SPATIAL PATTERN OF SOIL PROPERTIES IN AN IRRIGATED FIELD

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ABSTRACT

Denitrification from agricultural ecosystems is regarded as a major contributor to atmospheric N levels, but the actual rates of denitrification and the controls on these rates remain poorly understood. This study was conducted to examine landscape-scale patterns of denitrification and the soil properties that control these patterns. Two sampling grids (11-m by 11-m and 110-m by 110-m) were established in an irrigated field in an aridic Boroll (Brown Chernozemic) soil in southern Saskatchewan. The measured soil properties (denitrification rate, respiration rate, volumetric moisture content, bulk density, soluble organic and inorganic carbon, total and mineral N, *in situ* pH, and *in situ* redox potential) were correlated to slope properties and derived landform elements at the site to determine landscape-scale patterns and relationships. The soil properties occurred in one of three spatial patterns: (i) a random pattern for mineral N; (ii) a diagonal pattern for pH, soluble organic and inorganic carbon, and total N; and (iii) a depression-centered pattern for denitrification, bulk density, moisture, respiration and redox potential. Statistically distinct rates of denitrification were associated with the different landform elements: rates were lowest in the shoulder elements, intermediate in the footslope and level-convex elements, and highest in the level-concave elements. Hot-spots of denitrification activity, i.e., sampling sites with denitrification rates statistically identified as outliers, were all associated with the level elements and, predominantly, the level-concave elements.

INTRODUCTION

Denitrification is a primarily biological process by which nitrate (NO_3^-) is converted into nitrous oxide (N_2O) and dinitrogen (N_2) gases that are subsequently released to the atmosphere. Whereas N_2 is an inert gas that poses no known environmental risk, N_2O is one of the greenhouse gases that contribute to the destruction of the earth's protective ozone layer. Consequently, much attention has been directed at assessing the conditions under which N_2O is evolved and the absolute amounts produced.

The recent focus on denitrification has been triggered by an observed increase in total denitrification activity which, in turn, has been related to increases in both biological and chemical N_2 fixation (Delwiche, 1970; Pratt et al., 1977). Fixed N is subsequently made available for plant uptake and, along with any fertilizer-N, becomes susceptible to denitrification. The degree to which denitrification actually occurs is controlled in part by carbon (C) availability (Smith and Tiedje, 1979), substrate (i.e. NO_3^- and NO_2^-) availability, pH (Blackmer and Bremner, 1978), redox potential (Sorenson et al., 1980), and the presence of denitrifiers in the microbial population. In turn, these regulating factors (Davidson et al., 1990) respond to basic pedologic and hydrologic controls.

As observed by Davidson and Swank (1986), Robertson et al. (1988), and Groffman and Tiedje (1989), relationships between the basic controls and regulating factors give rise to landscape-scale patterns of denitrification. Although the closeness of the landscape - denitrification interaction differed between these studies, a common element emerged: landscape-scale patterns of these regulatory factors (e.g., drainage and texture) gave rise to distinct, replicable patterns of denitrification within a landscape.

The objectives of our study were to determine: (i) the spatial pattern and controls on denitrification in an irrigated Brown Chernozemic (aridic Boroll) field and (ii) the statistical correlation between denitrification rates and a variety of soil properties. In this paper we examine the relationship between a quantitative measure of landscape form (Pennock et al., 1987) and several soil parameters, including rate of denitrification. In subsequent papers, the results of this initial, spatially-based analysis are used to strengthen the interpretation of the soil property - denitrification relationship.

MATERIALS AND METHODS

Field Sampling and Description

The field area is located in the Brown (aridic) soil zone of Southern Saskatchewan. A 200-m by 200-m area was selected in a representative section of the field and two sampling grids were placed on the surface. The first was a square, 110-m by 110-m grid composed of 144 sample sites separated by a spacing of 10 m (Figure 1). A second grid, 11-m by 11-m, was placed within the larger grid (Figure 1) with 144 sampling sites separated a spacing of 1 m. The elevations at the sample sites, and a 30-m fringe around the large grid, were surveyed using a rod and transit.

The elevations were used to calculate a topographic map of the field area and to calculate a series of slope variables according to the procedure of Pennock et al. (1987). For each 10-m by 10-m segment of the field area, we calculated the slope gradient (°), plan or across-slope curvature ($^\circ$ m^{-1}), and profile or downslope curvature ($^\circ$ m^{-1}). The three slope variables were then used to classify each 10-m by 10-m segment of the landscape into one of four landform elements, i.e., segments of the landscape with a defined range of slope gradient and slope curvature (Pennock et al., 1987). The original landform element classification contained seven elements but, for the much flatter landscape used in this study, only four elements were defined: shoulders (elements with convex profile curvatures, i.e., $\geq 0.1^\circ$ m^{-1}), footslopes (elements with concave profile curvatures, i.e., $\leq -0.1^\circ$ m^{-1}), level-convex elements (0° m^{-1} < profile curvature < 0.1° m^{-1}), and level-concave elements (-0.1° m^{-1} < profile curvature $\leq 0^\circ$ m^{-1}). The rationale for choosing these criteria of landform element classification has been discussed by Pennock et al. (1987) and Pennock and de Jong (1987).

Sampling

Soil cores were collected from the 144 grid-intersection points in both the large (June 1, 1990) and small (June 27, 1990) grids. All soil samples were collected within 3 h of an irrigation event, during which 25 mm of water was applied through a central pivot system. Soil cores were collected in 10 cm × 4 cm i.d. aluminum cylinders, each of which had six holes (7 mm in diameter) located in two rows along opposite sides of the cylinders. Each soil core was placed in a Mason jar (975 cm^3) and sealed (note: the lids were modified to include a sampling port sealed with a rubber septum). Denitrification (N_2O evolution) was estimated using the acetylene-blockage technique (Yoshinari et al., 1977). All soil cores were incubated at ambient temperature. At the end of the incubation period, the cores were analyzed for CO_2 evolution (i.e., total respiration), water content, mineral N, total N, soluble inorganic carbon, soluble organic carbon, and bulk density. All values are reported on an oven-dry soil basis. In addition, measurements of the soil pH and redox potential were made in the field.

Assays

The acetylene-blockage technique of Yoshinari et al. (1977) was modified and used to determine N_2O production. Nitrous oxide determinations were carried out by gas chromatography using a modified Hewlett Packard gas chromatograph equipped with a ^{63}Ni electron capture detector and a Porapak Q column (80/100 mesh; 3.1 m × 3.2 mm i.d.). After the gas phase had been analyzed for N_2O, a subsample from each soil core was obtained and the water content determined gravimetrically by drying the soil at 105°C for 24 h. The water contents and the bulk densities of the samples were used to calculate the volumetric water contents. Only the volumetric water contents are considered in this paper.

Total soluble carbon (TSC) and soluble inorganic carbon (SIC) were determined using a total organic carbon analyzer (Beckman Tocomaster Model 915B). A 10 g portion of unprocessed (i.e., moist) soil from each core was shaken with 20 mL of deionized water for 1 h, centrifuged, and filtered through a single sheet of Whatman No. 42 filter paper. Total and inorganic fractions of the soluble carbon were determined on 40 μL subsamples of the extracts. Soluble organic carbon (SOC) was calculated as TSC - SIC.

Mineral N ($NH_4^+ + NO_3^- + NO_2^-$) was extracted by shaking 100 g of unprocessed soil with 200 mL of 2 *M* KCl for 1 h and then determined by steam distillation in the presence of MgO and Devarda alloy (Keeney and Nelson, 1982). Total N was determined by using a modified Kjeldhal digestion (Bremner and Mulvaney, 1982) followed by steam distillation in an all-glass distillation unit.

Respiration was determined by titrimetric analysis for CO_2. A vial containing 20 mL of 0.5 *M* NaOH was placed in each Mason jar to trap the CO_2 produced during incubation of the soil cores. The amount of CO_2 trapped was determined by titrating the NaOH with 0.1 *M* HCl from pH 8.3 to pH 3.7 in the presence of carbonic anhydrase (Underwood, 1961). Respiration was reported as $\mu g\ CO_2\ g^{-1}\ d^{-1}$.

In situ measurements of the soil redox potential (E_{Pt}) were made using bright platinum electrodes as described by Farrell et al. (1991a, 1991b). The E_{Pt} measurements were taken about 60 h after the electrodes were inserted in the soil and three hours after the site was irrigated. Values of E_{Pt} were converted to "standard redox potentials" (Eh) by adding in the standard potential of the saturated calomel reference electrode, i.e., 244 mV.

Statistical Analysis

The statistical analysis for this paper involved three stages: an exploratory data analysis, an assessment of the basic spatial pattern, and a quantification of the spatial pattern using variography (reported elsewhere). After identifying the spatial patterns of the variables, the patterns themselves were related to the slope characteristics discussed above.

Exploratory data analysis allows the nature of the frequency distribution for each variable to be assessed, the presence of outliers to be identified and examined, and the type of operation required to transform the observed distribution to one approximating a normal distribution determined. The fit of an original or transformed distribution to a normal distribution was assessed with the Shapiro-Wilk statistic ($\alpha = 0.05$) (Shapiro and Wilk, 1965). The distributions are described using both the mean (and related statistics) and the median (and related statistics). Although the mean is included to facilitate comparison with other literature values, the median is more resistant to the influence of long-tailed distributions and more robust to departures from normality. Outliers from a distribution were defined statistically as data values greater than 1.5 interquartile ranges from the median, and were identified from box plots produced by Proc Univariate of SAS (SAS Institute Inc., 1988).

One of the principles of soil landscape analysis is that complex statistical distributions of soil properties may be related to observable differences in the spatial patterns of those properties in the landscape. The initial step in the analysis of the spatial pattern was to generate maps of the quartiles for each soil parameter; thus, allowing the dominant spatial patterns to be identified visually. Quartile maps were generated for each soil parameter by assigning the value measured at each of the 144 sample sites to its appropriate quartile and plotting the results. In this way, trends across the grid area can be easily assessed. Moreover, a cluster of adjacent points in the same quartile indicates a departure from randomness. The use of quartiles eliminates some of the problems associated with mapping variables having long-tailed distributions, i.e., because no interpolation of values is required, the nature of the original distribution is irrelevant.

The final stage of the analysis was to determine if a statistically distinct range of values for the soil variables was associated with the landform elements discussed above. The significance of the differences between means was assessed using the Least Significant Difference test ($\alpha = 0.05$). The rationale for choosing this test is discussed in Carmer and Walker (1985).

RESULTS

Site Description

The field site is located on a very gently-sloping surface underlain by silty glaciolacustrine deposits. The mean slope of the surface is 1.0°; the highest slope observed for a 10-m slope segment was 3.2°. The topography of the study area was dominated by two major slopes in the NW and SE corners (Figures 2). A central depression runs through the center of the site but is separated into two distinct depressional areas by a rise of 0.2- to 0.4-m in the center of the grid. Both of the major depressions contained standing water after each irrigation event.

The soils of the study area are generally classified into the Fox Valley Association and are dominantly Orthic Brown Chernozemic soils (Aridic Haploboroll). The two major slopes are dominated by Calcareous Brown Chernozemic soils (Haplic Aridic Calciborolls) and Orthic Dark Brown Chernozemic soils (Aridic Haploboroll). The depressional areas are characterized by parent sediments higher in clay, and are dominated by Orthic Gleysols (Typic Cryaquepts) with Humic Eluviated Gleysols (Mollic Albaqualfs) at the edges. The soil associated with the rise in the center of the depressional areas has an Ah horizon and calcium carbonate-enriched B horizon overlying a highly gleyed Cg horizon. The genesis of this type of soil has been described by Knuteson et al. (1989) who attributed the formation of the calcic horizon to upward soil water flux and carbonate precipitation. The soil is classified as an Aeric Calciaquoll (Knuteson et al., 1989); there is no direct equivalent in the Canadian System of Soil Classification.

The study area is classified as very gently sloping terrain. The distribution of slope gradients for the 100-m^2 slope segments was positively skewed and log-normal (Table 1). Both plan and profile curvature had a slight negative skew (Table 1), but were normally distributed. The distribution of landform elements at the study area broadly corresponds to the elevation map of the area . The level elements comprise 66% of the study area (35.4% for level-concave and 30.6% for level-convex elements). The shoulder elements cover 14.6% of the area and the footslope elements 19.4%.

Large (110-m by 110-m) Grid Study

Exploratory Data Analysis

The initial statistical assessment indicated that only 4 of the 14 soil parameters had distributions which approximated the normal distribution (Shapiro-Wilk statistic, $\alpha = 0.05$) (Table 1). Total N and volumetric water content were the only soil variables normally distributed. Likewise, plan and profile curvature were the only slope variables normally distributed. Of the remaining variables which showed positive skew, respiration, SOC, mineral N, and slope gradient approximated the normal distribution after they were log-transformed.

Denitrification, pH, Eh, bulk density, and SIC could not be transformed to approximate a normal distribution. The distribution of pH values was negatively skewed and because of the log-transformation inherent in the pH scale no further transformation was attempted. The distribution of bulk density values was also negatively skewed. Soluble inorganic carbon exhibited a bimodal distribution with modes at 0 - 1 and 35 - 39 µg g^{-1}. The Eh distribution was also bimodal, with 8 of the values below 250 mV and the remaining values above 350 mV.

The distribution of denitrification rates exhibited very high positive skew and could not be transformed to approximate a normal distribution . Fourteen outliers were identified: 10 (with values ranging from 7.5 - 10.5 kg N ha^{-1} day^{-1}) were within three interquartile ranges and four (13.5 to 20 kg N ha^{-1} day^{-1}) were beyond this range. The occurrence of such outliers is very common in denitrification studies (e.g. Parkin, 1987).

Spatial Patterns and Continuity

Three basic spatial patterns were evident from the quartile maps (Figure 3, 4 and 5). The first pattern is that of mineral N (Figure 3) for which there was no observable clustering of values and an essentially random pattern occurs. The second pattern was observed for total N, SIC, SOC, and pH (Figure 4). This pattern forms a diagonal zone running from the NW corner of the grid to the SE corner and crosses the depression at the rise. The highest values for inorganic carbon and pH were associated with the diagonal zone and the values declined towards the SW and NE corners. Converesly, the values for SOC and total N were lowest in the diagonal zone and highest in the corners.

The quartile maps for Eh, moisture, bulk density, respiration, and denitrification (Figure 5) show what can best be described as a depression-centered pattern. Moisture contents and denitrification rates in the fourth quartile were predominantly associated with the depressions, however, small areas with high rates of denitrification occurred throughout the landscape. Conversely, values of Eh in the first quartile were associated with the depressions. The quartile map for respiration exhibited an intermediate pattern: high values of respiration were associated with the eastern-most depression in the study area but not with the other depressions. The lowest respiration rates were associated with the rise between the depressions.

Denitrification-Landform Relationships

The observed spatial pattern and the lack of spatial interdependence for denitrification suggests that distinct rates of denitrification may be associated with landform elements. The distribution of denitrification rates associated with each of the four landform elements was assessed. Despite the lack of a log-normal distribution for the complete denitrification data set, the distribution within each landform element was log-normally distributed.

The occurrence of these distinct distributions suggests that significantly different rates may be associated with each landform element. Three groups of landform elements were identified in the LSD analysis (Table 2): shoulders, footslopes and level-convex elements, and footslopes and level-concave elements. The standard deviations increase in sequence with the means, and reflect the range of rates associated with each mean. The range for shoulder elements was 3.5 (0.1 to 3.6 kg N ha^{-1} day^{-1}), 6.8 for footslope elements (0.2 to 7 kg N ha^{-1} day^{-1}), 13.1 for level-convex elements (0.1 to 13.2 kg N ha^{-1} day^{-1}), and 20 for level-concave elements (0.0 to 20 kg N ha^{-1} day^{-1}). Clearly, those observations identified as outliers in the initial analysis were all associated with the level elements and, predominantly, the level-concave elements.

DISCUSSION

When we assess the properties measured in the large grid distinct spatial patterns and relationships emerge. Three basic patterns were observed at the Birsay site: a random pattern (mineral N); a NW-SE trending diagonal pattern (pH, SIC, SOC, and total N); and a depression-centered pattern (denitrification rate, moisture, bulk density, Eh, and respiration rate). Each pattern can be related, at least in a preliminary sense, to differences in the conditions that control the rates of the pedogenic processes.

The simplest pattern is the random pattern, which was observed only for mineral N. Presumably, this pattern reflects the vagaries associated with the application of fertilizer-N onto the field.

In general, the diagonal pattern was strongly expressed, with a high degree of spatial continuity (as indicated by the well-defined semi-variogram models and low nugget variances) and pronounced anisotropy in the directional semi-variograms. The loci of high values of pH and SIC in the slight rise between the depressions is clearly related to the pedogenic and hydrologic processes responsible for secondary carbonate deposition (Knuteson et al., 1989). Likewise, the bimodal frequency distribution for SIC also reflects the influence of these basic pedologic controls. That is, sample sites dominated by vertical water movement and the leaching of carbonates are represented by the low mode, whereas sites of secondary carbonate enrichment, primarily in the rise and adjacent areas, are represented by the high mode. That low values of SOC and total N were associated with the rise indicates that there was an inverse relationship between carbonate deposition and SOC and total N. The mechanism responsible for this relationship, however, was not evident from our study.

Soil properties that exhibited a depression-centered pattern could also be related to fundamental controls on these properties. The pattern observed for bulk density was probably related to the glacial sedimentation pattern in the low-level hummocky landscape: i.e., relatively coarse, low-density sediments are deposited on the knolls whereas the finer, denser sediments are deposited in low-lying depressional areas (Gravenor and Kupsch, 1962). The moisture pattern presumably reflects differences in the rate of application of water from the center-pivot irrigation system and the subsequent concentration of water in the depressions via hillslope flow processes. Higher moisture contents in the depressional areas also reflect the fact that drainage in these areas is slower due to the occurrence of denser sediments (reflected in the higher bulk densities associated with the depressions).

The association of statistically distinct rates of denitrification with the landform elements indicates a strong topographical control of the factors regulating denitrification. Conditions suitable for high rates of denitrification were confined to level-convex and level-concave elements in the landscape. The occurrence of the statistically defined hot-spots within these elements indicates that their occurrence is not random, but instead shows a strong topographical control. Nevertheless, the pattern observed in the small grid indicates that denitrification may be random within a given landform element.

Although a clear landscape-scale pattern of denitrification emerged, the association of distinct rates of denitrification with small (100 m^2) landform elements suggests a possible explanation for why only a low degree of spatial continuity was observed in the semi-variograms for denitrification. The elements associated with high rates of denitrification occurred throughout the landscape and the resulting pattern was spatially discontinuous. The localized occurrence of high rates violates the intrinsic hypothesis for geostatistical analysis (Myers, 1988) and, hence, the use of these techniques may be inappropriate for the Birsay site.

Correlations between denitrification and the various soil properties form the focus of subsequent papers. As discussed above, however, properties with the same spatial pattern are responding to a single set of controls (either pedogenic, hydrologic, or anthropogenic) and should not be correlated with properties responding to a different set of controls. Thus, insofar as properties which have different spatial patterns are unlikely to be highly correlated, subsequent data analyses were necessarily conditioned by the results of the landscape analysis reported here.

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Figure Captions:

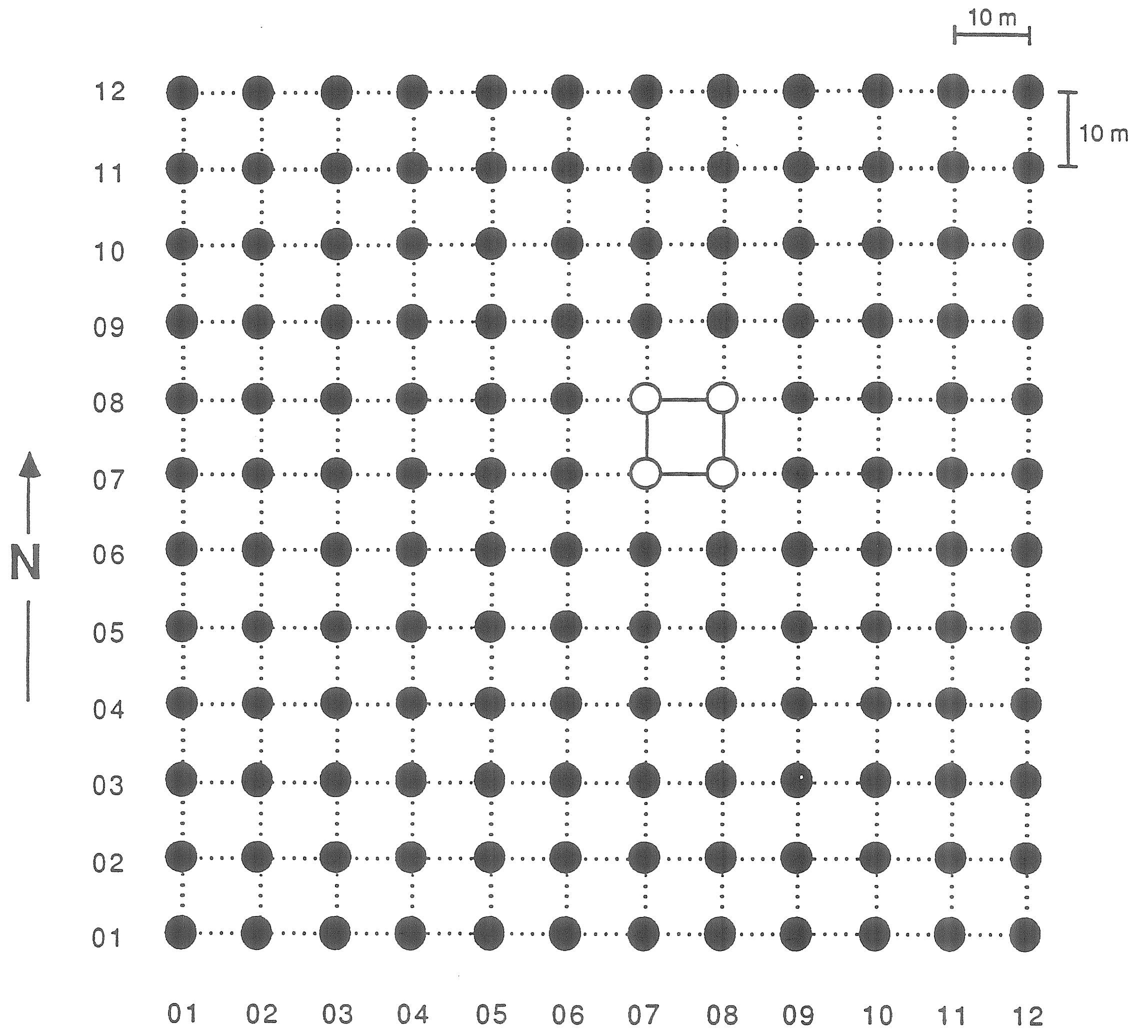
Figure 1: Sampling design at the Birsay site.

Figure 2: Contour map of the Birsay site (Contour interval = 0.2 m).

Figure 3: Quartile map for mineral Nitrogen.

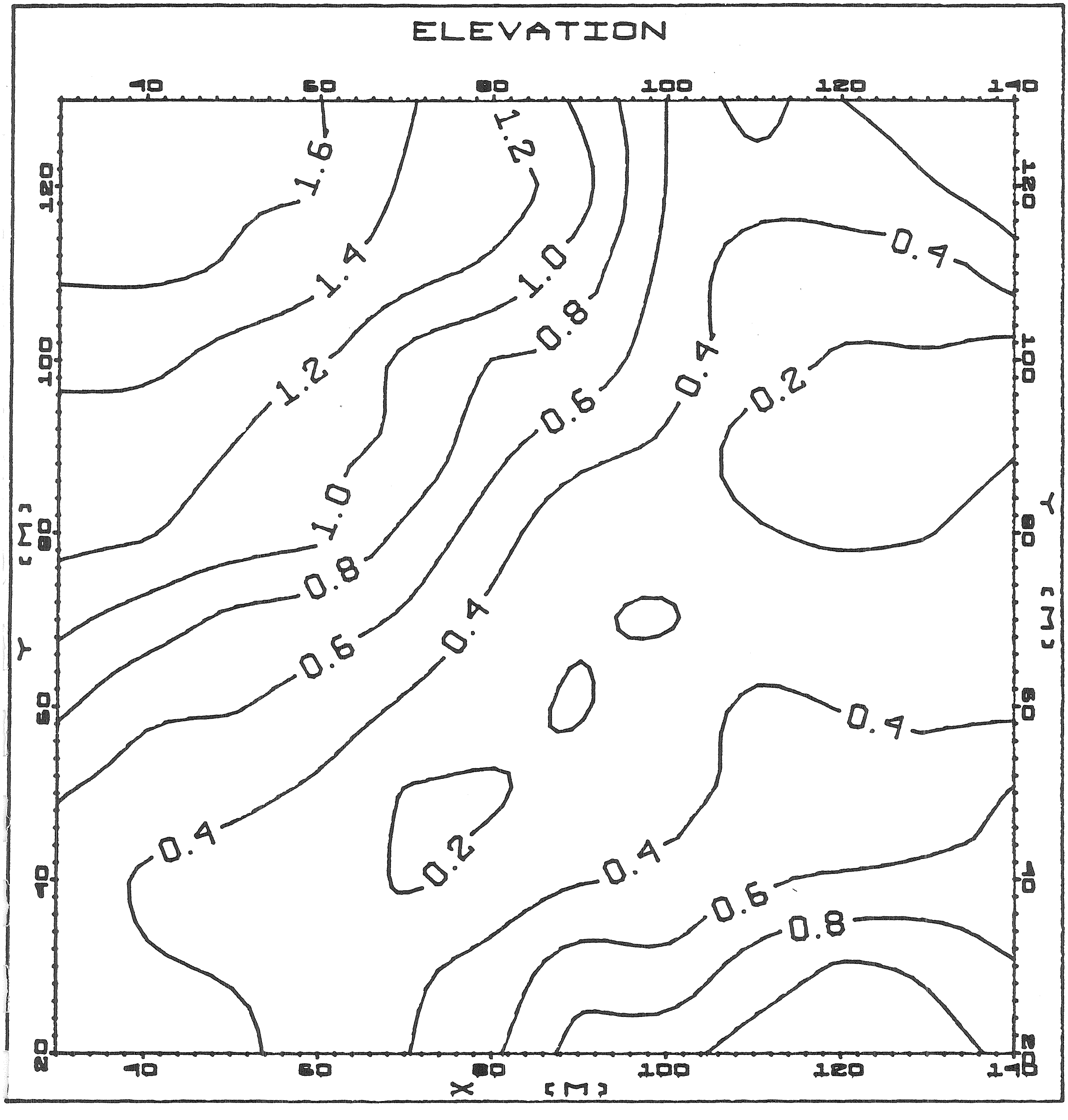
Figure 4: Quartile map for Soluble inorganic carbon.

Figure 5: Quartile map for denitrification.



● Sampling points

○ Sampling points marking the location of the small grid



ELEVATION

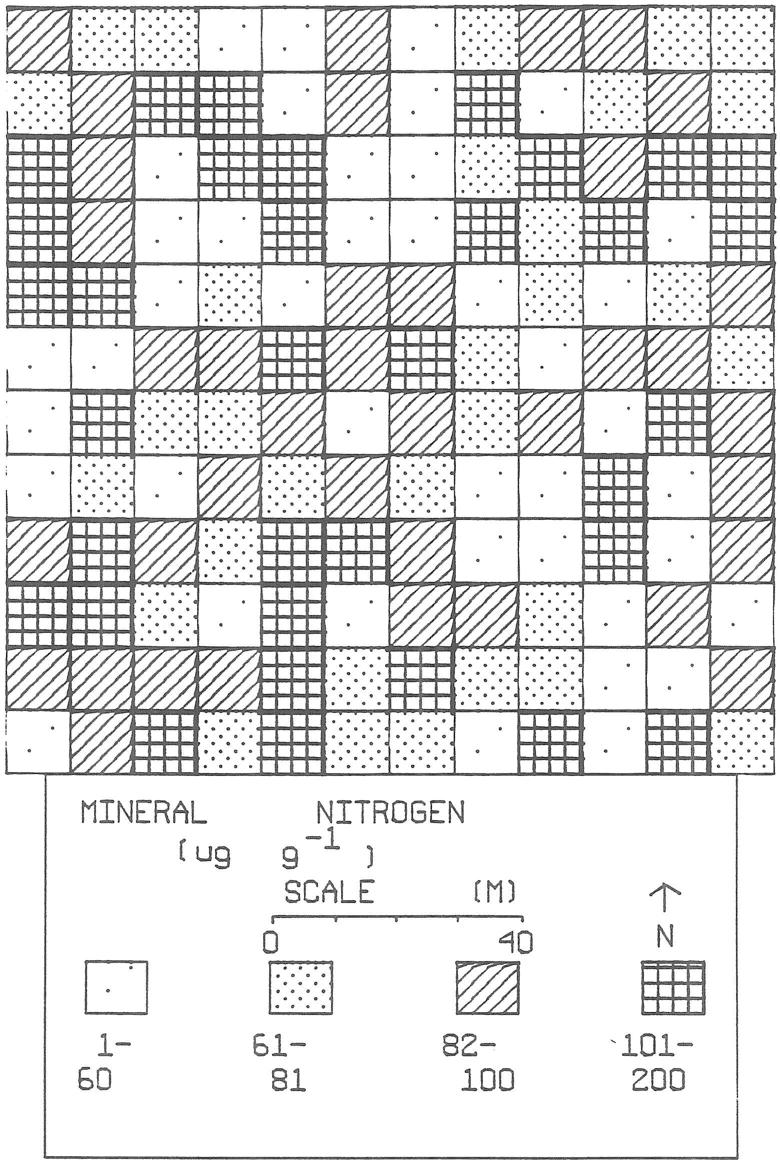
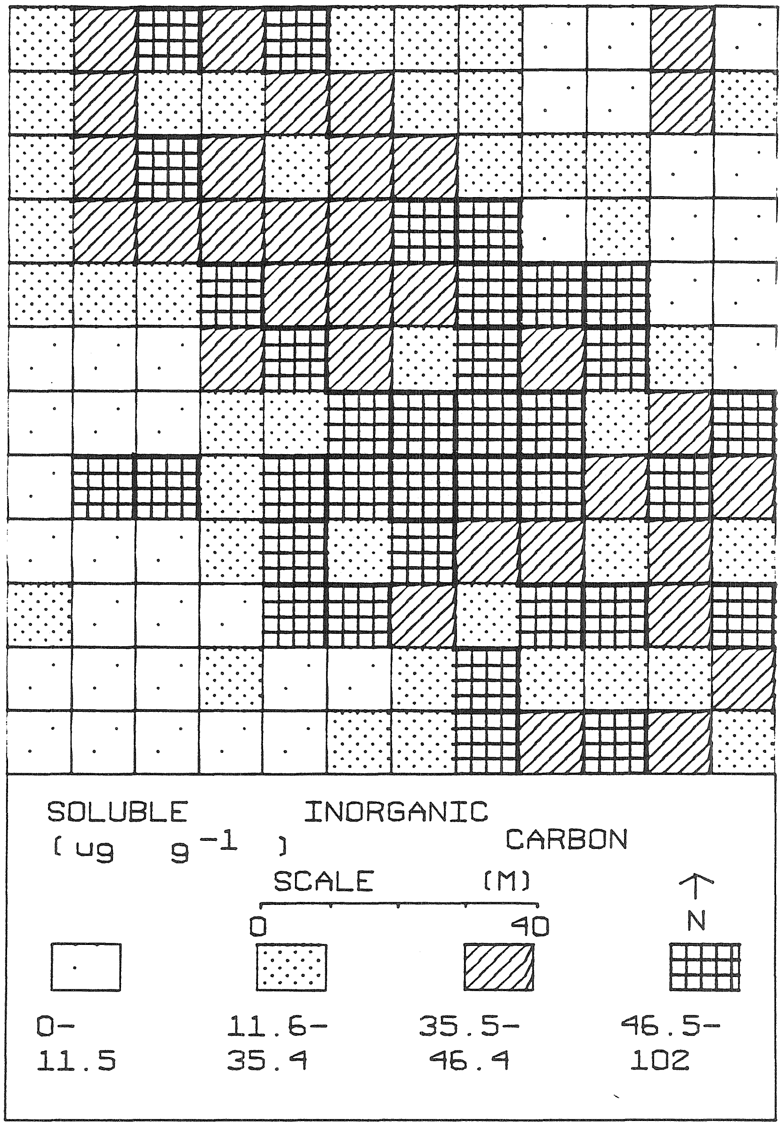

MINERAL NITROGEN
(ug g^{-1})
SCALE (M)
0
40
N
1-
60
61-
81
82-
100
101-
200

FIG 4


SOLUBLE INORGANIC CARBON
(ug g^{-1})
SCALE (M)
0
40
N
0-
11.5
11.6-
35.4
35.5-
46.4
46.5-
102

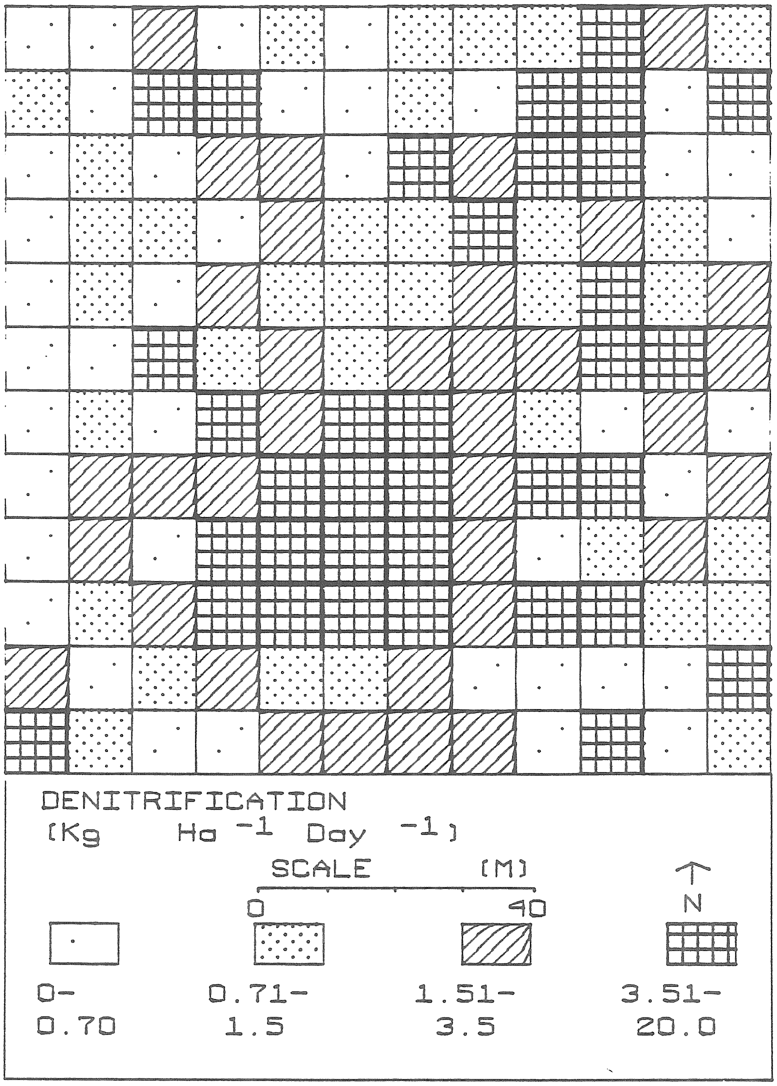

DENITRIFICATION
(Kg Ha $^{-1}$ Day $^{-1}$)
SCALE (M)
0
40
N
0-
0.70
0.71-
1.5
1.51-
3.5
3.51-
20.0

Table 1. Descriptive statistics for soil variables within the Birsay large (110-m by 110-m) grid.

Measurement	Units	Mean	Standard deviation	Median	Interquartile range	Skewness	C.V.	Min.	Max.
Denitrification†	kg ha^{-1} d^{-1}	2.74	3.39	1.5	2.8	2.77	123.6	0.0	20.0
Respiration†	µg C g^{-1} d^{-1}	30.6	13.9	27.6	18.6	1.09	45.6	7.8	76.9
Moisture	%	35.2	5.4	35.1	6.0	0.13	15.2	21.6	49.9
Bulk density	Mg m^{-3}	1.32	0.11	1.33	0.15	-0.61	10.9	0.86	1.61
Soluble inorganic C	µg g^{-1}	31.9	21.5	35.0	34.5	1.44	67.2	0	102.0
Soluble organic C†	µg g^{-1}	90.0	36.5	80.5	41.0	1.18	40.5	8.0	218.0
Total N	%	0.20	0.04	0.20	0.05	-0.35	18.9	0.10	0.28
Mineral N	µg g^{-1}	85.1	36.9	81.0	40.0	0.86	43.3	0.0	200.0
pH		7.6	0.5	7.8	0.7	-0.77	6.8	6.10	8.47
Eh	mV	474.4	107.3	458.5	48.5	-2.36	58.5	11.0	550.5

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† Required log transformation for statistical comparisons.

Table 2. Descriptive statistics and results of least significant difference test for untransformed and transformed denitrification rates. The transformation used is a log transformation of (untransformed rate + 1).

Landform element	Number of sites	Untransformed			Transformed		
		Mean[a]	Standard deviation	C.V.	Mean[b]	Standard deviation	C.V.
Shoulders	21	1.11	1.06	95.3	0.28[a]	0.19	67.9
Footslopes	28	2.19	1.83	83.4	0.44[bc]	0.23	51.3
Level-convex	44	2.46	2.89	117.9	0.43[b]	0.29	67.1
Level-concave	51	3.97	4.52	114.1	0.56[c]	0.33	59.4

[a] Units = kg N ha^{-1} d^{-1}.

[b] Means with the same letter indicates no significant difference exists (LSD, $\alpha = 0.05$).