Field-Scale Variability of Soil Properties in Central Iowa Soils

C. A. Cambardella,* T. B. Moorman, J. M. Novak, T. B. Parkin, D. L. Karlen, R. F. Turco, and A. E. Konopka

ABSTRACT

Spatial distributions of soil properties at the field and watershed scale may affect yield potential, hydrologic responses, and transport of herbicides and NO_3^- to surface or groundwater. Our research describes field-scale distributions and spatial trends for 28 different soil parameters at two sites within a watershed in central Iowa. Two of 27 parameters measured at one site and 10 of 14 parameters measured at the second site were normally distributed. Spatial variability was investigated using semivariograms and the ratio of nugget to total semivariance, expressed as a percentage, was used to classify spatial dependence. A ratio of <25% indicated strong spatial dependence, between 25 and 75% indicated moderate spatial dependence, and >75% indicated weak spatial dependence. Twelve parameters at Site one, including organic C, total N, pH, and macroaggregation, and four parameters at Site two, including organic C and total N, were strongly spatially dependent. Six parameters at Site one, including biomass C and N, bulk density, and denitrification, and 9 parameters at Site two, including biomass C and N and bulk density, were moderately spatially dependent. Three parameters at Site one, including NO_3^- N and ergosterol, and one parameter at Site two, mineral-associated N, were weakly spatially dependent. Distributions of exchangeable Ca and Mg at Site one were not spatially dependent. Spatial distributions for some soil properties were similar for both field sites. We will be able to exploit these similarities to improve our ability to extrapolate information taken from one field to other fields within similar landscapes.

An understanding of the distributions of soil properties at the field and watershed scale is important for refining agricultural management practices and for assessing the effects of agriculture on environmental quality. The level of variability associated with any estimate of a soil property will require an associated estimate of the variability of that property for a scale that is pertinent to the research question being considered. Soil classification and survey have been the most commonly used approaches for partitioning variation at the field and watershed scale (Trangmar et al., 1985). Soil survey data typically contain little information relevant to biochemical processes in soil.

Soil surveys generate maps of soil classes, where the average values of soil properties are estimated within a defined region or mapping unit (Webster, 1985). Values for soil properties are predicted for the majority of locations in the region where the values are not actually measured (Burgess and Webster, 1980). The variability of soil properties within fields is often described by classical statistical methods, which assume that variation is randomly distributed within mapping units. Soil variability is the outcome of many processes acting and interacting across a continuum of spatial and temporal scales and is inherently scale-dependent (Parkin, 1993). In addition, soil properties frequently exhibit spatial dependency. Generally, samples collected close to one another are more similar than samples collected at greater distances. Therefore, parametric statistics are inadequate for analysis of spatially dependent variables because they assume that measured observations are independent in spite of their distribution in space (Hamlett et al., 1986).

Geostatistical analyses have been used to estimate spatial variability of soil physical properties (Viera et al., 1981; Lascano and Hatfield, 1992), soil biochemical properties (Bonmati et al., 1991; Sutherland et al., 1991), pesticide distribution in soil (Rao and Wagenet, 1985; Wood et al., 1987), soil microbiological processes (Aiken et al., 1991; Rochette et al., 1991), and ecological parameters (Robertson, 1987; Rossi et al., 1992). Published research papers typically present information on the spatial variability of a single parameter or, at most, several parameters measured at one location. There is little information in the literature that presents a description of the spatial variability of a comprehensive list of soil parameters known to affect important biochemical processes in soil measured at multiple locations.

The objectives of this study were to describe the field-scale spatial variability of biological, chemical, and physical parameters known to affect soil biochemical processes and to define spatial classes of variables based on interpretation of geostatistical parameters.

MATERIALS AND METHODS

Site and Soil Description

The study was conducted on two farmer-operated fields located at the northwestern end of the Walnut Creek watershed in southern Boone County, Iowa. Soils within the Walnut Creek watershed were formed predominantly in calcareous glacial till deposited within the Des Moines Lobe during the Cary substage of glaciation, approximately 14 000 yr ago (Andrews and Dideriksen, 1981). The area is characterized by low relief swell and swale topography, and surface drainage is poorly developed due to the low relief and the area's geologic youth. Numerous closed depressional areas, commonly called potholes, exist that have accumulated material from surrounding sideslopes. Soils are predominantly the Clarion–Nicollet–Canisteo soil association. This association consists of well-drained Clarion soils located on higher or sloping areas, somewhat poorly drained Nicollet soils located on side slopes, Canisteo soils on poorly drained low areas, and very poorly drained Okoboji and Harps soils in the depressional areas (Soil Conservation Service, 1981). The soils that have been mapped are Canisteo silty clay loam (fine-loamy, mixed [calcareous],

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Abbreviations: EC, electrical conductivity; HPLC, high pressure liquid chromatograph; POM, particulate organic matter; CV, coefficient of variation.

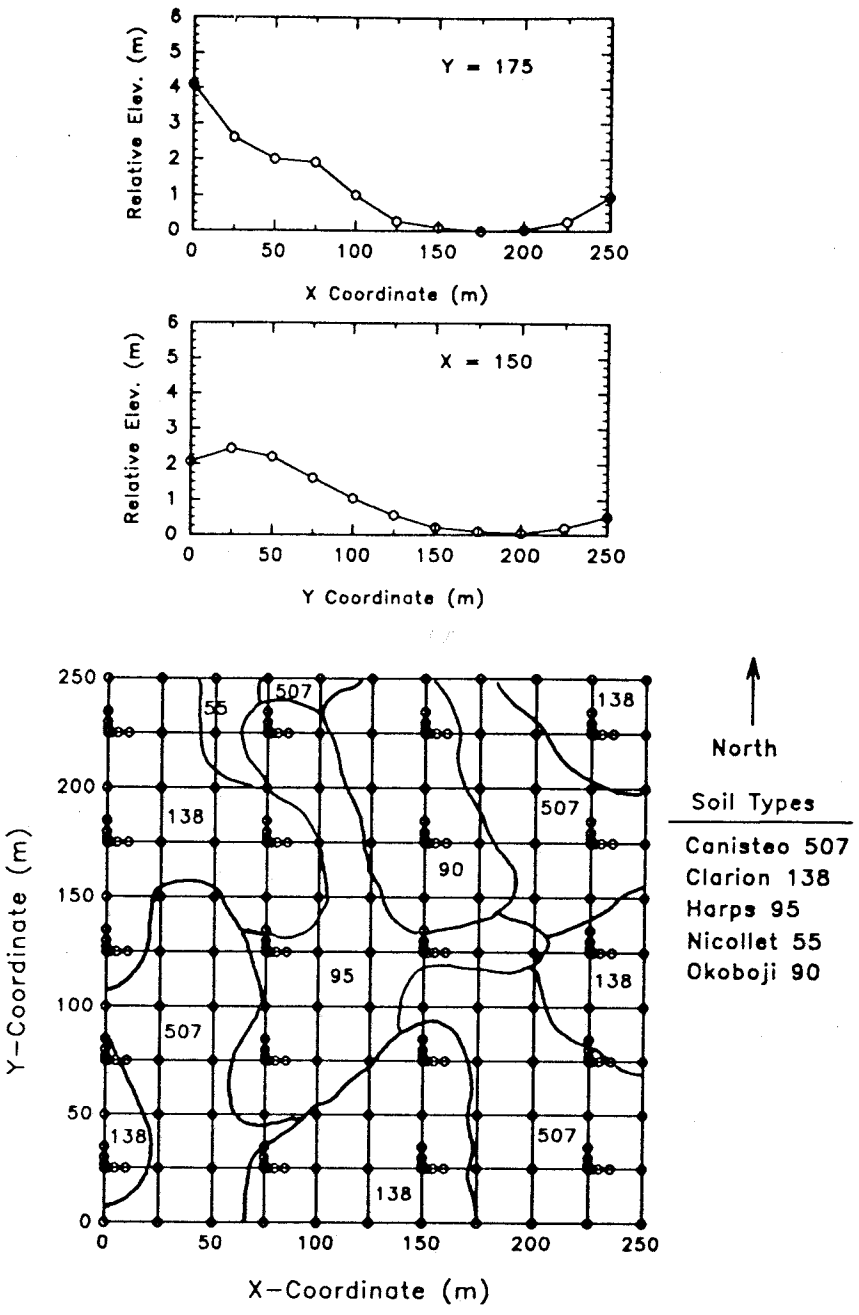

Fig. 1. Relative elevations across two transects of the pothole field and the sampling grid in relation to soil map units. A large depressional area is centered at approximate coordinates of (175,175); a smaller depressional area is at (250,0). The highest point in the grid is at (0,175). Open circles signify grid sampling points.

mesic Typic Haplaquoll), Clarion loam (fine-loamy, mixed, mesic Typic Hapludoll), Harps loam (fine-loamy, mesic Typic Calciaquoll); Nicollet loam (fine-loamy, mixed, mesic Aquic Hapludoll), and Okoboji mucky silt loam (fine, montmorillonitic, mesic Cumulic Haplaquoll) (Andrews and Dideriksen, 1981).

The first field has an area of 36 ha and is cropped to corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.]. Tillage is done in the fall with a chisel plow, and weeds are controlled with a combination of cultivation and herbicides. Anhydrous NH_3 fertilizer is applied in the fall. Unusually wet weather late in the fall of 1991 delayed the application of fertilizer until 5 Apr. 1992. Corn residue has been removed from the field in the fall after harvest since 1980. The field has an elevation gradient of 4.05 m from the lowest to the highest point and contains one drained and one undrained pothole. We will refer to this site as the pothole field.

The second site is located ≈2 km directly north of the pothole field and covers an area of 96 ha. The elevation gradient across the field is 4.24 m. Until 1991, this field had been under similar management practices as the pothole field except that corn residue was not removed. Since 1991, the field has not been chiseled because the farmer–operator began the transition to no-tillage. We will refer to the second field site as the no-till field. The no-till field was cropped to soybean in 1992 and no fertilizer was applied.

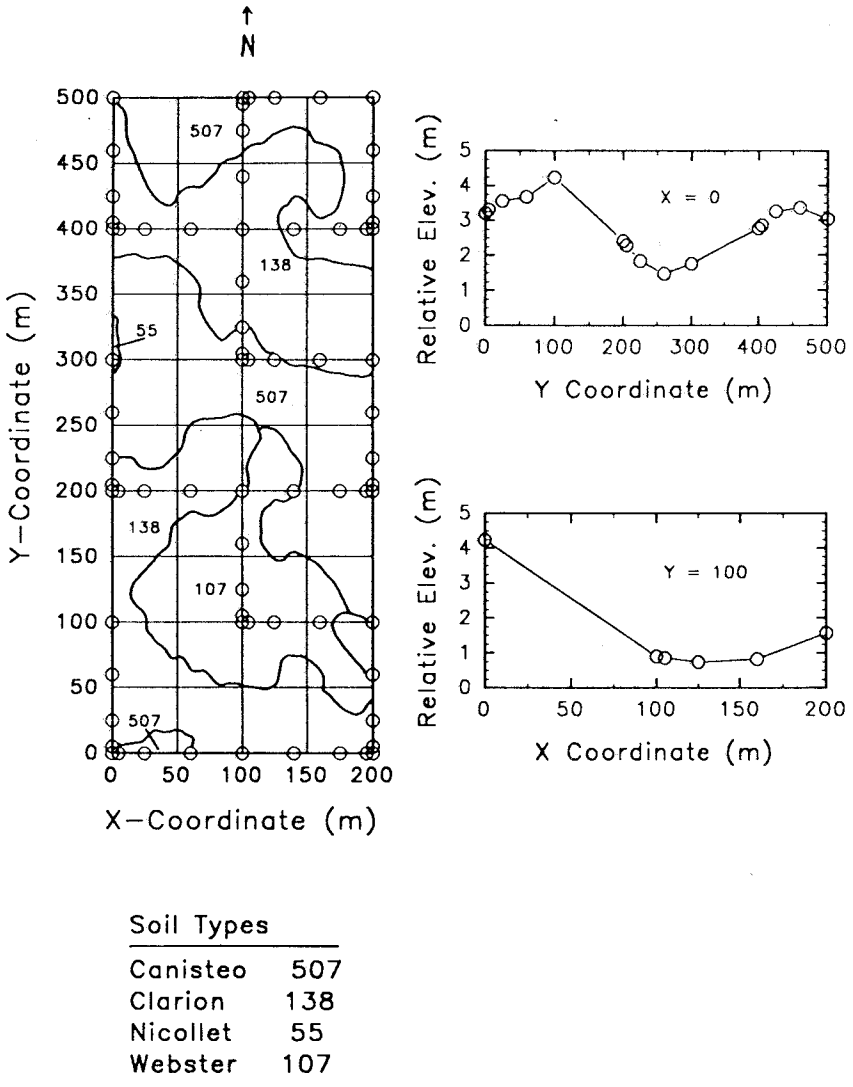

Fig. 2. Relative elevations across two transects of the no-till field and the sampling grid in relation to soil map units. The highest point on the grid is at (0,100), and the lowest is at (200,500). Drainage is generally from west to east. Open circles signify grid sampling points.

Sample Collection

Pothole Field

We established a 250 by 250 m square sampling grid (6.25 ha) on the southeast corner of the pothole field in the last week of April 1992 just before corn planting (Fig. 1). The grid encompassed soils formed in summit, backslope, and depression landscape positions. The grid pattern consisted of main intersection points separated by a distance of 25 m and secondary points at 2-, 5-, and 10-m intervals to produce a total of 241 sampling points. Each grid point was surveyed using a rod and transit to determine elevations.

Three randomly located soil cores were collected to a depth of 15 cm from within a 1-m circle around each grid point using a 6-cm i.d. coring tool. The three cores from each grid point were composited and stored in plastic bags for transport back to the laboratory.

Separate intact cores were removed from the main intersection points of the grid (121 samples) for estimates of denitrification and respiration. The cores were obtained by pounding a steel coring tube (5 cm i.d.) containing a plastic cylinder insert into the ground to a depth of 15 cm. The plastic insert was then removed from the coring tube and stoppered at both ends for transport back to the laboratory.

No-Till Field

Following soybean harvest in mid-October of 1992, a 200 by 500 m rectangular sampling grid (10 ha) was established on the southeast corner of the no-till field (Fig. 2). Elevation for each grid point was surveyed using a rod and transit. The grid encompassed soils formed in summit, backslope, and depressional landscape positions. The grid pattern consisted of main intersection points separated by a distance of 100 m and secondary points at 5-, 25-, and 60-m intervals to produce a total of 72 sampling points.

Four randomly located soil cores were collected in two depth increments (0–7.5 and 7.5–15 cm) to a depth of 15 cm with a 8-cm i.d. coring tube using a Giddings hydraulically driven soil coring unit (Giddings Machine Co., Ft. Collins, CO[1]). The cores were collected from the southeast quadrant

[1] Reference to trade names and companies is made for information purposes only and does not imply endorsement by the USDA or Purdue Univ.

of a 3-m-diam. circle around each grid point. The four cores from each grid point were composited and stored in plastic bags for transport to the laboratory. Values were summed for both depths.

Laboratory Methods

Bulk density was estimated using the core method (Blake and Hartge, 1986). Field-moist samples were pushed through an 8-mm-diam. sieve, and water content was determined gravimetrically after oven drying at 105°C overnight. A subsample was dried at 40°C and stored at room temperature prior to analysis. Another subsample was air dried, passed through a 2-mm-diam. sieve, and stored at room temperature prior to analysis. The remainder was stored moist at 4°C. All data were expressed on an oven-dry weight basis.

Denitrification and CO_2 production rate measurements of the intact cores from the pothole field were begun immediately upon returning to the laboratory. Denitrification rates were estimated by a C_2H_2 block technique (Parkin and Robinson, 1989). The gas samples were analyzed for N_2O with an electron capture detector-gas chromatograph, and CO_2 was determined with a gas chromatograph equipped with a thermal conductivity detector.

Soil pH, EC, and texture were determined for the air-dried 2-mm-sieved samples. The pH and EC were measured at a soil to solution ratio of 1:2. Particle size analysis was performed using a modification of the micro-pipette method of Miller and Miller (1987).

Soil organic matter fractions were isolated from the 2-mm sieved air-dried samples according to methods described by Cambardella and Elliott (1992). Total organic C (after removal of carbonates with 1 *M* H_2SO_4), total N, POM C and N, and mineral-associated C and N were measured using dry combustion methods in a Carlo-Erba NA1500 NCS elemental analyzer (Haake Buchler Instruments, Paterson, NJ).

Field-moist, 8-mm-sieved soil subsamples were extracted with 2 *M* KCl, and inorganic N [(NO_3 + NO_2) and NH_4] in the filtrate was determined using flow injection technology (Lachat Instruments, Milwaukee, WI). Mineralizable N was measured for the 2-mm-sieved, air-dried subsamples using methods described by Keeney and Bremner (1967).

Wet aggregate stability was assessed for air-dried samples according to methods described by Cambardella and Elliott (1993). Macroaggregation was calculated as the percentage of the total soil that was >250 μm in diameter (Tisdall and Oades, 1982).

Ergosterol extraction and measurement followed the procedure of Grant and West (1986) with minor modifications using field-moist 8-mm-sieved soil samples. Ergosterol was analyzed using a Hewlett Packard 1090A HPLC (Palo Alto, CA) equipped with a photodiode array detector (Eash, 1993).

Soil microbial biomass C and N were measured by fumigation and direct extraction with 0.5 *M* K_2SO_4 on duplicate 8-mm-sieved field-moist samples (Tate et al., 1988). Organic C in the fumigated and nonfumigated extracts was measured using a Dohrmann DC-180 carbon analyzer (Rosemount Analytical Services, Santa Clara, CA) calibrated with potassium phthalate standards. Biomass C was calculated using the correction factor (k = 0.33) of Sparling and West (1988). Total N was measured in the fumigated and nonfumigated extracts using Lachat flow-injection analysis (Lachat Instruments, Milwaukee, WI) following wet oxidation with the addition of Devarda's alloy to reduce NO_3–N to NH_4–N (Brooks et al., 1985a). Biomass N was calculated using equations presented in Brooks et al. (1985b) with a correction factor of 0.54.

Microbial biomass was also estimated by an alternative method that quantifies microbial phospholipid phosphate (Findlay et al., 1989). Phospholipids were extracted with a buffered solution of chloroform and methanol. The lipid-associated phosphate was hydrolyzed at 95°C in potassium persulfate after evaporation of the organic solvent, and the resultant phosphate concentrations were measured colorimetrically using ammonium molybdate and malachite green reagents.

Dehydrogenase assays were performed on field-moist soils that had been stored at 4°C. Soils were sieved (2 mm) and treated with $CaCO_3$ (Tabatabai, 1982). Triplicate 6-g subsamples were treated with a solution containing 100 mg mL^{-1} of yeast extract and 300 mg mL^{-1} of 2,3,5-triphenyltetrazolium chloride and incubated 24 h at 37°C. Triphenyl formazan was extracted with methanol and measured spectrophotometrically. The average recovery of triphenyl formazan added to soil and immediately extracted was 80%.

Atrazine (2-chloro-4-ethylamino-6-isopropylamino-1,3,5 triazine) sorption was determined on duplicate 4-g samples of 2-mm-sieved air-dry soil. Soil was equilibrated with 15 mL of solution containing 1.5 mg atrazine L^{-1} dissolved in 0.01 *M* $CaCl_2$ for 72 h, then centrifuged. Atrazine concentration in the equilibrium solution was analyzed using HPLC (J.M. Novak, 1993, personal communication).

Extractable P (Bray P1) (Knudsen and Beegle, 1988) and 1 *M* exchangeable K, Ca, and Mg (Brown and Warncke, 1988) were measured for each dried, 2-mm-sieved sample. Phosphorous concentrations were measured colorimetrically using ascorbic acid–ammonium molybdate reagents with a flow-injection analyzer (Lachat Instruments, Milwaukee, WI). The cations were measured using atomic absorption spectrophotometry.

Crop residue was estimated by removal of all surface residue from a 0.60-m^2 circular area at each grid point at the no-till field. Residue was removed from the same quadrant around the grid point as the soil cores. Residue amount was reported as grams of oven-dried residue per square meter of surface area.

Statistical Methods

Statistical analysis of the data was done in three stages: (i) frequency distributions were examined and background normality tests were conducted; (ii) the distributions were described using traditional summary statistics (mean, standard deviation, and CV) and with the median and interquartile range, which are less influenced by skewed distributions; and (iii) semivariograms were defined and differences in nugget and total semivariance and range examined for the variables.

Normality tests were conducted using the procedures of D'Agostino et al. (1990), which provides a rigorous chi-square test (K^2) for the combined effects of skewness and kurtosis. Non-normal data were log-transformed to stabilize the variance, and the normality tests were recalculated using the transformed data.

Geostatistical software (GS+, Gamma Design Software, St. Plainwell, MI) was used to analyze the spatial structure of the data and to define the semivariograms. Semivariance was calculated for log-transformed data to minimize the effects of extreme outliers. Semivariance calculations at the pothole field were based on a maximum lag distance of 125 m, which was divided into 31 lag distance classes separated by an average of 4 m. Each lag distance class contained at least 40 pairs of points for the calculation of semivariance and most distance classes contained at least 100 pairs of data points. At the no-till field, the maximum lag distance was set at 200 m, which

Table 1. Descriptive statistics for variables within the pothole field grid (250 by 250 m) to a depth of 0.15 m.

Variable†	*n*	Mean	Standard deviation	CV‡	Median	Interquartile range	Min.	Max.	K^2
OC, g m^{-2}	241	5377	1646	31	5207	2766	2731	9058	48.1§
TN, g m^{-2}	241	454	137	30	431	161	198	986	26.7§
MAC, g m^{-2}	241	4073	1275	31	3950	2083	2057	8173	13.1§
MAN, g m^{-2}	241	330	88	27	316	116	187	588	18.4§
POM C, g m^{-2}	241	1326	678	51	1237	940	77	4329	26.5§
POM N, g m^{-2}	241	127	74	58	116	93	10.5	548	91.0§
MBC, g m^{-2}	241	76	27	36	72	37	18	172	16.0§
MBN, g m^{-2}	241	13.3	6.12	46	13	7.95	0.41	39	25.0§
ERG, g m^{-2}	119	0.50	0.28	55	0.43	0.29	0.13	1.64	52.9§
MBP, μg PO_4 m^{-2}	241	2.07	0.78	38	1.88	0.85	0.54	6.84	117§
Respiration, g CO_2-C m^{-2} d^{-1}	121	3.46	6.42	185	1.93	1.25	0.57	37.54	134§
Denitrification activity, mg N m^{-2} d^{-1}	121	105	170	162	25	114	0.3	764	64.0§
Min N, g m^{-2}	241	1.9	10.9	585	2.0	8.9	−34.8	54.2	26.2§
K_d, L kg^{-1}	241	4.95	2.28	46	4.59	2.95	1.39	14.92	42.4§
K_{OC}	241	180	52	29	175	62	85	424	58.0§
NO_3-N, g m^{-2}	241	4.95	3.37	68	3.90	3.60	0.20	20.20	101§
Bray 1 P, g m^{-2}	241	25	11	43	26	16	0.20	56	2.83
K, g m^{-2}	241	37	13	35	33	15	17	83	46.2§
Mg, g m^{-2}	241	94	70	74	84	41	43	1089	483§
Ca, g m^{-2}	241	666	327	49	599	467	36	2950	118§
D_b, g cm^{-3}	121	1.32	0.18	14	1.33	0.27	0.86	1.61	7.85§
pH, log[H^+]	241	6.25	0.78	13	6.01	1.23	5.06	8.00	28.6§
EC, μS cm^{-1}	241	145	74	51	131	95	36	414	38.1§
Sand, %	241	33	12	37	33	18	3	58	8.14§
Silt, %	241	34	13	37	31	14	12	72	27.0§
Clay, %	241	33	13	39	31	16	6	66	5.87
Macroaggregation, %	241	59	9	15	59	12	26	82	6.89§

† OC = total organic carbon; TN = total nitrogen; MAC and MAN = mineral-associated (silt + clay) carbon and nitrogen; Min N = mineralizable N; POM C and POM N = particulate organic matter carbon and nitrogen; MBC and MBN = microbial biomass carbon and nitrogen; ERG = ergosterol; MBP = microbial lipid P; K_d = sorption coefficient (atrazine); K_{OC} = K_d ÷ % OC; D_b = bulk density; and EC = electrical conductivity.
‡ CV = coefficient of variation (%).
§ Data not normally distributed (α = 0.05).

resulted in 13 lag distance classes separated by an average of 15 m. Between 27 and 175 pairs of points were used in the semivariance calculations. Selection of models for semivariograms was made principally on visual fit and r^2 of the regression.

RESULTS AND DISCUSSION

The majority of soil parameters measured at the pothole field were highly skewed and non-normally distributed (Table 1). Extractable P and clay content were the only variables that were normally distributed. Total N, mineral-associated C and N, POM C and N, microbial biomass C, NO_3^-–N, bulk density, and residue amount were normally distributed at the no-till field (Table 2). The underlying reasons for normal and non-normal distributions of some of these variables at the two sites are unknown, but management and temporal effects seem to be likely causes. The highly skewed distribution of NO_3^- at the pothole field may be due to application of N fertilizer several weeks prior to sampling. High concentrations of NO_3^- could be expected in the application bands, causing the skewed distribution with large concentrations of NO_3^- in the minority of samples. Rapid microbial turnover of labile organic C and N in the early

Table 2. Descriptive statistics for variables within the no-till field grid (200 by 500 m) to a depth of 0.15 m.

Variable†	*n*	Mean	Standard deviation	CV‡	Median	Interquartile range	Min.	Max.	K^2
OC, g m^{-2}	72	4710	1040	22	4493	1335	2499	7967	6.98§
TN, g m^{-2}	72	417	69	17	413	85	240	582	0.37
MAC, g m^{-2}	72	3387	788	23	3271	1047	1856	5670	7.85§
MAN, g m^{-2}	72	248	53	21	239	75	140	415	2.55
POM C, g m^{-2}	71	1361	563	41	1266	779	160	2946	2.01
POM N, g m^{-1}	71	172	55	32	172	76	43	316	0.065
MBC, g m^{-2}	72	60	19	32	58	26	24	109	4.59
MBN, g m^{-2}	72	10.7	7.1	66	9.4	6.7	2.64	57	98.9§
NO_3-N, g m^{-2}	72	1.22	0.23	19	1.21	0.290	0.77	1.86	2.68
Min N, g m^{-2}	72	7.54	1.81	24	7.43	2.13	3.14	17.23	50.4§
Dehydrogenase activity, μg TPF g^{-1} h^{-1}	72	3.40	1.6	48	2.99	2.28	0.89	8.00	6.62§
D_b.d1, g cm^{-3}	72	1.032	0.18	17	1.030	0.245	0.660	1.148	0.70
D_b.d2, g cm^{-3}	72	1.241	0.16	13	1.265	0.255	0.890	1.570	3.66
Residue, g m^{-2}	72	514	186	36	493	259	0	893	0.09

† OC = total organic carbon; TN = total nitrogen; MAC and MAN = mineral-associated (silt + clay) carbon and nitrogen; Min N = mineralizable N; POM C and POM N = particulate organic matter carbon and nitrogen; MBC and MBN = microbial biomass carbon and nitrogen; D_b.d1 = bulk density (0–7.5 cm); D_b.d2 = bulk density (7.5–15 cm); and Residue = amount of residue.
‡ CV = coefficient of variation (%).
§ Data not normally distributed (α = 0.05).

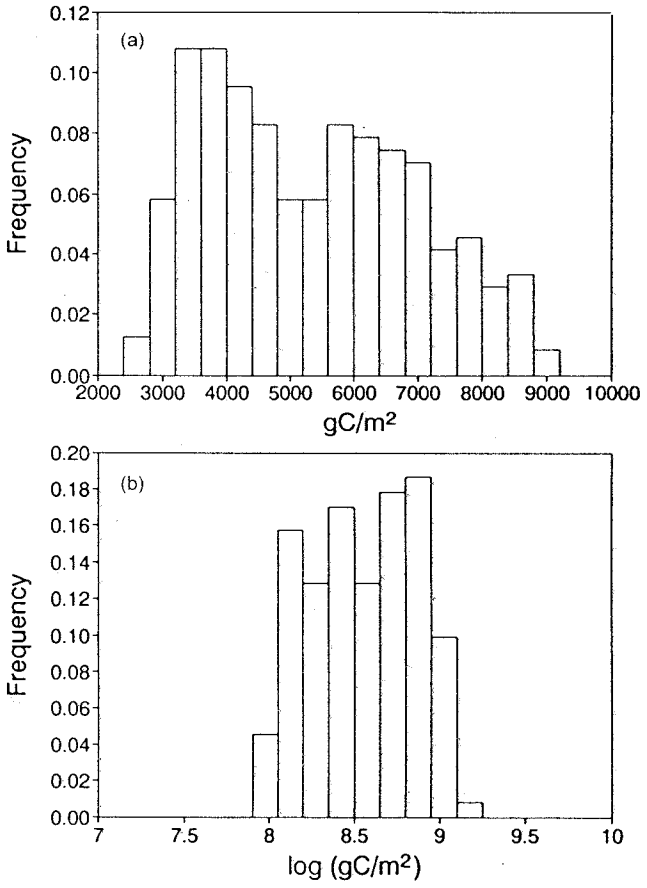

Fig. 3. Frequency distribution of (a) total organic C and (b) log-transformed total organic C at the pothole field.

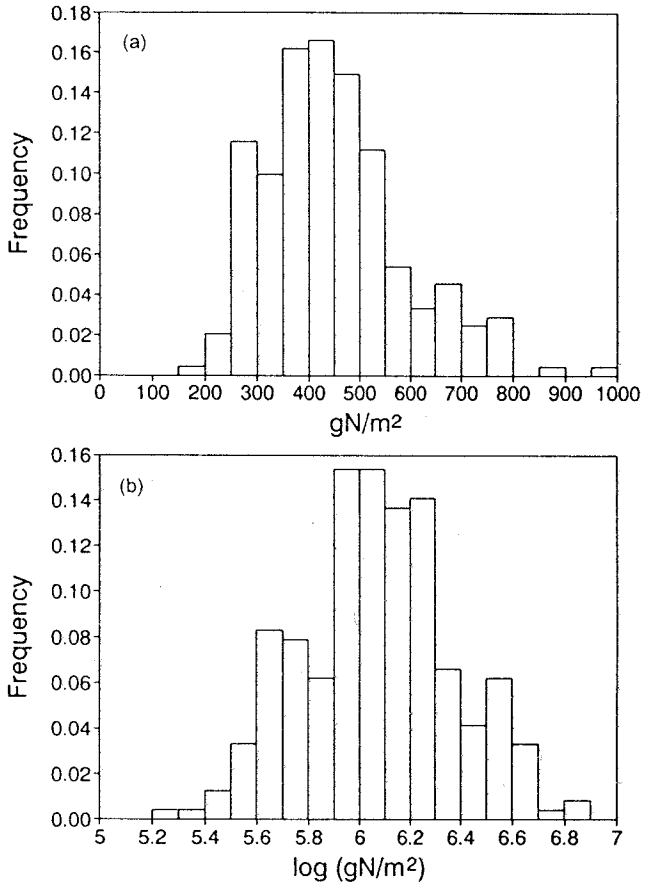

Fig. 4. Frequency distribution of (a) total N, and (b) log-transformed total N at the pothole field.

spring may have resulted in spotty areas of intense microbial activity, which could account for the skewed distributions for microbial biomass C and N and POM C and N. Presumably, these distributions become more normal as the season progresses.

Many soil parameters having skewed distributions have been reported to be log-normally distributed (Parkin and Robinson, 1992). Log transformations normalized some of the parameters and generally reduced skewness, but the K^2 test indicated that many variables remained non-normal after log transformation (data not shown). Frequency plots of organic C measurements from the pothole field before (Fig. 3a) and after (Fig. 3b) log-transformation show reduced skewness, but the distribution is still kurtotic. Log transformation of the data for total N produced a normal distribution, as illustrated by the frequency plots before (Fig. 4a) and after (Fig. 4b) transformation. When a variable did not pass normality tests after log transformation, a failure to reduce kurtosis occurred more often than a failure to reduce skewness.

The mean and median were used as the primary estimates of central tendency, and the standard deviation, CV, and interquartile range were used as estimates of variability (Tables 1 and 2). Despite the skewness of the distributions, the mean and median values for most parameters were similar, with the medians having smaller values than the means. This indicates that the measures of central tendency are not dominated by the outliers in the distributions. A similarity of means and medians were reported by Lascano and Hatfield (1992) for daily soil water evaporation, natural soil ^{15}N abundance (Sutherland et al., 1991) and natural soil denitrification rates (Parkin et al., 1987) measured at the landscape scale. However, Parkin et al. (1987) also reported occasional differences in the mean and median values for denitrification. They attribute this difference to the presence of localized areas with extremely high rates of denitrification.

Mean and median estimates of organic C, total N, mineral-associated organic C and N, POM C and N, and microbial biomass C and N were similar for the two field sites. Mean and median values for NO_3^--N and mineralizable N were lower at the no-till field compared with the pothole field, and variability for all soil parameters was higher at the pothole field (Tables 1 and 2). Seasonal fluctuations as well as the removal of corn residue may contribute to the observed higher variability at the pothole field. The higher values for NO_3^--N at the pothole field are probably due, in part, to the application of N fertilizer several weeks before sampling.

The fields were not selected to behave as identically replicated units, although they both are fairly representative of the geomorphology and agricultural practices of the local area. It is not possible with the sampling and statistical methods utilized in this study to discriminate between intrinsic and extrinsic sources of variability.

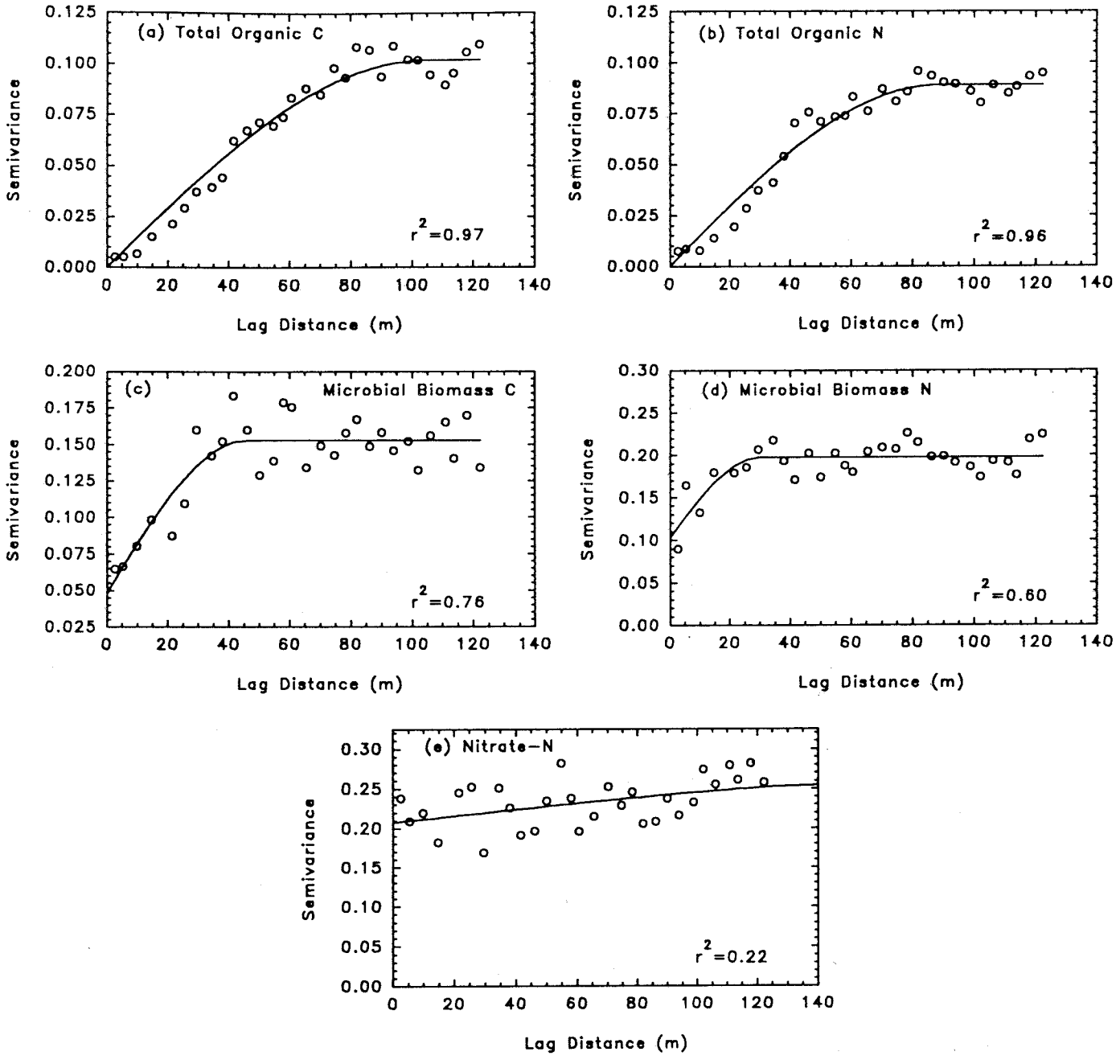

Fig. 5. Semivariograms for soil parameters at the pothole field: (a) organic C, (b) total N, (c) microbial biomass C, (d) microbial biomass N, and (e) NO_3^--N.

Intrinsic variability is due to natural variations in soils, and extrinsic variability is that imposed on a field as part of the crop production practices (Rao and Wagenet, 1985). Our results also probably reflect the influence of temporal dynamics on the measured parameters due to the spring sampling of the pothole field and fall sampling of the no-till field. Our sampling and statistical methods were not designed to assess temporal effects.

The soil properties displayed differences in their spatial dependence, as determined by their semivariograms (Fig. 5 and 6). Semivariance ideally increases with distance between sample locations, or lag distance (h), to a more or less constant value (the sill or total semivariance) at a given separation distance, called the range of spatial dependence. Samples separated by distances closer than the range are related spatially, and those separated by distances greater than the range are not spatially related. Semivariogram ranges depend on the spatial interaction of soil processes affecting each property at the sampling scale used (Trangmar et al., 1985). The semivariance at $h = 0$ is called the nugget variance (Webster, 1985). It represents field and experimental variability, or random variability, that is undetectable at the scale of sampling. Our sampling schemes were designed to allow the calculation of semivariance at small values of h relative to the size of the sampling grid.

There was no anisotropy evident in the directional semivariograms for any of the soil properites. Therefore,

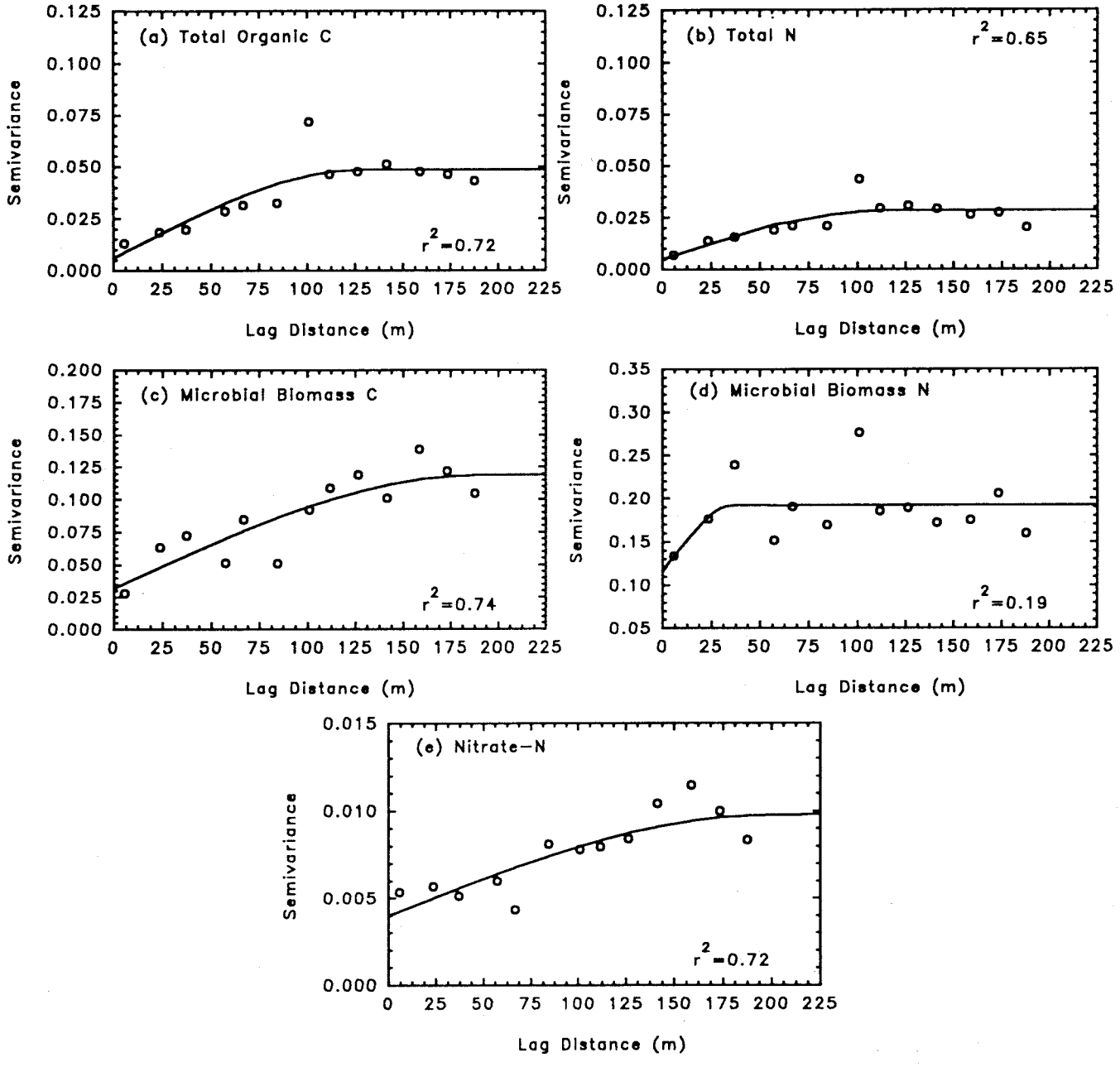

Fig. 6. Semivariograms for soil parameters at the no-till field: (a) organic C, (b) total N, (c) microbial biomass C, (d) microbial biomass N, and (e) NO_3^--N.

isotropic models for the semivariograms were fitted using nonlinear least-squares regression analysis. Spherical models were defined for all soil variables measured at both sites, except for Ca and Mg at the pothole field and POM C at the no-till field. In a few instances, where differences in r^2 were <0.05 between the spherical and alternative models, the spherical model was used to allow direct comparison of the nugget, sill, and range values among different soil parameters. In these cases, the alternative models generated estimates of nugget and total semivariance that were similar to the spherical model. Calcium and Mg were described by linear semivariograms (Table 3), which suggests that as the spatial distance between two samples increases, the difference between the two samples will also increase. If the linear model has a slope that is close to zero, then the total variance is equal to the nugget variance and the variables are described as spatially independent and completely random. Particulate organic matter C at the no-till field was defined by an exponential model. Soil properties have been found to fit both spherical and exponential models. Exponential models do not exhibit a finite range value but, for practical purposes, there is a point beyond which the semivariance stops increasing (Webster, 1985).

The nugget semivariance expressed as a percentage of the total semivariance enables comparison of the relative size of the nugget effect among soil properties (Trangmar et al., 1985). We used this ratio to define distinct classes of spatial dependence for the soil variables as follows: if the ratio was ≤25%, the variable was considered strongly spatially dependent; if the ratio was

Table 3. Parameters for variogram models for pothole field grid.

Variable†	Model‡	Semivariance		Nugget§	Range	Spatial¶ class
		Nugget	Total			
				%	m	
OC	Spherical	0.0001	0.1020	0.098	104	S
TN	Spherical	0.0001	0.0890	0.11	89	S
MAC	Spherical	0.007	0.108	6.5	110	S
MAN	Spherical	0.010	0.071	14.1	96	S
POM C	Spherical	0.175	0.362	48.3	118	M
POM N	Spherical	0.040	0.420	9.5	22	S
MBC	Spherical	0.048	0.153	31.4	46	M
MBN	Spherical	0.103	0.198	52.0	30	M
ERG	Spherical	0.029	0.0324	89.5	270	W
MBP	Spherical	0.029	0.127	17.0	70	S
Respiration	Spherical	0.066	0.391	16.9	68	S
Denitrification activity	Spherical	1.85	3.31	55.9	75	M
K_d	Spherical	0.004	0.216	1.9	87	S
K_{OC}	Spherical	0.020	0.075	26.7	71	M
NO_3-N	Spherical	0.208	0.263	79.1	201	W
Min N	Spherical	68.6	119.5	57.4	38	W
Bray's P	Spherical	23.4	134.7	17.4	71	S
K	Spherical	0.022	0.089	24.7	62	S
Mg	Linear	0.171	>0.203	–	>125	R
Ca	Linear	0.253	>0.428	–	>125	R
D_b	Spherical	0.0132	0.0356	37.1	129	M
pH	Spherical	0.060	0.760	7.9	117	S
Macroaggregation	Spherical	6.9	77.4	8.9	77	S

† OC = total organic carbon; TN = total nitrogen; MAC and MAN = mineral-associated (silt + clay) carbon and nitrogen; Min N = mineralizable N; POM C and POM N = particulate organic matter carbon and nitrogen; MBC and MBN = microbial biomass carbon and nitrogen; ERG = ergosterol; MBP = microbial lipid P; K_d = sorption coefficient (atrazine); $K_{OC} = K_d \div$ %OC; D_b = bulk density.
‡ Models are all isotropic.
§ Nugget = (nugget semivariance/total semivariance) × 100.
¶ S = Strong spatial dependency (% Nugget <25); M = Moderate spatial dependency (% Nugget between 25 and 75); W = Weak spatial dependency (% Nugget >75); R = Random.

between 25 and 75%, the variable was considered moderately spatially dependent; and if the ratio was >75%, the variable was considered weakly spatially dependent. Semivariograms indicated strong spatial dependence for variables such as organic C (Fig. 5a and 6a), total N (Fig. 5b and 6b), pH, and macroaggregation (Tables 3 and 4). Strongly spatially dependent properties may be controlled by intrinsic variations in soil characteristics, such as texture and mineralogy. Another class of variables, such as ergosterol content and NO_3^--N at the pothole field (Table 3; Fig. 5e and 6e), was characterized by variograms with nugget/total semivariance ratios >75%. Extrinsic variations, such as fertilizer application and tillage, may control the variability of these weakly spatially dependent parameters. These parameters may exhibit spatial dependence at scales smaller than those used for these studies. The majority of measured properties exhibited moderate spatial dependency, characterized by microbial biomass C (Fig. 5c and 6c), microbial biomass N (Fig. 5d and 6d), bulk density, and dentrification (Tables 3 and 4).

Total semivariance estimates for soil parameters at

Table 4. Parameters for variogram models for no-till field grid.

Variable†	Model‡	Semivariance		Nugget§	Range	Spatial¶ class
		Nugget	Total			
				%	m	
OC	Spherical	0.0058	0.0488	11.9	129	S
TN	Spherical	0.0049	0.0285	17.2	115	S
MAC	Spherical	0.0175	0.0505	34.7	130	M
MAN	Spherical	0.038	0.048	79.1	486	W
POM C	Exponential	0.171	0.279	61.3	81	M
POM N	Spherical	0.047	0.135	35.3	24	M
MBC	Spherical	0.032	0.119	26.9	190	M
MBN	Spherical	0.116	0.192	60.4	37	M
NO_3-N	Spherical	0.0040	0.0098	40.8	201	M
Min N	Spherical	0.0065	0.0380	17.1	65	S
Dehydrogenase activity	Spherical	0.151	0.241	62.7	51	M
D_b.d1	Spherical	0.0106	0.0353	30.0	223	M
D_b.d2	Spherical	0.0064	0.0256	25.0	115	M
Residue	Spherical	0.0001	1.05	0.0095	63	S

† OC = total organic carbon; TN = total nitrogen; MAC and MAN = mineral-associated (silt & clay) carbon and nitrogen; Min N = mineralizable N; POM C and POM N = particulate organic matter carbon and nitrogen; MBC and MBN = microbial biomass carbon and nitrogen; ERG - ergosterol; MBP = microbial lipid P; D_b.d1 = bulk density (0–7.5 cm); D_b.d2 = bulk density (7.5–15 cm); and Residue = amount of residue.
‡ Models are all isotropic.
§ Nugget = (nugget semivariance/total semivariance) × 100.
¶ S = Strong spatial dependency (% Nugget <25); M = Moderate spatial dependency (% Nugget between 25 and 75); W = Weak spatial dependency (% Nugget >75).

the pothole field were consistently higher than those at the no-till field with the exception of microbial biomass N (Tables 3 and 4; Fig. 5 and 6). Variability, as assessed by parametric statistics, was also higher for the pothole field parameters compared with the no-till field parameters (Tables 1 and 2). Seasonal variations and extrinsic management effects, such as tillage and residue removal, probably contributed to the observed differences in semivariance and variability.

The range values showed considerable variability among the parameters measured at each field site (Tables 3 and 4). For instance, at the pothole field, organic C has a range value of 104 m and the range of microbial biomass C is 46 m. There were some similarities in range values for individual soil parameters measured at both field sites, but differences in range were encountered with the same frequency as similarities (Tables 3 and 4). Estimates of range tend to be landscape dependent and may be intrepreted to indicate the distance across distinct soil types (Webster, 1985). At our sites, spatially dependent parameters, such as organic C, total N, and pH, have range values exceeding 100 m, which indicates spatial relatedness that can bridge several soil map units. For example, at the pothole field (Fig. 1), large range values encompassing several map units appear to indicate that these soils are related to one another by their position on the landscape. Thus, Nicollet, Canisteo, and Harps soils may constitute transition zones between Okoboji and Clarion soil units in terms of soil biochemical similarities.

Geostatistical techniques offer alternative methods to conventional statistics for the estimation of parameters and their associated variability. Semivariance analysis demonstrated that there were similarities in the patterns of spatial variability for some of the soil parameters at both of our field sites. This suggests that spatial relationships derived from one set of measurements for one field may have applicability at other field sites within the same or similar landscapes. Because spatial relationships are strongly influenced by the scale of the investigation, it remains to be seen whether or not this approach will be useful for extrapolating spatial information obtained at the field scale to the watershed or regional scale.

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