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Precision Farming Protocols: Part 1. Grid Distance and Soil Nutrient Impact on the Reproducibility of Spatial Variability Measurements

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Abstract. To determine temporal changes in soil nutrient status, reproducible results must be obtained at each time step. The objective of this paper was to determine the impact of grid distance on the reproducibility of spatial variability measurements. Soil samples from the 0 to 15 cm depth were collected from a 30 by 30 m grid in May 1995 in a 65 ha notill corn (*Zea mays* L.) field. Each bulk sample contained 15 individual cores, collected at sample points located every 11.4 cm along a transect that transversed 3 corn rows (57 cm). At each sampling point latitude, longitude, elevation, landscape position, and soil series were determined. The 30 m grid was used to develop 4 and 9 independent data sets having a 60 and 90 m grids, respectively. Semivariograms, nugget to sill ratios, and mean squared errors were calculated for each data set. At 60 m: (i) the total N, total C, and pH semivariograms, of different start points, were similar, while semivariograms for Olsen P, K, and Zn were different; (ii) the spatial dependence ratings, based on the nugget to sill ratio, for total N, total C, and pH semivariograms were consistent and suggested moderate spatial dependence; (iii) the spatial dependence rating for Olsen P, K, and Zn for the 4 semivariograms were not consistent and ranged from weak to moderate spatial dependence. At 90 m, all soil nutrients had different semivariograms for each start point, while the spatial dependence rating for each total N, total C, and pH start point were consistent and showed moderate spatial dependence. The total C, P, K, Zn, and pH MSE values at 60 m, were 30, 30, 41, 28, and 72% lower than the variance, respectively. This study showed that semivariogram, semivariance, MSE, and nugget to sill ratios reproducibility were dependent on soil nutrient and grid distance.

Keywords: C isotope, spatial variability, farming by soil type

Introduction

Semivariograms are useful for describing spatial variability, and can be characterized by the range, sill, and nugget values. The range is the distance where the

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semivariance values reach a plateau (Tabor et al., 1984; Isaaks and Srivastava, 1989). The sill is the semivariance value at the plateau, and the nugget is the y intercept. Isaaks and Srivastava (1989) used a simple semivariogram model ($y = 10(1 - e^{-0.3x})$) to demonstrate the relative effect of range, nugget, and sill values on kriged parameters. Using this model, they showed that: (i) doubling the range ($y = 10(1 - e^{-0.15x})$) reduced the minimum krige variance; (ii) increasing the nugget ($y = 5 + 5(1 - e^{-0.3x})$) to 1/2 of the sill increased the minimum krige variance and reduced the weighting factors associated with the closest points; and (iii) doubling the sill ($y = 20(1 - e^{-0.15x})$) doubled the minimum krige variance. A critical component in developing useful semivariograms is selecting an appropriate sampling protocol.

Generally, sampling costs increases exponentially with reduction in grid distances, while the number of important features missed increases with increased grid distances. In spite of the importance of sampling, universally accepted sampling protocols are not available. The selection of an appropriate sampling protocol is confounded by the fact that the scientific community has not reached a consensus on how samples should be collected. For example, Cambardella et al. (1994) collected 3 soil cores from a 1-m circle around each grid point. Tabor et al. (1984) collected 10 cotton (*Gossypium hirsutum* L.) petioles for a composite sample from a 2 by 2 m area around each sampling point. Ferguson et al. (1996) collected single cores from the center of 15.2 by 6.1 m cells. Froment et al. (1996) collected soil samples from 4 corners of 20 by 20 cm cells located on a 50 m grid. Franzen and Peck (1995) collected 5 soil samples from 5 m cells located on a 25 m grid. One soil core was located in the center of the cell and the other 4 were randomly located within the cell. Hergert et al. (1995) collected single soil cores on a 30 m grid.

Several different approaches have been used to evaluate sampling protocols. For example, Cambardella et al. (1994) suggested that the ratio between the nugget and the sill be used as a measure of spatial dependence. They stated that if the ratio: (i) was less than 0.25 then the parameter had a strong spatial dependence; (ii) was greater than 0.25 and less than 0.75, then the parameter had a moderate spatial dependence; and (iii) was greater than 0.75, then the parameter had a weak spatial dependence. Mohamed et al. (1996) used estimation errors to evaluate grid distances. They reported that the 20 by 20 m grid was 15 and 20% more accurate than the 40 by 40 m and 60 by 40 m grids, respectively. Vieira et al. (1981) measured water infiltration rates at over 1200 points in an 0.9 ha area and evaluated the sampling requirement using linear regression to compare known and estimated values. If a correlation coefficient (r) of 0.8 was acceptable, then 128 points out of the original data set were needed to estimate water infiltration rates.

There are several quantifiable approaches for evaluating sampling protocols. First, the impact of different sampling approaches on potential profitability can be estimated (Chang et al., 1999). Second, minimized error or kriging variances can be calculated (Isaaks and Srivastava, 1989). The problem with the minimized error variance is that this value represents a minimum variance and not the actual variance. Third, mean squared error (MSE) can be calculated using the following

equation:

$$\mathrm{MSE} = (1/n) \sum (X_{itrue} - X_{iest})^2 \quad [1]$$

where, X_{itrue} is the measured value at point i and X_{iest} is the estimated value at point i (Isaaks and Srivastava, 1989). An advantage of using MSE is that it represents the actual estimation error. Fourth, the experiment can be repeated to determine if the results can be reproduced. If one of the goals of the experiment is to measure temporal changes, then obtaining reproducible results at each time step is critical. The objective of this paper was to determine the impact of grid distance on the reproducibility of spatial variability measurements.

Materials and methods

The field used in the case study was a 65 ha no-tillage field located in east central South Dakota. The field was approximately square with latitude and longitude values of 44.17°N and 96.62°W, respectively. Corn (*Zea mays* L.) was planted in the spring of 1995 at a row spacing of 57 cm. Urea (46-0-0) fertilizer was broadcast on 8 November 1994 at the rate of 108 kg N ha^{-1}. During planting, 12 kg N was applied as a popup fertilizer and an additional 4 kg N was applied with a herbicide application. Total amount of N fertilizer applied was 124 kg ha^{-1}. At plant maturity, in October of 1995, grain yields were determined at points located on a 30 by 60 m grid. At each grid point, corn was harvested from 15 m of row using a 2-row plot combine. Grain yields in the rest of the field were measured using a combine equipped with a yield monitor and global positioning system (GPS). Corn yields and N balance for this site have been reported in Clay et al. (1997b).

Composite soil samples from the 0 to 15 cm depth were collected from a 30 by 30 m grid in May 1995. Each grid point sample contained 15 soil cores collected every 11.4 cm along a transect that transversed 3 corn rows (Clay et al., 1997a). Grid points were located using a differentially corrected GPS. The soil series was determined following standard NRCS methods at each sampling point (Soil Survey Staff, 1993).

Soil samples were air dried (35°C), ground with a ball mill (< 250 m), and analyzed for total N, total C, $\delta^{13}C$, NO_3-N, Olsen P, K, Zn, and pH. Total N, C, $\delta^{13}C$ were analyzed on an EUROPA 20-20 ratio mass spectrometer (Europa Scientific, Ltd, UK). The $\delta^{13}C$ value was calculated by the following equations:

$$\left(\delta^{13}C = \left(\left(\left({}^{13}C/{}^{12}C_{sample}\right)/\left({}^{13}C/{}^{12}C_{Reference}\right) - 1\right)*1000\right)\right)‰ \quad [2]$$

where, the reference material was the PeeDee Belemnite. Delta ^{13}C can be used to evaluate the relative amount of different C sources in the total C pool. Generally, $CaCO_3$ has higher $\delta^{13}C$ values than organic C, and therefore $\delta^{13}C$ can be used to identify areas where erosion occurred or $CaCO_3$ accumulated.

Nitrate-N and NH_4-N were extracted with 1.0 *M* KCl using a 10 : 1 solution to soil ratio and analyzed on a Wescan Ammonia Analyzer (Timberline, Boulder, CO). Olsen P was extracted with 0.5 *M* $NaHCO_3$ buffered to pH 8.5. The soil extract was filtered, a color reagent containing ascorbic acid and molybdate was added, and color development was measured on a colorimeter set at 882 nm (North Central Regional Publication, 1988). Soil K was extracted with 1 *M* NH_4OAc at pH 7 and analyzed on an atomic absorption/emission spectrometer (North Central Regional Publication, 1988). Soil Zn was extracted with 0.005 *M* DTPA (diethylenetriaminepentaacetic acid) at pH 7.3 and analyzed on an atomic absorption (AA) spectrometer. Soil pH was determined by a pH electrode in water using a 1 : 1 water to soil ratio.

Spatial analysis

The 30 by 30 m grid was subsampled to produce 4 independent data sets on a 60 by 60 m grid and 9 independent data sets on a 90 by 90 m grid. For example, if point 1 was selected from a 60 m grid, then the next sampling point would be 3 followed by 5, 13, 15, and 17 (Figure 1). Means, standard deviations, semivariances, skewness, and kurtosis were calculated using GEO-EAS (Englund and Sparks, 1991). The semivariance value at the shortest distance was defined as the nugget value and the maximum semivariance was defined as the sill. The nugget to sill ratio was used to qualitatively define spatial dependence. Values less than 0.25 were defined as having strong spatial dependence, values between 0.25 and 0.75 were defined as having moderate spatial dependence, and values greater than 0.75 were defined as having weak spatial dependence. Surfer: Version 6 (Golden Software, Inc.; Golden CO) was used to develop contour maps. Skewness provides an indication of symmetry, and a value of 0 indicates a symmetrical distribution. Negative and positive skewness values indicated distribution are skewed toward large and small values, respectively. Kurtosis represents the distribution spread, and a normal distribution has a kurtosis value of 3 (Ott, 1977).

1	2	3	4	5	6
7	8	9	10	11	12
13	14	15	16	17	18
19	20	21	22	23	24
25	26	27	28	29	30
31	32	33	34	35	36

Figure 1. The relative sampling sites for the 30, 60, and 90 m grids.

Semivariances were fit to either linear or exponential models. The exponential model was: $y_{(i)} = y_{(0)} + a(1 - e^{-bh})$, where h was distance and $y_{(i)}$ was the semivariance value at the i^{th} distance. The linear model was $y_{(i)} = Y_{(0)} + bh$. Both $y_{(0)}$ and b were ≥ 0.

Mean squared error

Mean squared errors were calculated for the 4 and 9 independent data set at 60 and 90 m grid, respectively (Eq. [1]). The MSE values were calculated by: using the 60 by 60 m or 90 by 90 m grids to calculate kriged estimated values for a 30 by 30 m grid; and MSE values were calculated by using Eq. [1]. Linear semivariogram and values within 2 lag distances were used for krige estimations (Isaaks and Srivastava, 1989). The linear model was used because it provided a good fit to the semivariances. Using this approach, 12 measured values were used to estimate each unknown value. Increasing the number of known points used to estimate unknown values would have had a limited impact on estimated values because samples were collected from a grid, and therefore known points greater than 2 lags away from the unknown point were screened by closer samples. A detailed discussion of screening on weighting factors is presented in Issaaks and Srivastava (1989). A F test was used to compare MSE values.

Sampling requirement from a specific landscape position

Toeslope, backslope, and summit areas were chosen to determine the random sampling requirement for a composite sample within a given topographic location. The toeslope, backslope, and summit areas contained 44, 41, and 65 sampling

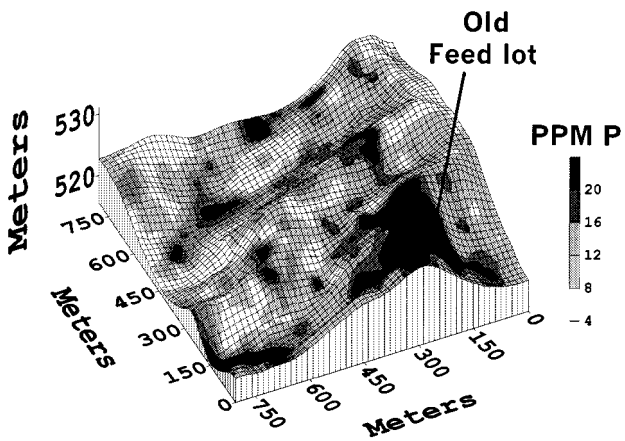

Figure 2. Contour maps of Olsen P based on the 30 by 30 m grid.

points, respectively. Soil sampling requirements were determined following the procedure of Clay et al. (1997a). In this approach, a computer randomly selected the specified number of cores from the data set. The average value of the selected cores was then subtracted from the average value of all cores. This difference was used to characterize if the composite sample mean was within 20% of the field mean. This process was repeated 1000 times for each specified number of cores.

Site climatic conditions

Air temperatures and rainfall were measured at a weather station located approximately 5 km northwest of the research site. Growing degree days (GDD) in for corn were calculated using the following equation:

$$GDD = ((Tmax + Tmin)/2) - Tcrit \quad [3]$$

where Tmax was the maximum daily temperature in degrees C and can not exceed 30°C, Tmin was the minimum daily temperature and can not be less than 10°C, and Tcrit was 10°C. In April and May in 1995 there were 124 growing degree days, which was less than the long term average of 164 (30 year average between 1951 and 1981). During the remainder of the growing season the long term average and measured growing degree days (1288) were similar. Precipitation during the growing season was 66.9 cm which was higher than the 30 year average of 47.3 cm.

Results and discussion

Spatial variability

The coefficients of variations ranged from 0.69 for NO_3-N to 0.06 for $\delta^{13}C$ (Table 1). Skewness values showed that the population distributions of total N and C were not skewed and $\delta^{13}C$, NO_3-N, P, K, Zn, and pH were skewed toward small values. Total N, total C, $\delta^{13}C$, NO_3-N, P, K, and Zn had probability distributions with tails larger than a normal distribution, while pH had a probability distribution with tails smaller than a normal distribution. A closer investigation of the P probability distribution revealed that it was bimodal (data not shown). One peak was centered between 8 to 15 ppm, while the second peak was centered between 20 to 30 ppm. Bimodal population distributions are not uncommon for soil nutrients and may result from a population being influenced by both intrinsic and management induced processes (Clay et al., 1995). A contour map, of this field, showed a high P concentration was located in the west central portion. This area corresponds to an old feedlot present during the 1930 and 40's (Fig. 2).

For the 30 m grid, the semivariances for all parameters between 30 to 195 m followed a linear model (Table 2). The ratio between semivariance values at 25 and 195 m ranged between 0.28 for pH to 0.6 for total N. Based on Cambardella et al. (1994) criteria, all parameters had moderate spatial dependence.

Table 1. The mean, standard deviation, skewness, and kurtosis values for total N, total C, $\delta^{13}C$, nitrate-N, Olsen P, K, Zn, and pH for the whole field

	N	C	$\delta^{13}C$	NO_3	P	K	Zn	pH
	g kg^{-1}		‰	mg kg^{-1}				
Mean	2.41	29.2	−16.9	12.4	13.1	193	1.30	6.48
s	0.32	3.71	0.95	8.59	7.71	59.0	0.83	0.77
Skewness[f]	0.09	−0.05	0.93	1.12	1.70	1.81	4.90	1.02
Kurtosis[§]	4.97	3.48	10.1	3.26	6.45	9.18	49.8	2.72
Cv	0.13	0.13	0.06	0.69	0.59	0.31	0.63	0.12

[f] Values greater than 0.321 and 0.464 were significantly greater than 0 at the 0.05 and 0.01 level, respectively.
[§] Values greater than 3.33 and 3.52 were significantly greater than 3 at the 0.05 and 0.01 level, respectively.

For the 60 m grid, total N (Figure 3), total C, and pH semivariograms were similar for the different start points. However, the semivariograms for P (Figure 4), K, and Zn were influenced by start point. Using P as an example, the exponential model provided a good fit for start point 1, while the linear model provided a good fit for start points 2, 3, and 4 (Table 3). Based on the semivariograms, the nugget values ranges from 11.6 for start point 1 to 45.5 for start point 2. The spatial dependence rating, based on the nugget to sill ratio for total N, total C, and pH showed moderate spatial dependence, while the spatial dependence rating for P, K, and Zn ranged from moderate to weak. If the sampling goal was to rank spatial dependence into strong, moderate, or weak categories or to calculate semivariograms the 60 m grid undersampled Olsen P, K, and Zn.

Table 2. Semivariance values for the different lag distances for total N, total C, $\delta^{13}C$, NO_3-N, Olsen P, K, Zn, and pH

Lag Average distance	N	C	$\delta^{13}C$	NO_3	P	K	Zn	pH
m	$\Sigma(X_i - X_{i+1})^2/2n$							
25	0.054	4.74	0.518	22.1	26.1	1910	0.444	0.180
48	0.056	4.34	0.502	25.2	33.4	2210	0.558	0.236
78	0.067	5.91	0.710	30.7	40.1	2720	0.601	0.309
107	0.070	6.21	0.856	31.0	48.4	3150	0.554	0.407
136	0.077	6.46	0.693	39.0	52.7	3500	0.755	0.465
165	0.099	8.08	0.764	38.0	53.5	3290	0.642	0.562
195	0.090	8.20	0.845	46.0	58.4	3600	0.957	0.630
Linear semivariograms $(Y_i = Y_{(0)} + bh)$								
Y_0	0.046	3.79	0.50	18.9	24.6	1840	0.39	0.108
b	0.0003	0.023	0.002	0.131	0.186	10	0.0023	0.003
r^2	0.89	0.92	0.65	0.95	0.95	0.89	0.74	0.99

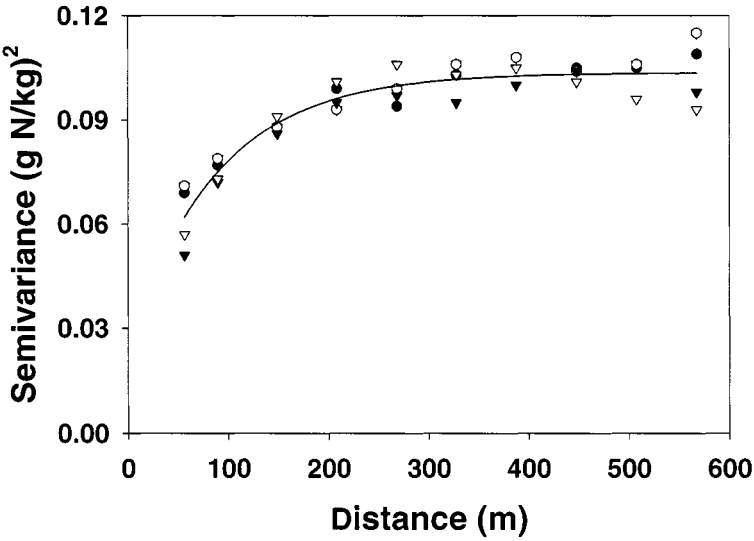

Figure 3. The influence of start point and sampling distance (60 m) on soil total N semivariance values. Each symbol represents a different start point.

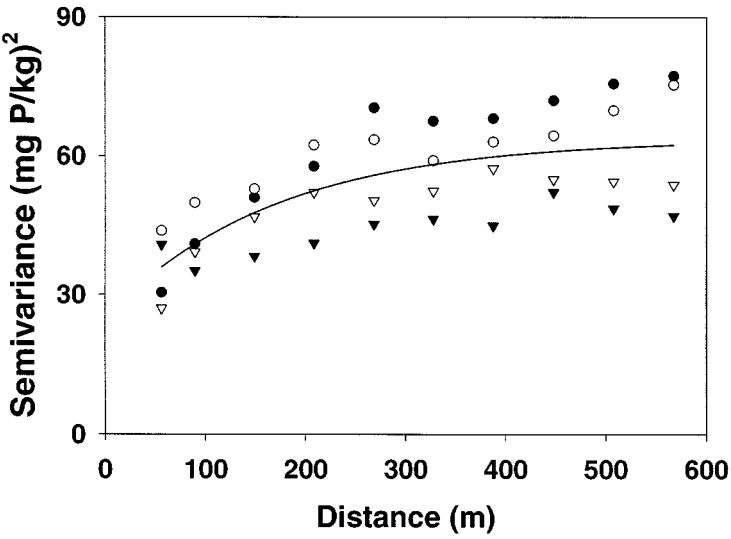

Figure 4. The influence of start point and sampling distance (60 m) on soil Olsen P semivariance values. Each symbol represents a different start point.

Table 3. The influence of start point and grid distance on P semivariogram models

Start point	Grid dist.	$y_{(h)} = y_{(0)} + a(1 - e^{-bh})$				$y_{(h)} = y_{(0)} + bh$		
		$\tau_{(0)}$	a	b	R^2	$\tau_{(0)}$	b	r^2
	m							
	30	15.6	51.3	0.089	0.99			
1	60	11.6	65.7	0.006	0.98			
2	60					45.5	0.049	0.86
3	60					36.6	0.024	0.71
4	60					7.06	0.012	0.89
1	90	12.6	73.9	0.083	0.82			
2	90					42.8	0.013	0.41
3	90	21.7	70.4	0.003	0.98			
4	90	54.4	50.0	0.009	0.83			
5	90					47.3	0.03	0.49
6	90					45.6	0.04	0.49
7	90					49.1	0.03	0.36
8	90					37.7	0.02	0.41
9	90	13.15	36.19	0.004	0.91			

At 90 m, semivariances for N (Figure 5), C, pH, P (Figure 6), K, and Zn were influenced by start point and distance. Using P as an example, the nugget values of the P semivariograms ranged from 13.2 to 54.1 (Table 3). The exponential model was appropriate for 4 of the start points and the linear model provided a good fit

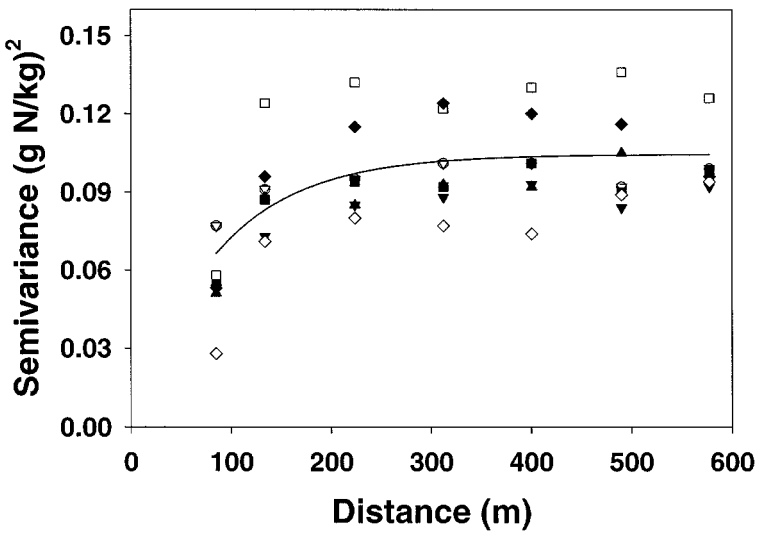

Figure 5. The influence of start point and sampling distance (90 m) on soil total N semivariance values. Each symbol represents a different start point.

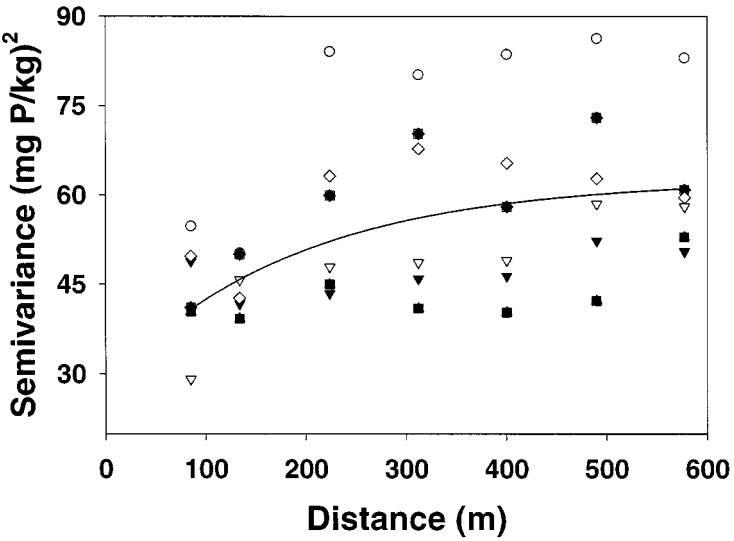

Figure 6. The influence of start point and sampling distance (90 m) on soil Olsen P semivariance values. Each symbol represents a different start point.

for 5 of the start points. Clearly, at 90 m semivariances and semivariograms for all parameters were not reproducible. Based on the nugget to sill ratio, for all start points, total N, total C, and pH showed moderate spatial dependence. If the objective was to rank spatial dependence, then the 90 m grid adequately sampled total N, total C, and pH and undersampled P, K, and Zn. However, if the objective was to evaluate spatial relationships using semivariograms, then the 90 m grid undersampled total N, total C, Olsen P, K, Zn, and pH.

Estimation variances

The ratios between the largest and smallest MSE value for a given sampling start point were 1.16, 1.25, 1.25, 1.18, 1.17, and 1.21 for N, C, P, K, Zn, and pH (Table 4), respectively. These ratios indicate that MSE was influenced by start point. On average, the MSE values for organic C, P, K, Zn, and pH were 30, 30, 41, 28, and 72% lower than the variances, respectively. At 90 m the MSE values for Olsen P at the different start points were 51.0, 44.6, 47.9, 46.9, 43.6, 52.5, 52.2, 39.5, and 42.4. The ratio between the largest and smallest value was 1.32, which was higher than the 1.25 ratio for the 60 m grid. On average the phosphorus MSE values at 90 m were 21% lower than the variance. These findings indicate that kriging, regardless of start point, reduced estimation errors relative to using single value to represent field P concentrations.

Table 4. The variance and the mean squared error values (MSE) for the different start points and soil nutrients of the 60 m grid. The degrees of freedom for the MSE and variance values were approximately 450 and 615, respectively

Soil Parameter	Start points				Field variance
	1	2	3	4	
	MSE			s^2	
N	0.1134	0.0945	0.0967	0.0979	0.102
C	10.69	9.46	8.57	9.50	13.76
P	41.4	37.0	41.0	46.1	59.4
K	1924	1931	2080	2274	3481
Zn	0.535	0.534	0.456	0.457	0.689
pH	0.167	0.154	0.184	0.152	0.590

Soil sampling requirement from a given landscape position

A computer resampling procedure (Clay et al., 1997a) was used to determine the impact of number of samples included in a composite on the probability of that sample being within 20% of field mean (Figure 7). If the criteria was that 80% of the composite sample mean were being within 20% of the field mean was selected, then random sampling requirements for K were lower than those for NO_3-N, Olsen P, and Zn. For K, Olsen P, and Zn, the sampling requirements were similar for the three topographic areas, while for NO_3-N the sampling requirement was lowest for backslope areas. If samples were collected from 10 to 15 sampling sites from within a soil type or landscape position, then all of the nutrients would exceed the given level of precision (20% of the mean 80% of the time). These findings were consistent with other papers that have used computer resampling to estimate sampling requirements (Clay et al., 1995; Clay et al., 1997a; Starr et al., 1992).

Conclusions

This study demonstrated that the reproducibility of spatial variability measurements can not be assumed. To obtain reproducible spatial variability measurements a denser grid for P, K, and Zn was required than N, C, and pH. Specific findings from this study showed that: (i) different sampling objectives require different sampling protocols; (ii) sampling protocols are soil nutrient dependent; (iii) total C, P, K, Zn, and pH MSE values for the 60 and 90 m grids were lower than field variances, and therefore kriged estimates, regardless of start point, had lower estimation errors than using a single sample to represent the nutrient concentrations; and (iv) if samples were collected from 10 to 15 sampling sites from within a soil type or landscape position, then all nutrients exceed the specified level of precision (20% of the mean 80% of the time).

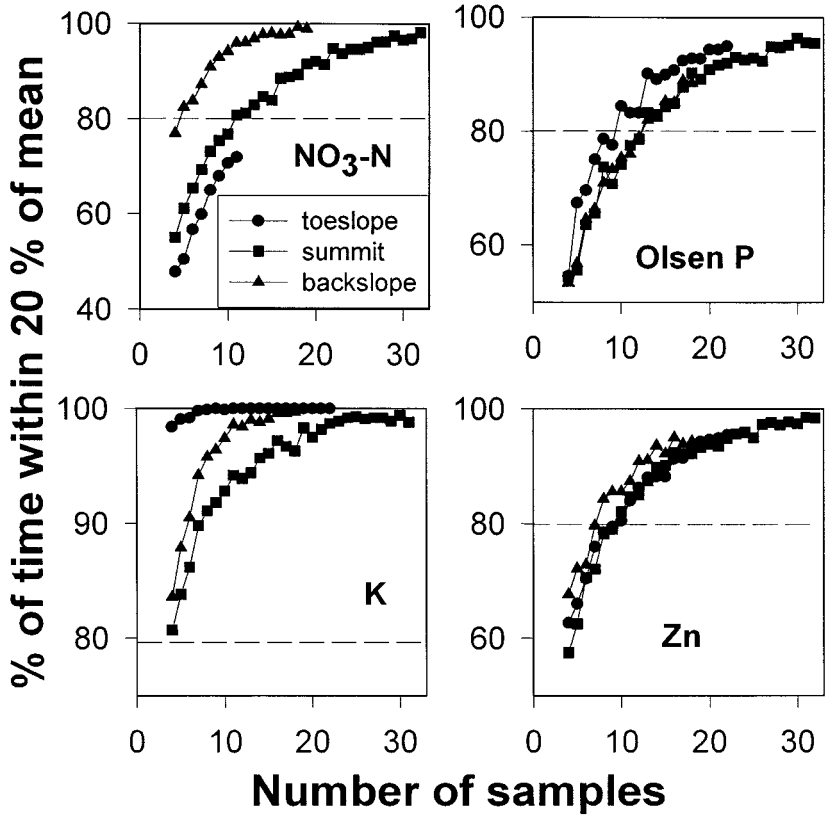

Figure 7. The influence of the number of samples collected on the percent time that a composite sample was within a 20% of the sample mean.

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