1996

SPATIAL PATTERNS ANALYSIS OF FIELD MEASURED SOIL NITRATE

Farida Shaukat Goderya
University of Nebraska-Lincoln

Mohamed F. Dahab
University of Nebraska-Lincoln, mdahab1@unl.edu

Wayne E. Woldt
University of Nebraska-Lincoln, wwoldt1@unl.edu

Istvan Bogardi
University of Nebraska-Lincoln, ibogardi1@unl.edu

Goderya, Farida Shaukat; Dahab, Mohamed F.; Woldt, Wayne E.; and Bogardi, Istvan, "SPATIAL PATTERNS ANALYSIS OF FIELD MEASURED SOIL NITRATE" (1996). *Biological Systems Engineering: Papers and Publications*. 514.
http://digitalcommons.unl.edu/biosysengfacpub/514

In Geostatistics for Environmental and Geotechnical Applications (ASTM, 1996)

Farida S. Goderya[1], M. F. Dahab[2], W. E. Woldt[3], and I. Bogardi[2].

SPATIAL PATTERNS ANALYSIS OF FIELD MEASURED SOIL NITRATE

REFERENCE: Goderya, F. S., Dahab, M. F., Woldt, W. E., Bogardi, I., "**Spatial Patterns of Field Measured Residual Soil Nitrate,**" *Geostatistics for Environmental and Geotechnical Applications, ASTM STP 1283,* R. Mohan Srivastava, Shahrokh Rouhani, Marc V. Cromer, A. Ivan Johnson, Alexander J. Desbarats, Eds., American Society for Testing and Materials, 1996.

ABSTRACT: The purpose of this study was to assess the spatial variability of residual soil nitrate, measured in three contiguous 16 ha fields. Available data for residual soil nitrate were examined using conventional statistics. Data tended to be skewed with the mean greater than the median. Geostatistical methods were used to characterize and model the spatial structure. Three dimensional spatial variability was examined using two semivariograms: horizontal-spatial and vertical. Two dimensional horizontal-spatial semivariograms were also computed for each 0.3m (1ft) layer. Semivariogram analysis showed that there were similarities in the patterns of spatial variability for all fields. The results suggest that the spatial patterns in residual soil nitrate may be correlated with irrigation practices. Furthermore, a trend was found to be present along the vertical direction, which may be related to the time of sampling.

KEYWORDS: spatial variability, 3-D semivariogram, 2-D semivariogram, directional semivariogram, residual soil nitrate.

INTRODUCTION

Nitrate contamination in groundwater is often related to nitrogen fertilizer applied in excess of crop needs. Residual soil nitrate is frequently the largest source of inorganic N available to crops. The amount of nitrate in the soil profile is important for determining a fertilizer nitrogen recommendation that ensures sufficient nitrogen for crop production as well as preventing potential groundwater problems.

The origin and nature of soil resource variability includes natural and management induced soil parameters, and factors exhibiting variability in space and

---

[1] Graduate Research Assistant, and [2] Prof., Dept. of Civil Eng., University of Nebraska, Lincoln, NE 68588
[3] Assistant Prof., Dept. of Biological Systems Engineering, University of Nebraska, Lincoln, NE 68583.

time (Bouma and Finke 1992). It is an outcome of many processes acting and interacting over a continuum of spatial and temporal scales. Nitrate is a mobile nutrient, also, soil resource and meteorological variability obscures the contemplation of its spatial structure. For example, soil nitrate concentrations from individual samples are usually quite variable, in addition, the non-uniform distribution of irrigation water complicates the issue.

Classical statistical procedures have traditionally been used to assess the variability of various properties in soils (Biggar et al., 1973; Biggar and Nielsen 1976; Bresler 1989). The use of these techniques assumes that observations in the field are independent of one another, regardless of their location. However, there is a significant volume of literature in various disciplines such as geology (Davis, 1986; Journel 1989), mining (Guaracio et al., 1975; Isaaks and Srivastava 1989; Journel and Huijbregts 1978) and soil science (Beckett and Webster 1971; Dahiya et al., 1984; Bhatti et al., 1991), which shows that variations in geologic properties tend to be correlated across space. Thus, the classical methods may be inadequate for interpolations of spatially dependent variables, because it assumes random variation and does not consider spatial correlation and relative location of samples.

The geostatistical approach has received increasing attention in science and engineering during the last decade (Kalinski et al., 1993; Woldt et al., 1992; Woldt and Bogardi, 1992; Tabor et al., 1985; Berndtsson et al., 1993; Jury et al., 1987; Mulla 1988; Ovalles 1988; Rolston et al., 1989; Sutherland et al., 1991). The primary reasons for the adoption of geostatistics in various fields are that this methodology (1) provides an estimate for the minimum distance for the spacing of independent samples, (2) provides a basis for an efficient monitoring program from an initial reconnaissance survey, (3) allows the quantification of unbiased measurements of location and spread, (4) furnishes optimal, unbiased estimates of regionalized variables at unsampled locations, based on neighboring data, and (5) can also be used to characterize associated uncertainty using geostatistical simulations.

To date, we are not aware of any attempts to characterize the spatial variability of the residual soil nitrate using three dimensional spatial statistics. This information is necessary since the spatial variability in residual soil nitrates has been considered a major factor associated with inherent leaching of nitrate in many production agriculture situations.

The primary objective of this study is to measure quantitatively the spatial variability of residual soil nitrates in three fields. The hypothesis is that the variability of residual soil nitrate in a field contributes to the variability of leaching to the groundwater from the available soil-N pools. The analysis conducted in this study will be further utilized in the modeling of nitrate contamination to groundwater. The eventual goal of the project is to explore variable rate application methods by relating residual soil nitrates and other parameters to the amount of nitrate leaching to groundwater using geostatistical simulation and transport models.

METHODOLOGY

Samples from three contiguous 16 ha fields with differing management histories were used to determine the spatial variability of residual soil nitrates (Peterson and Schepers, 1992). Two fields are 396m x 426m, and one fields is 365m x 426m. Field data consist of residual soil nitrate measurements at each location on a 30.5m x 30.5m (100ft x 100ft) grid with a spacing of 20-40m from the boundaries. At each grid location, a single 5 cm (2-inch) diameter, 1.5m (5 ft) long soil core was collected and divided into 0.3 m(1 ft) increments. Hence, each layer in three separate fields contained 156, 156, and 143 points respectively. Each sample was analyzed separately and the results are reported as nitrate-nitrogen in 0.3 m (1 ft) depth increment. The data for each point were used to study the 3-dimensional and 2-dimensional spatial continuity of the residual soil nitrate.

Classical statistical parameters such as the mean, the standard deviation and the coefficient of variation were calculated for each layer. Statistical parameters for the overall three dimensional data sets (vertically averaged over core), as well as for profile (vertically integrated nitrate content for each hole), were also calculated.

Structural analysis of the field data was used to evaluate the semivariogram function using programs from GSLIB (Deutsch and Journel, 1993). Semivariograms (Journel and Huijbregts 1978) were used to examine the spatial dependence between measurements at pairs of locations as a function of distance of separation. Three dimensional spatial variability was examined for each of the fields using two semivariograms: horizontal-spatial semivariogram and vertical semivariogram. The semivariogram for horizontal spatially related data identifies the variability due to distance and is combined for all the depths. However, the vertical semivariogram describes the variabilities due to depth irrespective of horizontal location. Hence, for the available data set of each field, two semivariograms were constructed.

Two dimensional horizontal-spatial semivariograms also were calculated for each layer, that is for each 0.3 m (1 ft) layer, resulting in 5 different semivariograms for each field. Furthermore, a 2-dimensional horizontal semivariogram also was prepared for the vertically integrated nitrate content at each sample location.

In order to explore anisotropies, directional semivariograms were calculated for each field in the horizontal spatial direction, keeping the direction of the vertical dimension constant. They were prepared using the concept of layers, in which semivariograms were calculated in different spatial directions, by restricting the search window in the vertical dimension.

RESULTS AND DISCUSSION

Residual soil nitrate in the profile was highly variable, ranging from 64 to 650 kg/ha (57 to 580 lbs/acre) with a mean of 192 kg/ha (173 lbs/acre). Table 1 shows the statistical parameters for the three fields. For each layer, data tended to be skewed with the mean greater than the median. The general trend was toward an increase in the values of coefficient of variation and a decrease in the values of residual soil nitrogen with increasing depth. For overall 3-dimensional measurement values, the distribution of data was skewed with large coefficient of variation.

TABLE 1--Residual soil nitrate from three fields.

Field	Layer	Minimum (kg/ha)	Maximum (kg/ha)	Mean (kg/ha)	Median (kg/ha)	Std. dev (kg/ha)	C.V (%)
Field 1	1	19.35	239.9	84.95	81.45	41.18	48.47
	2	9.27	144.35	39.87	33.67	25.02	62.67
	3	8.06	125.0	30.63	24.6	20.46	66.79
	4	8.47	123.78	32.76	23.79	22.98	70.15
	5	7.66	95.57	29.73	23.79	18.85	63.39
	profile	68.14	650.76	217.94	198.17	96.24	44.16
	overall	7.66	239.90	43.6	31.85	34.09	78.20
Field 2	1	20.16	271.76	73.81	68.95	33.32	45.15
	2	9.27	117.33	35.87	30.64	20.05	57.16
	3	7.26	151.6	31.12	26.81	21.83	70.14
	4	7.66	157.65	28.10	22.18	21.26	75.64
	5	6.45	75.8	25.97	25.4	14.44	55.61
	profile	64.11	574.16	194.87	177.61	91.73	47.07
	overall	6.45	271.76	39.00	30.24	29.08	74.61
Field 3	1	17.34	160.47	72.71	67.33	30.53	41.99
	2	12.5	124.99	32.87	30.24	15.13	46.04
	3	6.85	75.4	25.51	23.79	11.93	46.78
	4	6.85	51.61	19.30	17.74	8.01	41.48
	5	5.24	43.55	14.86	13.31	6.67	44.87
	profile	65.72	362.48	165.25	156.44	51.68	31.27
	overall	5.24	160.50	33.01	24.60	26.70	80.7

** C.V Coefficient of Variation

The horizontal-spatial semivariograms are shown in Figures 1a, 2a and 3a for the three fields. The semivariograms for all three fields have similar shapes. Theoretically, the semivariogram should pass through the origin when the distance is zero. However, all sample semivariograms appeared to approach non-zero values as distance decreased to zero, indicating the presence of a nugget effect.

The vertical experimental semivariograms and the models fitted are shown in Figures 1b, 2b, and 3b. The maximum distance considered in the computation of the semivariogram cannot exceed half the maximum dimension of the field, (i.e. 0.75 m) for the vertical semivariogram (Journel and Huijbregts, 1975). Thus, only the first two values of the vertical semivariogram are reliable. All vertical semivariograms do not reach a sill, indicating a trend in the property studied. If the information contained in the semivariogram is to be used for kriging at unsampled locations, the trend may need to be removed, or universal kriging may be used. A reason for this trend is most probably related to the presence of high amounts of residual soil nitrate in the surface layer. Figure 4 shows the average amount of nitrate-N in each layer for the three fields. Significant differences between the top layer and subsequent layers may be related to the time of sampling. The results probably exhibit the influence of temporal dynamics due to the spring sampling of the fields. This may be because high mineralization and almost no precipitation/irrigation occurred at the time of sampling of these fields. For this reason, two different types of theoretical models were fitted to the vertical semivariograms; power and spherical models. If the data are to be used for simulation purposes, then the power model may not be used, and hence, another model should be used.

Fitting a model to the experimental semivariogram is a significant step in the geostatistical analysis. It is important to select an appropriate model for the semivariogram because each model yields different values for the nugget effect and range. A satisfactory fit to the sample variogram was accomplished by the trial and error approach as described by Isaaks and Srivastava (1989). Due to resource constraints only omni-directional horizontal spatial semivariograms and vertical semivariograms were fit to the sample variogram for each field. Table 2 provides the values of semivariogram models for the above mentioned cases. Parameters for the two types of theoretical semivariograms for the vertical direction also are provided in Table 2. Good agreement was obtained between calculated semivariogram values and the corresponding models, as shown in Figures 1, 2, and 3.

The range values for horizontal-spatial semivariograms showed considerable variability among the fields: the scale of horizontal-spatial correlation varies from about 150 m to 244 m (500 ft to 800 ft). The range of the semivariogram model for Field 1 was significantly larger than for the other two fields. In the vertical direction the range varied between 1.5 m to 3 m (5 ft to 10 ft). There was two orders of magnitude difference between the ranges of horizontal-spatial and vertical dimension. This represents a system in which the vertical plane is much smaller in scale than the horizontal plane. A typical approach employed for this system is to examine the transport process locally as a vertical one-dimensional flow perpendicular to any layering in the medium (Jury et al., 1987). The complete structural analysis for both the horizontal-spatial dimension and the vertical dimension represents a combination of geometric and zonal anisotropy. The complete structural analysis of hydraulic properties for both dimensions may show the same pattern.

There were no data available for lag distances less than 30 m (100 ft) in the

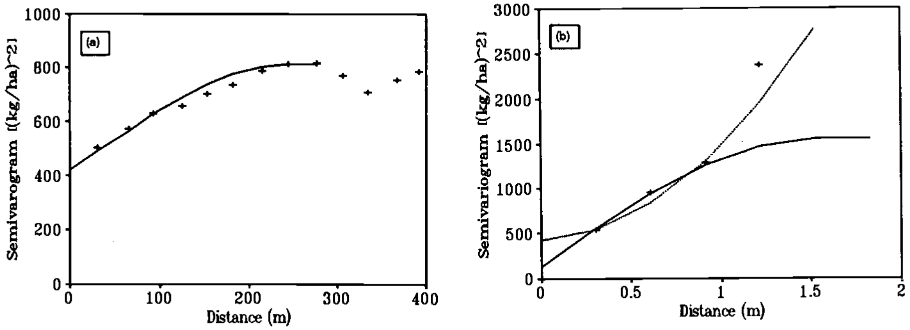

FIGURE 1--Experimental (symbols) and theoretical (lines) semivariograms for Field 1; (a) horizontal-spatial and (b) vertical, (—) spherical model and (···) power model.

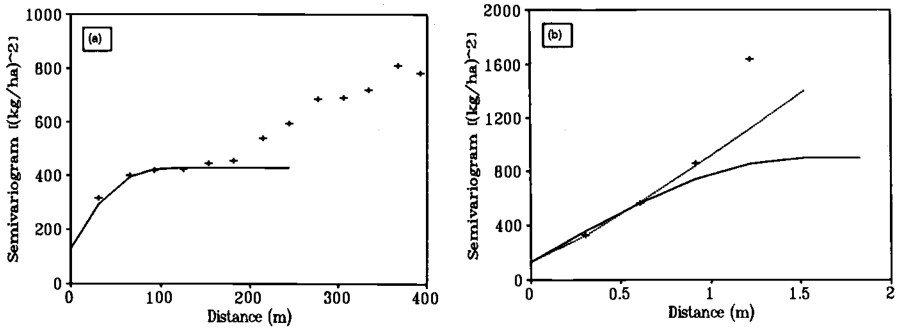

FIGURE 2--Experimental (symbols) and theoretical (lines) semivariograms for Field 2; (a) horizontal-spatial and (b) vertical, (—) spherical model and (···) power model.

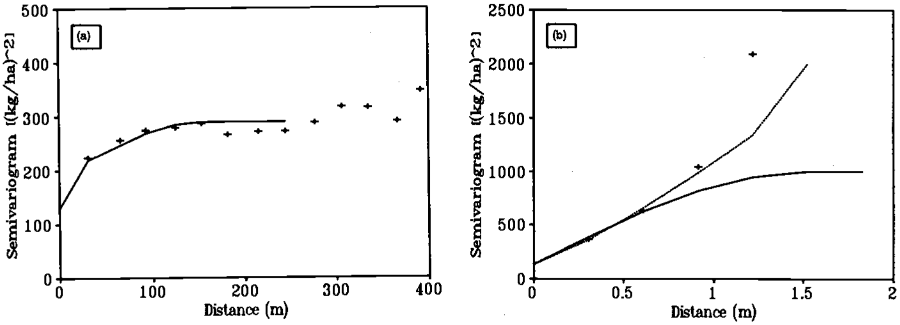

FIGURE 3--Experimental (symbols) and theoretical (lines) semivariograms for Field 3; (a) horizontal-spatial and (b) vertical, (—) spherical model and (···) power model.

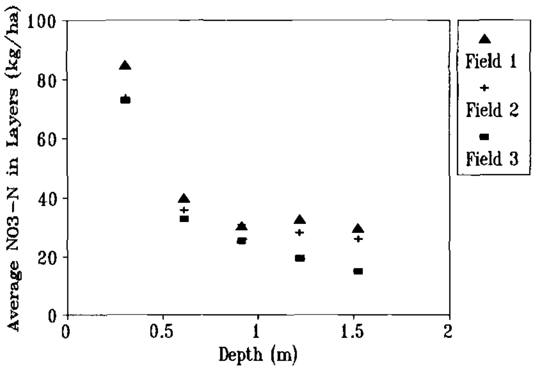

FIGURE 4--Amount of average residual soil nitrate in each layer.

TABLE 2--Semivariogram parameters of residual soil nitrates for three fields.

		Field 1	Field 2	Field 3
Horizontal-Spatial	Nugget $(kg/ha)^2$	420	130	130
	Sill $(kg/ha)^2$	810	330 (1) 430 (2)	190 (1) 290 (2)
	Range (m)	244	30.5 (1) 122 (2)	30.5 (1) 152.4 (2)
Vertical-Model 1	Nugget $(kg/ha)^2$	420	130	130
(Power)	Slope $(kg/ha)^2$	110	200	230
	Power	1.0	1.15	1.2
Vertical-Model 2	Nugget $(kg/ha)^2$	130	130	130
(Spherical)	Sill $(kg/ha)^2$	1550	900	1000
	Range (m)	1.5	1.5	1.5

** numbers in parenthesis refers to nested structures 1 and 2.

horizontal-spatial direction; hence, the nugget effect was estimated by visual inspection. There appears to be two different values for the nugget effect in the horizontal and the vertical directions for Field 1. The small nugget effect of the vertical semivariogram may be detected because of the small spacing between data points in the vertical direction. See Figures 1a and 1b.

Spatial variability can also be investigated using the semivariogram and the relative nugget effect, that is the ratio of nugget to total semivariance expressed as percentage. A ratio less than 25% indicates strong spatial dependence, between 25% and 75% indicates moderate spatial dependence, and greater than 75% indicates weak spatial dependence (Cambardella 1994). The horizontal-spatial semivariograms may be described as having moderate spatial dependence for residual soil nitrate. However, if one considers the spherical model for vertical semivariograms, then the vertical semivariograms may be characterized by strong spatial dependence; exhibiting ratios of less than 25%. Strong to moderate spatially dependent structures may be controlled by intrinsic and extrinsic variations as well as seasonal variations.

Two dimensional horizontal semivariograms are shown in Figures 5, 6, and 7. These semivariograms are calculated individually for each layer and also for the profile (i.e. the sum of amounts in all layers for each grid location), without any regard to the vertical dimension. If one compares the form of spatial variability of each individual layer with that of a profile, it is obvious that the form of the structure is similar to the top layer, indicating that the top layer structure is representative of the overall spatial structure. The large impact of the top layer semivariogram on the profile semivariogram is due to the larger variance of residual nitrate concentrations in the top layer relative to other layers (see Table 1). As a result, if one has to measure the field again or measure other fields with a similar structure, it may be appropriate to assess each location to a depth of 0.3m (1 ft) and then sample every fourth or fifth location at lower depths. However, classical statistics reveal high coefficient of variation values for the deeper layers as compared to the first layer. Further analysis is necessary to determine an ideal sampling approach.

There was less nitrogen in the soil profile in the third field, and there was less variability in samples from different layers of this field, as compared to the other two fields. However, overall (vertically averaged over core) sample variability was the same or higher (see Table 1 and Figures 3 and 7). Further investigation indicated that this field received more irrigation water in the previous two years than the other two fields. It is probable that the excessive application of irrigation water leached much of the nitrate from the profile and reduced the amount and spatial variability of residual soil nitrate.

Six directional semivariograms were calculated for each field. All directions corresponded to rotations in the horizontal plane only. The directions considered were North, N30E, N60E, N90E, N120E, and N150E, with azimuth half tolerance of 45 degrees. Directional semivariograms are presented as a contour map of the sample variogram surface (planimetric form) in Figures 8, 9, and 10 for Fields 1, 2, and 3, respectively. The values contoured are the semivariance in every direction to a distance of at least 200 meters, with a contour interval units in $(kg/ha)^2$. Differences between direction-dependent semivariograms for the fields studied could be the result of the differences in geology, topography, and/or management of the area.

In this case it is speculated that these significant effects of north-south and east-west directions across each field were largely due to the irrigation pattern in the fields. These fields were surface irrigated with water being distributed on the west side of the field. Hence, residual soil nitrate appears to follow trends in irrigation water supply. The variogram surface in the east-west direction is more continuous

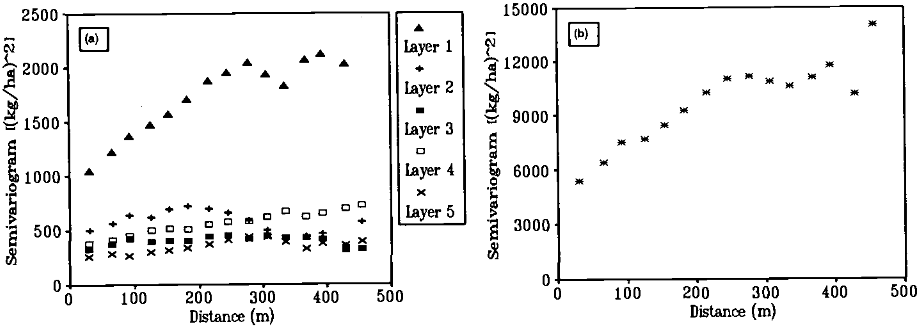

FIGURE 5--2-D semivariograms for Field 1; (a) five depths; and (b) total in profile.

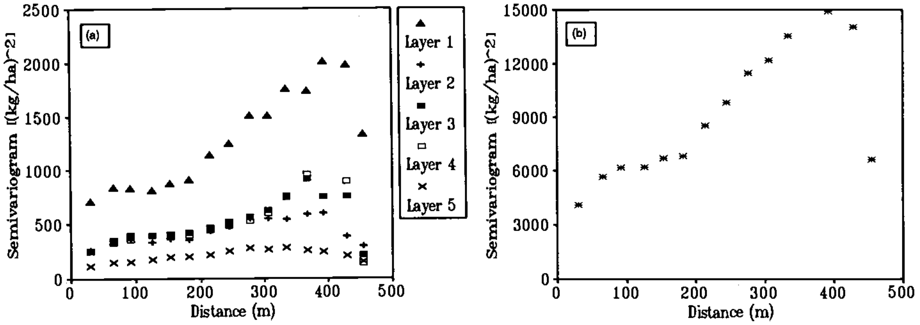

FIGURE 6--2-D semivariograms for Field 2; (a) five depths, and (b) total in profile.

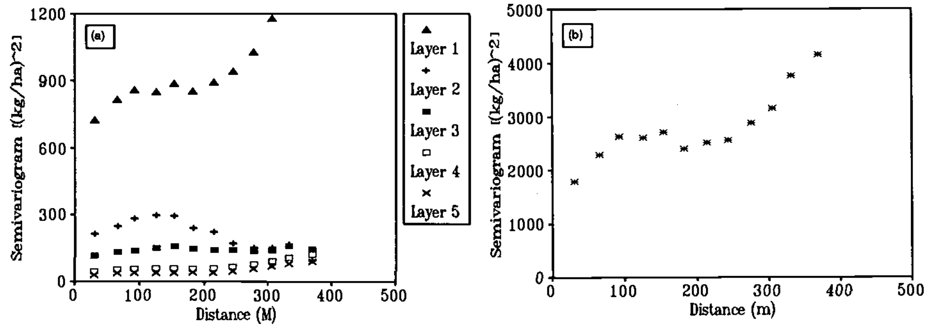

FIGURE 7--2-D semivariograms for Field 3; (a) five depths, and (b) total in profile.

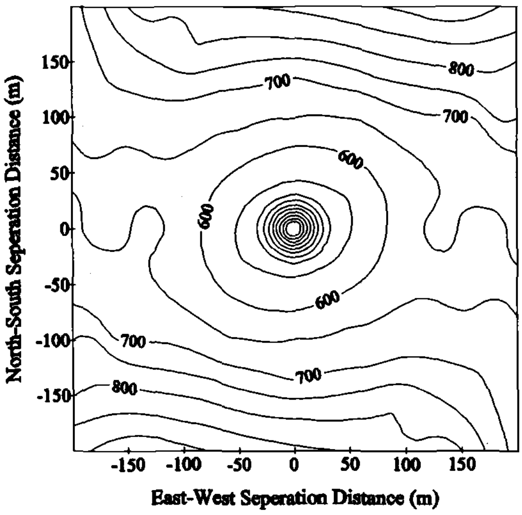

FIGURE 8--A contour map of the semivariogram values for Field 1. Contour interval is 50 (kg/ha)^2.

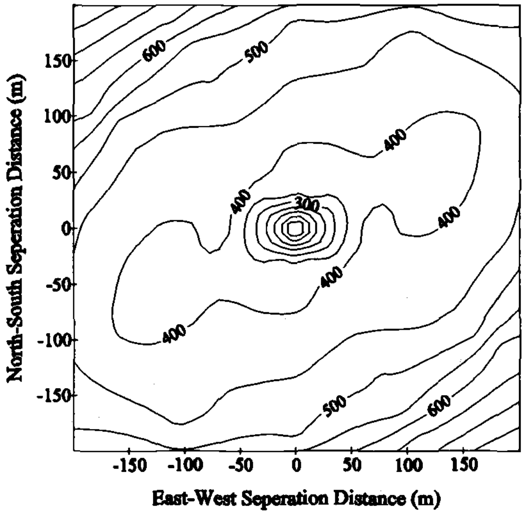

FIGURE 9--A contour map of the semivariogram values for Field 2. Contour interval is 50 (kg/ha)^2.

than in the north south direction. In other words, the irrigation pattern seems to result in high variability (larger sill values) with the variogram surface rising rapidly in the north-south direction. Hence, the directional semivariograms indicates the

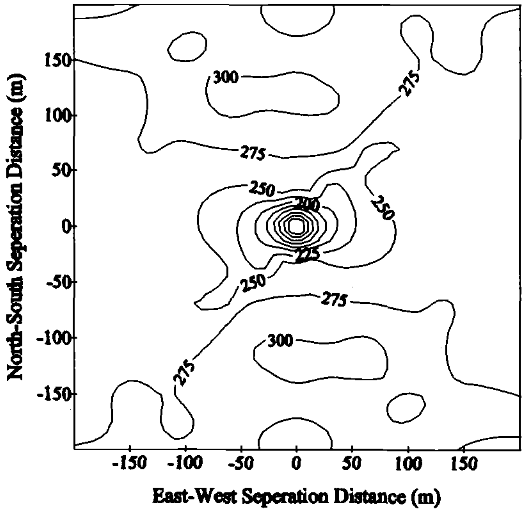

FIGURE 10--A contour map of the semivariogram values for Field 3. Contour interval is 25 (kg/ha)^2.

presence of anisotropy. However, this can be classified as a mild case of geometric and zonal anisotropy case which is apparent in all three fields at larger distances.

SUMMARY AND CONCLUSIONS

Geostatistical analyses showed that residual soil nitrates in three fields were spatially structured. This spatial structure is important to consider, both for fertilizer application and for evaluation of potential pollutant transport to the groundwater. The apparent spatial variability in the residual soil nitrate has the potential to seriously limit the efficiency of fertilizer application according to traditional practices. Conventional statistical analysis showed that the residual soil nitrate in the profile was variable, ranging from 64 to 650 kg/ha (57 to 580 lbs/acre) with a mean of 192 kg/ha (173 lbs/acre). Data tended to be skewed with the mean greater than the median.

Geostatistical techniques offer alternative methods to conventional statistics for the estimation of parameters and their associated variability. Three-dimensional semivariograms were calculated for each field. Two different semivariograms were also calculated for each field, horizontal-spatial semivariogram and vertical semivariogram. In addition, two dimensional semivariograms were prepared for each layer. Finally, six directional semivariograms also were calculated for each field.

Semivariogram analysis demonstrated that there were similarities in the patterns of spatial variability for the three fields. This may suggest that spatial relationships derived from one set of measurements for one field, may have applicability at other field sites. Since spatial structures are 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.

The 3-dimensional and 2-dimensional semivariogram analysis resulted in similar structure and form for all three fields. Three dimensional horizontal-spatial semivariograms showed that for all three fields, the range was about 120 to 245 m. In the vertical direction the range varied between 1.5 to 3m (5 to 10 ft). The complete structure for both the horizontal-spatial dimension and the vertical dimension represents a combination of geometric and zonal anisotropy. The complete structural analysis of hydraulic properties for both dimensions may show the same pattern. Three-dimensional vertical semivariograms also displayed a significant trend which may be related to conditions at the time of data collection.

The nugget values expressed as a percentage of the total semivariance defines different classes of spatial dependence. Horizontal-spatial semivariograms indicated moderate spatial dependence, while the vertical semivariograms were characterized by strong spatial dependence, exhibiting ratios less than 25%. Strong to moderate spatially dependent structures may be controlled by intrinsic and extrinsic variations as well as seasonal variations.

The two dimensional analysis showed a strong spatial pattern in the top layer, which is displayed in the overall structure of the 2-dimensional semivariograms. The analysis further revealed that the soil nitrates at 0.6m to 1.5m (2 to 5 ft) depths may be sampled without a great sensitivity to location with a resulting similar variance. Direction-dependent semivariograms showed that residual soil nitrates apparently followed trends in irrigation water supply. This pattern resulted in high variability in the direction perpendicular to irrigation water flow.

The structural information can be useful in the management of production agriculture systems in which variable rate application of nitrogen can be used to increase production and reduce the risk of groundwater contamination. The balance between crop uptake rates and residual soil nitrogen can also lead to a more cost-effective fertilizer application rates without increasing the risk of groundwater pollution.

ACKNOWLEDGEMENT

This paper was supported, in part, by the Center for Infrastructure Research, the Water Center, and the University of Nebraska-Lincoln and, in part, by the Cooperative State Research Service (CSRS) of the U.S. Department of Agriculture (Grant Number 92-34214-7457). Assistance provided by Dr. T.A. Peterson from Department of Agronomy of University of Nebraska-lincoln is acknowledged.

REFERENCES

Beckett, P. H. T., and Webster, R., 1971, "Soil variability: A review", Soils and Fertilizers, Vol. 34, No. 1,pp. 1-15

Berndtsson, R., Bhari, A., and Jinno, K., 1993, "Spatial dependence of geochemical elements in a semiarid agricultural field: I. Geostatistical properties", Soil Science Society of America J., Vol. 57, pp. 1323-1329

Bhatti, A. U., Mulla, D. J., Koehler, F. E., and Gurmani, A. H., 1991, "Identifying and removing spatial correlation from yield experiment", Soil Science Society of America J., Vol. 55.pp.1523-1528

Biggar, J.W., Nielsen, D. R., and Erh, K. T.,1973, "Spatial variability of field-measured soil-water properties", Hilgardia, Vol. 42, No. 7, pp. 214-259

Biggar, J.W., and Nielsen, D. R., 1976, "Spatial variability of the leaching characteristics of a field soil", Water Resources Research, Vol. 12, No. 1,pp. 78-84

Bouma, J., and Finke, P. A., 1992, "Origin and nature of soil resource variability", 1992, Proceedings of the Soil Specific Crop Management Conference, Minneapolis, Minnesota, April 14-16

Bresler, E., 1989, "Estimation of statistical moments of spatial field averages for soil properties and crop yields", Soil Science Society of America J., Vol. 53, pp. 1645-1653

Cambardella, C.A., Moorman, T. B., Novak, J. M., Parkin, T. B., Karlen, D. L., Turco, R. F., and Konopka, A. E., 1994, "Field-scale variability of soil properties in central Iowa soils", Soil Science Society of America J., Vol. 58 (In press)

Dahiya, I. S., Ritcher, J., and Malik, R. S., 1984, " Soil spatial variability: A review", International Journal of Tropical Agriculture, Vol. 11, No. 1, pp. 1-102

Davis J., 1986, "Statistics and Data Analysis in Geology", John Wiley & Sons, New-York, NY

Deutsch, C.V., and Journel, A. G., 1992, "GSLIB: Geostatistical Software Library and User's Guide", Oxford University Press, New York, NY

Guaracio, M., David, M., and Huijbregts, C. J., 1975, "Advanced Geostatistics in the Mining Industry", D. Reidel Publishing Company, Dordrecht, Holland

Isaaks, E. H., and Srivastava, R. M., 1989, "An Introduction to Applied Geostatistics", Oxford university press, New York, NY

Journel, A. G., and Huijbregts, C. J., 1978, "Mining Geostatistics", Academic press, New York, NY

Jury, W. A., Russo, D., Sposito, G., and Elabd, H., 1987, "The spatial variability of water and solute transport properties in unsaturated soil; I. Analysis of property variation and spatial structure with statistical models", Hilgardia, Vol. 55, No. 4, pp. 1-32

Kalinski, R.J., Kelly, W. E., Bogardi, I., and Pesti, G., 1993, "Electrical resistivity measurements to estimate travel times through unsaturated ground water protective layers", Journal of Applied Geophysics, Vol. 30, pp. 161-173

Mulla, D. J., 1988, "Estimating spatial patterns in water content, metric suction, and hydraulic conductivity", Soil Science Society of America J., Vol. 52, pp.1547-1553

Ovalles F. A., and Collins, M. E., 1988, "Evaluation of soil variability in northwest Florida using geostatistics", Soil Science Society of America J., Vol. 52, pp. 1702-1708

Peterson T. A., and Schepers J. S., 1992, "Spatial distribution of soil nitrate at the Nebraska MSEA site", Agriculture Research to Protect Water Quality, Poster Paper, USDA Agricultural Research Service, University of Nebraska, Lincoln, NE

Rolston, D. E., and Liss, H. J., 1989, "Spatial and temporal variability of water soluble organic carbon in a cropped field", Hilgardia, Vol.57, No.3, pp. 1-19

Sutherland, R. A., Kessel, C. V., and Pennock, D. J., 1991, "Spatial variability of Nitrogen-15 natural abundance", Soil Science Society of America J., Vol. 55, pp. 1339-1347

Tabor, J. A., Warrich, A. W., Myers, D. E., and Pennington D. A., 1985, Spatial variability of nitrate in irrigated cotton: II. Soil nitrate and correlated variables, Soil Science Society of America J., Vol. 49, pp. 390-394

Webster, R., and Burgess, T. M., 1983, "Spatial variation in soil and the role of Kriging", Agricultural Water Management, Vol. 6, pp. 111-122

Woldt, W., and Bogardi, I., 1992, "Ground water monitoring network design using multiple criteria decision making and geostatistics", Water Resource Bulletin, Vol. 28, No. 1, pp. 45-62

Woldt, W., Bogardi, I., Kelly, W. E., and Bardossy, A., 1992, "Evaluation of uncertainties in a three-dimensional groundwater contamination plume", Journal of Contaminant Hydrology, Vol. 9, pp. 271-288