling times, respectively.

Soil moisture was greatest at the early-season sampling time in 1997, but was least in 1998. Also, absolute differences among LEC median values were smallest at the "wettest" sampling time, mid-season of 1998 when soil profiles in all LEC approached field capacity. This is contrary to the observations of Halvorson and Doll (1990) and Miller et al. (1988), who found that the landscape control of moisture distribution was least apparent under dry conditions.

The apparent landscape influence on moisture redistribution is regulated by the intensity of precipitation relative to infiltration and soil water-holding capacity, the form of precipitation, precipitation distribution, and evapotranspiration. The landscape influence would be limited with low intensity rainfall with near complete infiltration into the soil profile, as observed by Halvorson and Doll (1990). Precipitation received as snow is subject to drifting, and soil recharge from snowmelt is affected by frost. The larger differences among LEC and soil series at the early-season sampling may have been due to accumulation of snow in convergent areas. As well, the presence of frost likely limited hydraulic conductivity of the surface soil in the early spring, retarding recharge from snowmelt in divergent areas and thereby accentuating the landscape influence on moisture redistribution. In both years, absolute differences among LEC and soil series decreased from early season to harvest. Later in the growing season, lateral movement of water in the landscape and among soil series was likely attenuated by the growing crop.

Addition of N fertilizer may increase the amount of moisture used by a growing crop (Campbell et al. 1977). Volumetric soil moisture did not vary with estimated plant-available N supply with the exception of the harvest sampling time 1998, at which time volumetric soil moisture was significantly and inversely correlated to plant-available N supply across the entire site (not shown). Under moisture-deficient conditions experienced in 1997, it was likely that all available soil moisture was utilized regardless of N treatment. In 1998, there was ample soil moisture due to June precipitation (15.3 cm), such that differences in volumetric soil moisture among N treatments were negligible at mid-season sampling (not shown). However, additional fertilizer and soil residual N greatly stimulated biomass and leaf area production, delayed senescence, and likely resulted in additional transpiration, which resulted in observable differences at the harvest sampling time in 1998 (Table 2). Within each LEC and soil series, 1998 volumetric soil moisture at harvest sampling generally decreased with additional N increments. Differences among median volumetric soil moisture at harvest between the check and 135 kg ha^{-1} treatment were 7.3, 3.5, and 3.4 cm, for the upper, mid and lower LEC, respectively. Respective differences within soil series were 3.7, 2.7 and 6.9 cm for Newdale, Varcoe and Angusville series. The magnitude of the differences in volumetric soil moisture among N treatments at harvest sampling time in 1998 were greater than those among LEC and soil series over all N rates. This illustrated the potential influence of soil fertility in assessments of moisture redistribution in the soil-landscape.

While a meaningful method of partitioning the landscape into areas of unique productive potential is required for site-specific management, it must be done in light of the extent of temporal variability. Relative amounts of soil moisture were consistent among LEC and soil series, but moisture levels differed more among growing seasons than among either LEC or soil series. 1997 was a dry year, in which 10.0 cm of precipitation was received from May to the end of July. As a result, soil moisture was depleted over the course of the growing season, such that early season volumetric soil moisture was highest (27.9 cm), mid-season was intermediate (26.1 cm), and harvest was lowest (21.8 cm), across LEC. Over the winter and in the early spring of 1998, precipitation was low, but in the period from May to July, 23.7 cm of rainfall was received. As a result, mid-season volumetric soil moisture was the highest (35.5 cm), and early season the least (24.9 cm). Volumetric soil moisture at harvest in 1998 (28.9 cm) was relatively high as well, as 13.2 cm of precipitation fell in the month of August. Due to the variable nature of growing season precipitation, soil moisture in LEC and soil series must be characterized over a number of years.

Residual Nitrate

Differences in soil residual nitrate among LEC and soil series were considered to a depth of 90 cm. Soil test labs generally consider nitrate to a depth of 60 cm (Selles et al. 1992), but residual nitrate to 120 cm is also accessible (Soper and Huang 1963). For the purposes of production, it is differences in plant-available N supply which are of interest. Nitrate was largely partitioned within 30 cm of the surface in both growing seasons and in all LEC, but measurable concentrations did occur at depth in both seasons.

In spring of 1997, nitrate (0–90 cm) values were relatively low. Overall, there was a median amount of 48 kg ha^{-1}, ranging from extremes of 18 to 146 kg ha^{-1} (Table 3). Median amounts in each individual LEC were 44, 47 and 52 kg ha^{-1} in the upper, mid and lower LEC, respectively. While the lower LEC was statistically unique from the other LEC, such differences were negligible for agronomic purposes. Median amounts of 48, 44 and 49 kg ha^{-1} were measured in the Newdale, Varcoe and Angusville soils, respectively. These differences were not statistically significant, such that stratifying by soil series accounted for less variation in soil residual nitrate than stratifying by LEC.

In spring of 1998, there were residual effects due to the 1997 fertilizer treatments, such that it was necessary to evaluate differences between LEC and soil series within individual N treatments. Median amounts of 35, 35, 54 and 86 kg ha^{-1} were observed for the 0, 45, 90 and 135 kg ha^{-1} N treatments, across the site. A landscape effect persisted in 1998, as amounts in the upper LEC were consistently lower than those observed in the lower and mid LEC. For example, within the check treatment, amounts of 24, 35 and 40 kg ha^{-1} were observed in the upper, mid and lower LEC,

Table 3. Descriptive statistics, spring and fall (1998 only) residual nitrate to a depth of 90 cm (kg ha^{-1}) and residual exchangeable ammonium to a depth of 30 cm, within LEC, soil series and individual N fertilizer treatments

N rate (kg ha^{-1})	Residual nitrate and exchangeable ammonium nitrogen (kg ha^{-1})																	
	NO3 97^z	NH4 97	ES NO3 98				ES NH4 98				H NO3 98				H NH4 98			
	All		0	45	90	135	0	45	90	135	0	45	90	135	0	45	90	135
Overall (n = *210)*																		
Median	48	8	35	35	54	86	7	10	12	8	29	31	33	56	23	24	23	24
Minimum	18	0	12	12	17	57	3	6	7	5	16	15	19	32	13	12	13	9
Maximum	146	34	295	67	112	152	16	26	26	11	69	57	382	108	51	53	73	52
Upper (n = *35)*																		
Median	44*a*	7*a*	24*a*	29*a*	43*a*	70*a*	10*c*	11*a*	9*a*	9*ab*	40*b*	27*a*	33*ab*	73*a*	33*b*	26*a*	28*b*	34*ab*
Minimum	27	5	12	22	17	67	7	6	7	7	22	15	21	39	15	14	16	17
Maximum	85	28	295	54	67	73	16	17	10	10	58	41	46	108	51	53	39	52
Mid (n = *126)*																		
Median	47*a*	8*a*	35*a*	35*ab*	57*a*	91*a*	7*b*	10*a*	13*b*	8*a*	27*a*	32*ab*	40*b*	65*a*	26*ab*	24*a*	27*b*	28*b*
Minimum	18	1	19	12	26	57	3	6	7	5	16	15	22	32	13	13	15	20
Maximum	146	18	48	59	100	110	15	26	26	11	69	54	382	100	43	48	73	38
Lower (n = *49)*																		
Median	52*b*	8*a*	40*a*	43*b*	52*a*	89*a*	4*a*	9*a*	13*b*	10*b*	26*a*	35*b*	29*a*	43*a*	17*a*	22*a*	20*a*	17*a*
Minimum	32	0	17	22	29	60	3	6	8	8	18	22	19	34	13	12	13	9
Maximum	129	34	68	67	112	152	14	19	24	11	47	57	60	68	30	51	25	28
Newdale (n = *151)*																		
Median	48*a*	8*b*	34*a*	33*a*	53*a*	88*a*	8*a*	11*a*	12*a*	8*a*	29*a*	31*a*	33*a*	62*a*	24*a*	24*a*	26*b*	25*a*
Minimum	23	0	12	12	17	57	3	6	7	5	16	15	19	32	13	13	14	16
Maximum	146	28	295	58	94	152	16	26	26	11	69	54	382	108	51	51	59	52
Varcoe (n = *21)*																		
Median	44*a*	7*ab*	29*ab*	42*a*	47*a*	82*a*	8*a*	9*a*	12*a*	9*a*	27*a*	27*a*	27*a*	56*a*	20*a*	25*a*	17*a*	14*a*
Minimum	18	4	24	27	29	60	4	8	8	8	22	23	23	44	13	19	16	9
Maximum	74	16	34	67	73	104	11	17	18	9	31	48	43	68	28	30	21	18
Angusville (n = *39)*																		
Median	49*a*	7*a*	42*b*	39*a*	57*a*	73*a*	5*a*	9*a*	13*a*	8*a*	27*a*	33*a*	35*a*	55*a*	22*a*	24*a*	22*b*	33*a*
Minimum	30	1	33	22	40	61	3	6	9	5	20	16	29	36	13	12	13	10
Maximum	129	34	68	60	112	108	14	19	18	10	58	57	82	56	38	53	73	38

^{z}NO3 97 = 1997 soil nitrate; NH4 97 = 1997 exchangeable ammonium; ES NO3 98 = early-season soil nitrate 1998; ES NH4 98 = early-season exchangeable ammonium 1998; H NO3 98 = harvest soil nitrate 1998; H NH4 98 = harvest exchangeable ammonium 1998.
a–c Median values followed by the same letter were not significantly different when compared among LECs or among soil series at $\alpha = 0.20$ (Kruskal-Wallis multiple comparison procedure).

respectively. Within the 135 kg ha^{-1} treatment, median amounts 70, 91 and 89 kg ha^{-1} were observed in these respective LEC. Relative amounts among individual soil series were not consistent and differences were largely statistically insignificant. However, the amount of nitrate in the Angusville series (42 kg ha^{-1}) was significantly greater than in the Newdale series (34 kg ha^{-1}) within the check treatment.

In the fall of 1998, the treatment effect persisted as expected, as treatments were applied identically in 1998. Across the site, median nitrate values (0–90 cm) were 29, 31, 33 and 56 kg ha^{-1} for the 0, 45, 90 and 135 kg ha^{-1} N treatments (Table 3). However, the landscape effect was decidedly different from the spring observations. While most treatments did not appear to differ consistently among LEC and few differences were significant, the lower LEC had the lowest median nitrate for all but the 45 kg ha^{-1} treatment. This tendency was most notable for the 135 kg ha^{-1} treatment, with median nitrate values of 73, 65 and 43 kg ha^{-1} in the upper, mid and lower LEC, respectively. Again, there were no significant differences among soil series within individual N treatments, and relative amounts of nitrate were not consistent among soil series, but most often the Varcoe series had the lowest residual levels. While lower residual amounts observed in the lower LEC and Varcoe soil series were generally not significantly different, losses, and potential consumption of N by competing weeds, probably increased with convergent landscape character. With greater amounts of soil organic carbon (Manning et al. 2001) and ample moisture throughout the growing season and subsequent to maturity, it is quite possible that denitrification reduced nitrate levels in both the lower LEC and Varcoe profiles. Pennock et al. (1992) observed greater rates of denitrification within local depressions of a hummocky agricultural landscape. Greatly elevated nitrate concentrations were not observed below the 60-cm increment in this study, so leaching losses were not observed unless discrete events occurred in-season.

While higher spring nitrate concentrations in the lower LEC may imply greater mineralization as convergent landscape character increased, this was not consistent with season-long estimates of N mineralization. Using crop removal data from the check strips, LEC and soil series were compared under the assumption that all mineralized N was taken up by the crop. Median nitrogen uptake values within the checks were essentially alike in all LEC in 1997 and 1998. Median nitrogen uptake values in 1997 were 53, 51 and 53 kg ha^{-1} in the upper, mid and lower

Table 4. Descriptive statistics, total aboveground N uptake and apparent N mmineralization/loss balance (1998) (kg/ha), within LEC, soil series and individual N fertilizer treatments

	N removal and N balance (kg ha^{-1})											
N rate	Total Aerial N Uptake 1997				Total Aerial N Uptake 1998				N Balance 1998			
(kg ha^{-1})	0	45	90	135	0	45	90	135	0	45	90	135
						Overall (n = *210)*						
Median	53	74	89	100	53	82	118	143	37	26	2	–27
Minimum	35	55	57	80	20	54	72	110	–210	–19	–63	–109
Maximum	90	101	133	117	69	123	155	160	82	84	340	25
						Upper (n = *35)*						
Median	53*a*	73*a*	85*a*	87*a*	51*a*	86*b*	112*ab*	143*a*	52*b*	28*a*	7*ab*	3*b*
Minimum	42	62	83	80	20	70	74	133	–210	–1	–26	–20
Maximum	62	86	92	95	59	113	146	152	71	62	34	25
						Mid (n = *126)*						
Median	51*a*	74*a*	87*a*	101*a*	53*a*	82*b*	121*ab*	143*a*	36*ab*	24*a*	9*b*	–25*ab*
Minimum	35	57	57	85	37	54	85	110	11	–3	–51	–78
Maximum	76	101	113	117	69	123	155	160	82	84	340	16
						Lower (n = *49)*						
Median	53*a*	74*a*	93*a*	99*a*	55*a*	77*a*	97*b*	141*a*	29*a*	18*a*	–28*a*	–54*a*
Minimum	37	55	59	92	33	58	72	118	8	–19	–63	–109
Maximum	90	100	133	110	63	106	140	150	57	51	25	–12
						Newdale (n = *151)*						
Median	53*b*	74*ab*	85*a*	100*a*	52*a*	81*a*	117*b*	140*a*	40*a*	23*a*	6*b*	–26*a*
Minimum	35	55	57	80	20	54	74	110	–210	–8	–51	–109
Maximum	76	89	113	117	65	123	155	156	82	84	340	25
						Varcoe (n = *21)*						
Median	43*a*	64*a*	88*ab*	101*a*	42*a*	75*a*	90*a*	133*a*	31*a*	18*a*	–29*a*	–37*a*
Minimum	41	57	80	92	38	58	72	118	27	–19	–54	–61
Maximum	44	101	94	110	45	113	119	148	34	38	14	–12
						Angusville (n = *39)*						
Median	58*b*	76*b*	98*b*	101*a*	57*b*	87*a*	120*b*	150*a*	31*a*	27*a*	2*ab*	–31*a*
Minimum	45	68	74	85	49	73	88	137	8	9	–63	–35
Maximum	90	100	133	105	69	113	155	160	69	62	71	–13

a, *b* Median values followed by the same letter were not significantly different when compared among LECs or among soil series at $\alpha = 0.20$ (Kruskal-Wallis multiple comparison procedure).

LEC, respectively (Table 4). In 1998, crop nitrogen uptake in the check strip was nearly identical to that of 1997; median values were 51, 53 and 55 kg ha^{-1} in the upper, mid and lower LEC, respectively. Nitrogen uptake did, however, differ significantly among soil series. Check treatment nitrogen uptake values in 1997 were 53, 43 and 58 kg ha^{-1} in the Newdale, Varcoe and Angusville soils, respectively. Corresponding 1998 check treatment nitrogen uptake values were 52, 42 and 57 kg ha^{-1}. In both years, nitrogen uptake in the Varcoe soil was significantly lower than that of the Angusville and Newdale series. This suggested that net mineralization was lower in the Varcoe series.

An estimate of apparent in-season mineralization (a mineralization/loss balance) using spring and fall soil residual nitrate levels and crop nitrogen uptake as employed by Campbell et al. (1988) was utilized to compare differences among LEC and soil series in 1998. This simple nitrogen balance indicated that within all N rates, mineralization was in fact less, or potential losses were greater, moving from the upper to the lower LEC. Similarly, net mineralization was generally greater in the relatively more arid Newdale profiles. Within each N treatment, median net mineralization values were least in the Varcoe series. Within LEC and soil series, apparent net mineralization also decreased as N fertilizer rate increased. There was a maximum of 54 kg NO_3 ha^{-1} that was unaccounted for in the lower LEC within the 135 kg ha^{-1} treatment (Table 4).

Exchangeable Ammonium

In general, exchangeable ammonium concentrations were low, and median spring residual amounts did not exceed 12 kg ha^{-1} in both years. In 1997, there were no significant differences among residual amounts among individual LEC (Table 3). While the Newdale soils contained significantly more ammonium than the Angusville profiles, the difference of 1 kg ha^{-1} in the 0- to 30-cm depth increment was of no practical consequence. In spring of 1998, while some differences among LEC were statistically significant, variation among treatments and LEC were not consistent. In the check treatment, amounts were progressively lower moving from the upper to the lower; the opposite was observed for the 90 and 135 kg ha^{-1} treatments, in the 0- to 30-cm depth increment. Among soil series, amounts were quite consistent; within N treatments, soil series were separated by a maximum difference of 3 kg ha^{-1}. The relatively low amounts, and negligible differences between soil series and LEC, indicated that residual spring exchangeable ammonium would have been of limited utility in any N balance, and would not be of use in explaining crop responses.

Table 5. Descriptive statistics, extractable soil P (Ext P) to 30 cm, exchangeable K (Exch K) to 30 cm, and sulphate-sulphur (SO4-S) to 120 cm (kg ha^{-1}), within LECs and soil series

	Nutrient (kg ha^{-1})					
	1997			1998		
	Ext P	*Exch K*	*SO4-S*	*Ext P*	*Exch K*	*SO4-S*
			Overall (n = *210)*			
Median	46	783	78	51	761	93
Minimum	8	343	22	11	256	19
Maximum	164	4594	9012	186	3330	10534
			Upper (n = *35)*			
Median	39*a*	699*a*	49*a*	45*a*	707*a*	60*a*
Minimum	15	453	31	18	256	19
Maximum	128	1229	333	99	1071	199
			Mid (n = *126)*			
Median	45*ab*	778*b*	79*b*	47*a*	722*a*	98*b*
Minimum	8	443	22	11	398	25
Maximum	154	4594	9012	184	3330	10534
			Lower (n = *49)*			
Median	51*b*	895*b*	158*c*	68*b*	828*b*	163*c*
Minimum	16	343	46	30	557	35
Maximum	164	1977	4710	186	2071	7905
			Newdale (n = *151)*			
Median	43*a*	774*a*	67*a*	46*a*	718*a*	79*a*
Minimum	8	343	22	11	256	19
Maximum	154	4594	2727	184	3330	4760
			Varcoe (n = *21)*			
Median	34*a*	718*a*	282*c*	43*a*	804*ab*	434*b*
Minimum	16	471	51	23	624	65
Maximum	121	1398	9012	150	1314	10534
			Angusville (n = *39)*			
Median	82*b*	900*a*	88*b*	91*b*	865*b*	88*a*
Minimum	21	403	44	36	571	35
Maximum	164	2031	1683	186	2071	1399

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

Extractable Phosphorus

The vast majority of extractable phosphate was found within the surface 30 cm, which averaged 51 kg ha^{-1} across the site in both years. Phosphate concentrations increased with convergent landscape character in the landscape in both 1997 and 1998 (Table 5). In 1997, median amounts of 39, 45 and 51 kg ha^{-1} were observed in the upper, mid and lower LEC, respectively. In 1998, 45, 47, and 68 kg ha^{-1} were observed in these respective LEC. Phosphate is relatively insoluble and immobile; therefore, concentrations were expected to be similar among growing seasons. In both years, only the lower LEC emerged as statistically distinct. Within soil series, amounts of 43, 34 and 82 kg ha^{-1} were observed in the Newdale, Varcoe and Angusville soils, respectively; and correspondingly, 46, 43 and 91 kg ha^{-1} were observed in 1998. In both years, the Angusville series was statistically unique from the Newdale and Varcoe soils. Phosphate was significantly proportional to “A” horizon depth, solum depth and soil organic carbon in 1997 and 1998 (not shown). Mulla (1993) also found that available phosphate tended to increase with convergent landscape character, and accordingly, with soil organic carbon and soil profile moisture. Partitioning the site into soil series accounted for more variability in soil-extractable phosphate, evidenced by the greater range of median values among soil profile types. Soil properties such as “A” horizon depth, solum depth and soil organic carbon are more uniform within individual soil series than within LEC (Manning et al. 2001).

Exchangeable Potassium

Median amounts of exchangeable potassium in the surface 30 cm were 783 and 761 kg ha^{-1} overall for 1997 and 1998. The distribution of potassium was not unlike that of phosphate, and increased with convergent character in the landscape and accordingly, with progressive solum development (Manning et al. 2001). This was consistent with the results of Walker et al. (1996). In 1997, 699, 778 and 895 kg ha^{-1} potassium were observed in the upper, mid and lower LEC, and in 1998, 707, 722, and 828 kg ha^{-1} were observed in those respective LEC, in the surface 30 cm. In both seasons, the lower LEC was distinct from the upper, but not the mid LEC in 1997. Within the Newdale, Varcoe and Angusville soils, median values of 774, 718 and 900 kg K ha^{-1} were observed in 1997, and 718, 804 and 865 kg ha^{-1} in 1998. Only the Angusville series emerged as distinct from the Newdale soil in 1998. As it was for phosphate, higher potassium content in the Angusville soils was likely a function of higher organic matter content relative to the Varcoe and Angusville series. Potassium, like phosphate, is a relatively stable nutrient, and sampling variability was likely a major contributor to variability among growing seasons.

Sulphate-sulphur

Across the site, median values of 78 and 93 kg ha^{-1} sulphate were observed in 1997 and 1998 respectively. Sulphate also increased with convergent landscape character; to a depth of 120 cm, median amounts of 49, 79 and 158 kg ha^{-1} were observed in 1997 and 60, 98, and 163 kg ha^{-1} for 1998, in the upper, mid and lower LEC, respectively. All of the LEC were statistically unique. Hydrologic differences among soil series were made apparent by differences in concentrations of the relatively mobile sulphate. Median amounts of 67, 282 and 88 kg ha^{-1} were observed in the Newdale, Varcoe and Angusville series in 1997, respectively; and correspondingly, median values of 79, 434 and 88 kg ha^{-1} were observed in 1998. In 1997, all soils were statistically unique, while in 1998 levels in the Angusville and Newdale series were unique from those in the Varcoe, but not one another. The elevated sulphate concentrations in the Varcoe soil illustrated that these Gleyed Rego Blacks had the lowest net downward moisture flux of the three series. The greater loss of moisture by evapotranspiration in the Varcoe soils, a function of their proximity to the Angusville soils occupying the most convergent landscape positions, results in the accumulations of mobile sulphate salts within 120 cm of the surface. Overall, sulphate levels were somewhat consistent between years, despite the fact that sulphate is a mobile nutrient. Extremely high concentrations of sulphate occurred in the 90- to 120-cm depth increment of some Varcoe profiles, which resulted in amounts in excess of 4000 kg ha^{-1}. These high sulphate concentrations were persistent between two growing seasons.

CONCLUSIONS

In seeking to implement variable N management, a common approach is to delineate discrete management units which capture meaningful variability in soil residual mineral N, potential mineralization and crop yield potential are required. Using LEC as management units rather than soil series was considered to be more practical from a management perspective in this study. While not always statistically significant, nitrate, phosphate, potassium and sulphate increased with convergent character in the landscape, such that lower LEC > mid LEC > upper LEC. Differences in spring residual nitrate were negligible among LEC and soil series, such that yield potential, largely a function of moisture supply, would have played the most important role in determining crop response to N fertilizer. Variation in soil moisture was expressed at a scale more consistent with the LEC delineations than those of soil series. For example, moisture content of eluvial soils in localized depressions within the upper LEC were more similar to that of surrounding orthic soils than that of the eluvial soils which occurred in the depression of the lower LEC. Even so, we must remain sensitive to unique genetic soil character when considering variable rate N application. For example, potential environmental implications of high rates of applied N rate would be very different on a Varcoe soil with weak leaching potential, compared with a strongly leached (eluviated) Angusville soil. Regardless of how management units are delineated, variability in the factors determining the need for variable rate N application must be put in the context of temporal variability in these factors. Growing conditions were very different between 1997 and 1998, for example. Optimum N fertilizer requirements within a management unit must be sufficiently different among management units, and sufficiently temporally stable within, before variable rate N application will be feasible for a given location.

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