Spatial Variability of Soil Nutrients at Selected AESA Soil Quality Benchmark Sites

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EXECUTIVE SUMMARY

The Alberta Environmentally Sustainable Agriculture Program (AESA) Soil Quality Resource Monitoring Program has provided a data set containing soil organic matter (OM), nitrogen (N), phosphorus (P), potassium (K), electrical conductivity (EC), and pH for three AESA sites in central Alberta. The data set has been used to assess the spatial variability of soil properties and evaluate the current sampling scheme. At each site, soil sampling locations along a transect are marked with global positioning systems (GPS) at the upper, mid and lower slope positions. Two transects at each slope are sampled to evaluate the spatial dependence of the selected soil properties. Spatial analysis of the soil properties will quantify the distance of spatial correlation with a view to expanding the current sampling scheme of 2 m.

Current AESA soil sampling protocol involves sampling from the 0 to 2 m area surrounding a central marker. A preliminary study by Cathcart and Haung, (2005), indicated that this area could be expanded to 4 m to provide additional sample locations. To confirm this finding, three AESA sites, Dapp (681), Carvel (684), and Tomahawk (692) were sampled in October, 2005. Soil from 162 locations at the 0-15 cm depth is analyzed for OM, N, P, K, EC and pH.

The variability of sampled soil nutrients is highest for K and lowest for EC based on the variance. The coefficient of variation (CV) confirmed this observation. All soil nutrients are positively skewed and most of the soil nutrients have a negative kurtosis. Spatial trends are evident for all soil variables except N which shows no clear trend. Histograms for each of the soil nutrients visually confirmed these descriptive statistics.

The range of spatial correlation determined by modeling the experimental, isotropic variogram varies among the soil properties from 3.5 m for EC to 21 m for P. Spatial dependence generally appears to be longest for phosphorus followed by organic matter, potassium and pH, EC and nitrogen. The N experimental, omni directional variogram is uncorrelated when calculated over all 3 sites but spatial correlation occurred at the mid slope and Carvel (684) site. Mobility of these elements in the soil, parent material, climate and topography may explain why N is uncorrelated at short distances while the other soil properties are spatially dependent at greater distances.

Directional variograms of the soil properties indicated that the short range spatial correlation varied from 1 to 20 m while long range correlation varied from 10 to 40 m. The strongest direction of correlation is in an east-west direction except for pH which is north-south. There are no directional trends for nitrogen. Consequently, the sampling area may be expanded up to 6 m in the direction of the slope and 4 m in the opposite direction from the central marker except EC which can only be expanded 1 m in the north-south direction. These directional trends are not evident at the individual AESA sites and additional transects at each site are needed to verify this conclusion.

Spatial analysis of selected soil properties sampled at three AESA sites indicated that the sampling area could be expanded except for N. Further soil nutrient sampling in different ecoregions will validate this initial conclusion.

ACKNOWLEDGEMENTS

I would like to thank Jason Cathcart of AAFRD, Conservation and Development Branch for his help in formulating approaches to analyzing and evaluating the data from the Soil Quality Monitoring Program. I would also like to thank Jody Heinz for preparing data files and Gemar Lohstraeter for coordinating the field sampling. Thanks to the AESA staff involved in the project for their diligence and dedication in the field work to ensure the best possible data quality.

1.0 Introduction

1.1 Soil Spatial Variability

Soil properties vary considerably with pH the least variable in a soil mapping unit; cation exchange capacity showing moderate variability; and organic matter and K having high variability (Yates and Warrick, 2002). The *mean* and *variance* are used to describe and compare soil nutrient variation in classical statistical analysis. This variation has also been characterized by the coefficient of variation (CV) which ranges from 50 to 300% for selected soil properties (Yates and Warrick, 2002).

Spatial variation has been studied using geostatistics, which is a set of tools where the assumptions of sample independence and homogeneity are removed (Upchurch et al., 1991). These tools measure the degree of dependence of samples. They have been applied extensively in mining and petroleum exploration with the objective of quantifying resources, but have been used on a limited basis in soil science (Bourgault et al., 1997; Deutsch & Journel, 1998; Goovaerts, 1997; Isaaks & Srivastava, 1989; Journel & Huijbregts, 1978).

A geostatistical analysis of soil nutrients could consist of (1) exploratory data analysis using descriptive statistics, and (2) spatial continuity of soil nutrients (Deutsch & Journel, 1998; Goovaerts, 1997; Isaaks & Srivastava, 1989). Spatial continuity of variables has led to the theory of regionalized variables. A random function (RF) is a set of random variables (RV) $Z(\mathbf{u})$ defined over multiple locations, $\mathbf{u}$. The mathematical representation of this spatial variability may be provided by a random function concept (Isaaks & Srivastava, 1989; Journel & Huijbregts, 1978).

Spatial modeling begins with determining the variogram parameters for a particular model. Variogram analysis can be used to compare observations at different distances and directions. Soil nutrients have significant large scale variability (Gallichand et al., 1992; Trangmar et al., 1985; Yost et al., 1982). Researchers found this distance to vary from 4 m for pH, 32 km for phosphorus, 120 m for EC, and 10 and 32 km for K (Trangmar et al., 1985; Gallichand et al., 1992; Yost et al., 1982).

Variogram models can be fit for mapping. Nested spherical models were fit to empirical variograms for pH and EC, respectively (Gallichand et al., 1992; Trangmar et al., 1985). In a second study, exponential models were fit to data from soil pH, K and phosphorus (Yost et al., 1982).

1.2 Variography

When soil nutrient data are correlated in space they will have a lower variance, γ, at smaller separation distances (h) than at larger separation distances (Figure 1). The nugget represents unexplained variation due to measurement error and/or sources of spatial variation at very small distances. As separation distance increases beyond some distance called the range, the variance values often stay constant at a value known as the sill (Deutsch & Journel, 1998).

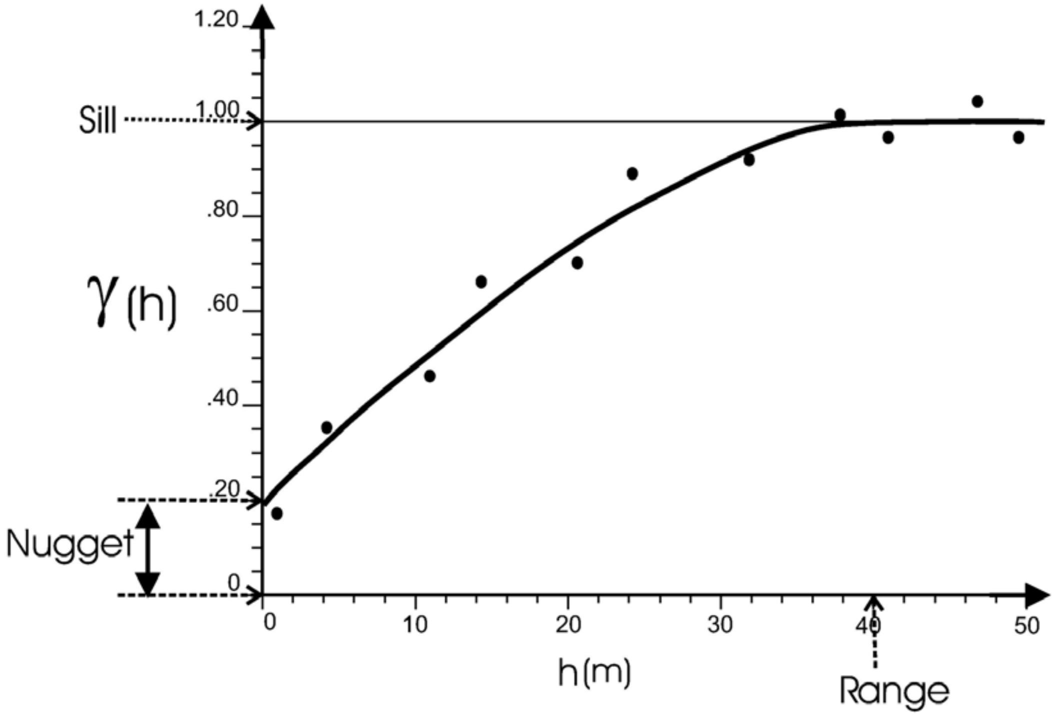


Figure 1. A variogram function for a spherical, isotropic model with a nugget variance (0.20). The dots represent calculated points of the experimental variogram while the solid line is the model variogram**.**

A variogram model can be constructed as a sum of variogram functions:

$$\gamma(h) = \sum_{i=1}^{nst} C_i \Gamma_i (h)$$

where (h) is a variogram model for direction and distance vector h, *nst* is the number of variogram functions or "nested structures", C_i. $i = 1, \ldots nst$ are the variance contributions for each nested structure, and $\Gamma_i, i = 1 \ldots nst$ are the variogram functions. The variance contributions of each nested structure sum to one that is the sill. Each nested structure could have different range parameters in different directions.

Variogram models are often fit to experimentally calculated points. Each variogram model has a lag distance *h* as a parameter. This distance is calculated by breaking down the distance vector **h**, into its 3 principal directions, vertical (h_{vert}), major horizontal ($h_{h\text{-}major}$) and minor horizontal ($h_{h\text{-}minor}$):

$$h = \sqrt{\left(\frac{h_{vert}}{a_{vert}}\right)^2 + \left(\frac{h_{h-major}}{a_{h-major}}\right)^2 + \left(\frac{h_{h-minor}}{a_{h-minor}}\right)^2}$$

The distance range parameters, *a*, in a_{vert}, $a_{h\text{-}major}$ and $a_{h\text{-}minor}$ correspond to each direction for the nested variogram structure. Geometric anisotropy results from variograms that have the same sill but different ranges whereas zonal anisotropy occurs when the sill changes with direction. Each structure may have its own anisotropy (Deutsch & Journel, 1998).

Typical variogram models include linear, spherical, exponential, Gaussian, and Power Law. A model for an empirical variogram is the spherical and Gaussian model given by:

$$\gamma(h) = C^{*}Sph(h) = \begin{cases} C^{*}[1.5(h) - 0.5(h)^{3}] & \text{if } h \leq 1 \\ C & \text{if } h \geq 1 \end{cases}$$

$$\gamma(h) = \begin{cases} C * [1 - \exp(-3h)^{2}] & \text{if } h \leq 1 \\ C & \text{if } h \geq 1 \end{cases}$$

where *C* is the variance contribution for each nested structure. The range is 1 if *h* is normalized as above. Directional trends or anisotropy in soil nutrient data are common (Deutsch & Journel, 1998).

1.3 Sampling

Transect sampling involves establishing one or more transect lines, parallel or nonparallel, across the area of interest. If the lines are parallel, this sampling approach is similar to systematic grid sampling. The advantage of transect sampling over systematic grid sampling is the relative ease of establishing and relocating transect lines as opposed to an entire grid. Samples are collected at regular intervals along the transect line at the surface and/or at a specified depth(s). The distance between the sample locations is determined by the length of the line and the number of samples to be collected.

Sampling using transects has been acceptable to determine spatial correlation (Wirth, 2001). Wirth (2001) investigated the spatial variability of organic carbon (C_{org}), hot-water soluble carbon (C_{hwl}), total nitrogen (Nt), potential cation exchange capacity (CEC), pH and texture at 89 locations over 151 km. The transect sampling strategy and the variogram analysis proved to be suitable to evaluate spatial patterns of soil properties at the regional scale, including C_{mic} as a reliable, quantitative measure of soil chemical and physical properties.

Solie et al., (1999) reported on a variance analysis of soil properties such as soil N, P, K, organic C, and pH using 21.34 m transects. Range of correlation varied from 1.9 m for P to 5.3 m for organic C with sampling occurring on a 0.3 x 0.3 m grid.

Morton et al., (2000) discussed sampling on 10 m intervals using a 100 m transect for monitoring pH, P, S, K and organic C in 77 New Zealand fields. The range of correlation varied from 10 to 100 m.

The Environmental Protection Agency (Anonymous, 2002) has provided a guide on applying standard statistical sampling designs (such as simple random sampling) and more advanced sampling designs (such as ranked set sampling, adaptive cluster sampling) to environmental applications. This guide also discusses spatial designs under systematic or grid sampling. Transects are grids in one dimension and are practical and convenient to implement in the field. They are appropriate if there is no information about a soil property and the objective is to determine spatial correlation or if the spatial pattern is known, to determine the shape of the pattern or its strength. Constant distance intervals between sampling locations for a transect allows for the efficient estimation of trends and patterns over space, as well as the correlation structure needed for modeling.

Buscaglia and Varco (2003) used transects to measure spatial variability of N, C, P, Ca, K, Mg, Na, Zn, and pH. In Transect 1, there was long range variability of 300 m while in Transect 2 most of the soil properties had a range of correlation of 46 m. A total of 144 samples per transect was analyzed for spatial correlation using correlograms.

Baert et al., (2005) explains the differences between design and model based sampling techniques. Sampling is traditionally done by taking a sample and estimating population parameters from the sample, making use of the Central Limit Theorem and the normal distribution. This has been the classic approach to sampling and is known as design-based sampling. Judgmental, random and systematic or grid sampling are examples of design based sampling. More recently, a model based approach to sampling, where a formal model describes the sampling process, is being implemented. Often this is done from a Bayesian or probabilistic viewpoint. Nested sampling is a form of model based sampling to account for spatial correlation at different scales. Model based sampling accounts for dependence of samples and spatial autocorrelation. Transect sampling of soils was found to be more effective with systematic compared to random sampling along the transect as discussed by Baret et al., (2005).

Soil properties pH, EC, OM, P, Ca, K, Mg, and Na had a range of correlation of 4 to 32.9 m using grids sampled every m^2 in two 10 X 10 m areas (Chung et al., 2000). This sampling technique differed from the above since a grid was used. In geostatistics, we assume data are stationary and representative of the area of interest. For this study, this assumption was violated and the data were detrended prior to fitting the variogram to ensure the data were stationary.

Variograms and scatter grams of soil bulk density were used to evaluate sampling methods on a 1 x 1 m soil block 6 inches thick (Entz and Chang, 1991). The authors found a stratified grid scheme to be suitable if the distribution of the soil parameter is unknown, there is periodicity in the data, time constraints are a concern, and there is no variogram available. Stratified grid is a systematic approach where the sample sites are chosen according to grids or transects within each class. The research area is divided into relatively similar areas and the sample sites are chosen based on the grid or transect. This ensures that areas are not over- or under-sampled.

Riha et al., (1985) sampled soil for pH and OM every 5 m over two 60 m transects with each transect perpendicular to the other. Greatest spatial variability occurred at 1 m or less for pH while for OM, there was little spatial correlation. Variograms were used to ascertain these conclusions.

1.4 Objectives

The Alberta Soil Quality Monitoring Program was initiated to provide baseline soil information, monitor changes in soil quality, evaluate landscape effects on soil quality, and to provide data for validating simulation models (Cannon, 2002).

A landscape-based field project was established in 1997/98 across the white area of Alberta. Forty-two Benchmark Sites were selected representing seven ecoregions (Peace Lowland, Mid-Boreal Upland, Boreal Transition, Aspen Parkland, Moist Mixed Grassland, Fescue Grassland and Mixed Grassland) of the Boreal Plains and Prairies ecozones. At each benchmark site, a suite of soil chemical, physical and biological properties is measured along a topographical sequence. The measured properties include: soil fertility (N, P, K, S), pH in water and $CaCl_2$, EC, SAR (if EC >4), mineralizable N, total organic and light fraction carbon (McKeague 1978, Campbell et al., 1997, Gregorich and Ellert 1993) in addition to crop yield.

The main objectives of the fall benchmark sampling across Alberta is to provide baseline soil information, to evaluate landscape effects on soil quality, to provide a data set to test and validate simulation models (i.e., crop growth, wind erosion, water erosion, etc.) and to monitor changes in soil quality over time on a field landscape basis. As data is collected annually at the same location, the Benchmark Sites also give an indication of temporal changes in soil fertility at the same point, and provide data on the landscape effects upon soil properties.

To meet the program objectives, annual sampling at each of the sites is required. To date, this sampling protocol has been confined to an area within 2 meters of a central marker. At sites where the sampling location is a tilled field, as would occur under conventional cropping practices, the soil is homogenized and the sampling holes backfilled yearly. At pasture, or long-term no-till sites, backfilling of sampling holes is not always possible. This may eventually result in significant differences in soil characteristics within the two-meter radius of the central marker, owing to the repeated removal of soil cores (which will begin to effect inherent soil properties, e.g., preferential flow). Sampling at the Benchmark Sites must be expanded to a larger radius to avoid significant differences as a result of changes in soil properties adjacent to the central marker.

Preliminary investigations conducted in the spring of 2005 concluded that there was little difference in soil properties between the two data sets collected in the fall of 2004. However, an error was made in the laboratory and sampling was repeated on alternate sites in the fall of 2005 to confirm this initial observation. The 2005 sampling strategy involves sampling from the 0 to 2 m area surrounding the central marker, and again from a 2 to 4 m area, as suggested by Method 2 by Cathcart and Haung, (2005). This sampling strategy will be conducted at 4 sites in each region of the province (Peace, Northern, Central and Southern Regions), for a total of 16 comparative sites.

To gain an understanding of the spatial variation of selected soil properties at the Benchmark Sites and investigate the current sampling protocol, three additional Benchmark Sites in central Alberta (Dapp (681), Carvel (684), and Tomahawk (692)) were sampled in the fall of 2005 to permit the calculation of variograms for selected soil properties at those sites. The goal of this research was to sample in a transect pattern and determine the spatial dependence of selected soil nutrients at distances beyond 2 m.

2.0 Methods

2.1 Soil Sampling

Each fall prior to freeze-up, a composite soil sample consisting of approximately ten cores each taken from the 0 to 15 and 15 to 30 cm depths is collected. These samples are collected within a radius of 2 meters from a global positioned central marker at each of three landscape positions (upper, mid and lower slope positions). In October, 2005, soil samples from the 0 to 15 cm depth were taken from two perpendicular transects at three slope positions. Each transect measured 32 m in length, crossing over the central marker at each of three Benchmark Sites in central Alberta (Dapp (681), Carvel (684), and Tomahawk (692)) as illustrated in Figure 2.

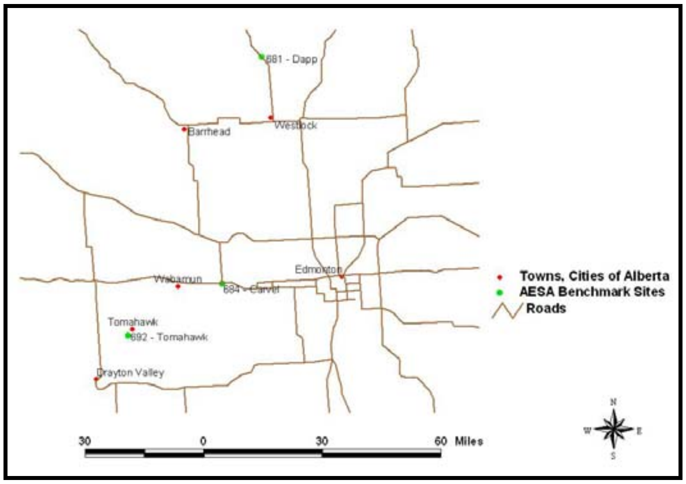


Figure 2. Location of the AESA selected Benchmark Sites for spatially sampling selected soil nutrients.

To identify spatial patterns of selected soil chemical properties collected from the Benchmark Sites, two transects at each slope position at a benchmark site are marked. Transect 1 is perpendicular (i.e. along the same elevation as the slope position) while Transect 2 is at an 8.1941° angle upslope from that elevation (Figure 3). The transects are measured, starting at "0 m", 4 m from the central marker for each of the two transects, crossing over the central marker, and extending 24 m beyond the 4 m mark on the opposite side of the existing sampling area, for a total transect length of 32 m. Geographic locations for each of the ends of the two transects were GPS referenced. Since these sample locations were known relative to the central marker, we were able to calculate X and Y coordinates for each soil core with distances in meters, and this enabled us to calculate the distances among all possible pairs of samples for use in geostatistical analysis. The sampling interval doubles from the location of 0.25 cm following the sampling pattern described in Table 1. At each location, two cores, each 2.5 cm wide, side by side to a depth of 15 cm are collected to provide sufficient soil for analysis. Samples were bagged and sent to the laboratory for analysis. Soil from these sampling intervals was analyzed for organic matter (OM % by weight), nitrate (NO_3-N, mg/kg), phosphorus (P, mg/kg), potassium (K, mg/kg), electrical conductivity (EC, dS/m at 25^0C) and pH (McKeague 1978, Campbell et al., 1997, Gregorich and Ellert 1993).

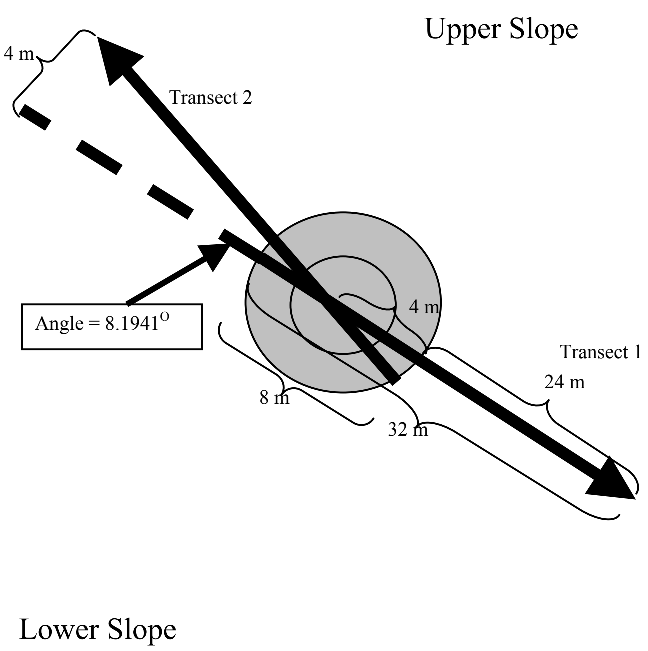


Figure 3. Orientation of sampling transects (Transect 1 and 2) at the AESA selected Benchmark Sites.

Table 1. Soil sampling intervals per transect used at three AESA Benchmark Sites in central Alberta.

0.00 m	1.0 m	8.0 m
0.25 m	2.0 m	16.0 m
0.50 m	4.0 m	32.0 m

2.2 Spatial Analysis

On completion of the soil chemical analysis, the data is analyzed using geostatistical procedures, to produce variograms for the selected soil properties using the public domain software GSLIB (Deutsch & Journel, 1998).

A mathematical representation of spatially distributed variables is the "random function" concept (Isaaks & Srivastava, 1989; Journel & Huijbregts, 1978). Uncertainty in the soil nutrient, $z(\mathbf{u})$, at location $\mathbf{u}$ is modeled with a random variable (RV), $Z(\mathbf{u})$. The random variable, $Z(\mathbf{u})$, is location dependent. A set of RV's is called a random function (RF) denoted by $\{Z(\mathbf{u}), \mathbf{u} \in$ study area A$\}$.

For N locations $\mathbf{u}_i, i = 1, ..., N$, there corresponds a vector of N random variables $(Z(u_1), ..., Z(u_N))$ that is characterized by an N-variate or N-point cumulative distribution function (cdf):

$$F(\mathbf{u}_1, ..., \mathbf{u}_N; z_1, ...z_N) = \text{Prob}\{Z(u_1) \leq z_1, ..., Z(u_N) \leq z_N\}$$

This describes the joint probability distribution of the N values $(z(\mathbf{u}_1),...,z(\mathbf{u}_N))$. The concept of a random function allows modeling the degree of correlation between any number of RV's and updating of prior cdf's.

A one-point cdf $F(\mathbf{u}; z) = \text{Prob}\{Z(\mathbf{u}) \leq z\} \in [0, 1]$ has a first order moment that is also known as the expectation or mean of the random variable, $Z(\mathbf{u})$, defined as:

$$E\{Z(\mathbf{u})\} = m(\mathbf{u}) = \int_{-\infty}^{+\infty} z dF(\mathbf{u}; z)$$

The expected value operator can be thought of as a probability weighted average. In practice, a continuous integral may be solved by creating a large number, *L*, of equal probability values. The variance of Z(**u**) is a second order moment about the expectation *m*(**u**):

$$Var\{Z(\mathbf{u})\} = \sigma^2(\mathbf{u}) = E\{[Z(\mathbf{u}) - m(\mathbf{u})]^2\}$$

The covariance for two locations $\mathbf{u}_1$ and $\mathbf{u}_2$ is defined as:

$$C(\mathbf{u}_1, \mathbf{u}_2) = E\{[Z(\mathbf{u}_1) - m(\mathbf{u}_1)]\}E\{[Z(\mathbf{u}_2) - m(\mathbf{u}_2)]\}$$

The variogram for two locations $\mathbf{u}_1$ and $\mathbf{u}_2$ is defined as:

$$2\gamma(h) = E\{[Z(\mathbf{u}_1) - Z(\mathbf{u}_2 + h)]^2\}$$

where $2\gamma(h)$ is the variogram, separated by vector **h** and a semi-variogram is one half a variogram, (h).

The mean *m*(**u**) is a measure of central tendency and the variance $\sigma^2(\mathbf{u})$ is a measure of spread. The covariance measures correlation or similarity of two RV's whereas the variogram measures variability or dissimilarity of two RV's.

The first and second order moments described above depend on location **u**. Statistical inference may require many repetitive realizations to calculate distributions and expected values. Such replication is unavailable and we must pool data from different locations. Then the F{Z(**u**), **u** ∈ study area A}is said to display first order stationarity since its univariate cdf and first order moment, the mean, are invariant. A decision of stationarity allows inference (Journel & Huijbregts, 1978). We further assume that pairs of data approximately a distance h apart within the study area, A, are repetitions of the pair $[Z(\mathbf{u}_1),Z(\mathbf{u}_2)]$ where $\mathbf{u}_1 - \mathbf{u}_2 \simeq \mathbf{h}$. This means that the statistical relationship between two data values does not depend on their positions within A, but only on their separation distance. This is a decision of second order stationarity. The concept of "stationarity" is the assumption of "spatial homogeneity" over a study area. More precisely, a RF is stationary if the two RVs $\{Z(\mathbf{u}_1), ...,Z(\mathbf{u}_N)\}$ and $\{Z(\mathbf{u}_1 +\mathbf{h}), ...,Z(\mathbf{u}_N +\mathbf{h})\}$ have the same N-variate distributions whatever the distance, **h**. According to this definition, the stationary expected values are written:

$$E\{Z(\mathbf{u})\} = m, \ \forall \mathbf{u} \in A$$
$$Var\{Z(\mathbf{u})\} = \sigma^2 = E\{[Z(\mathbf{u}) - m]^2\}, \ \forall \mathbf{u} \in A$$
$$C(\mathbf{h}) = E\{Z(\mathbf{u} + \mathbf{h}) \cdot Z(\mathbf{u})\} - m^2 \ \forall \mathbf{u} \in A$$
$$2(\mathbf{h}) = E\{[Z(\mathbf{u} + \mathbf{h}) - Z(\mathbf{u})]^2\}, \ \forall \mathbf{u} \in A$$

The decision of stationarity for developing reliable inferences lies with the practitioner. If more data becomes available or the scale of the study changes, the decision of stationarity may change.

When soil nutrient data are correlated in space they will have a lower variance at smaller separation distances than at larger separation distances (Figure 1). The nugget represents unexplained variation while the range is the separation distance and the variance values often stay constant at a value known as the sill (Deutsch & Journel, 1998).

Variogram models are fit to experimentally calculated soil nutrient data points. Each variogram model has a lag distance, **h** as a parameter. This distance is calculated by breaking down the distance vector **h**, into its vertical, major horizontal and minor horizontal directions. Geometric anisotropy results from variograms that have the same sill but different ranges whereas zonal anisotropy occurs when the sill changes with direction. Typical variogram models include linear, spherical, exponential, Gaussian, and Power law.

Model variograms are assumed to represent experimental variograms for soil nutrient data. Curve fitting of a model variogram relies on expert judgment that is subject to interpretation. Geographic location information that indicates where soil nutrient data is sampled is subject to error during collection.

3.0 Results

3.1 Descriptive Analysis

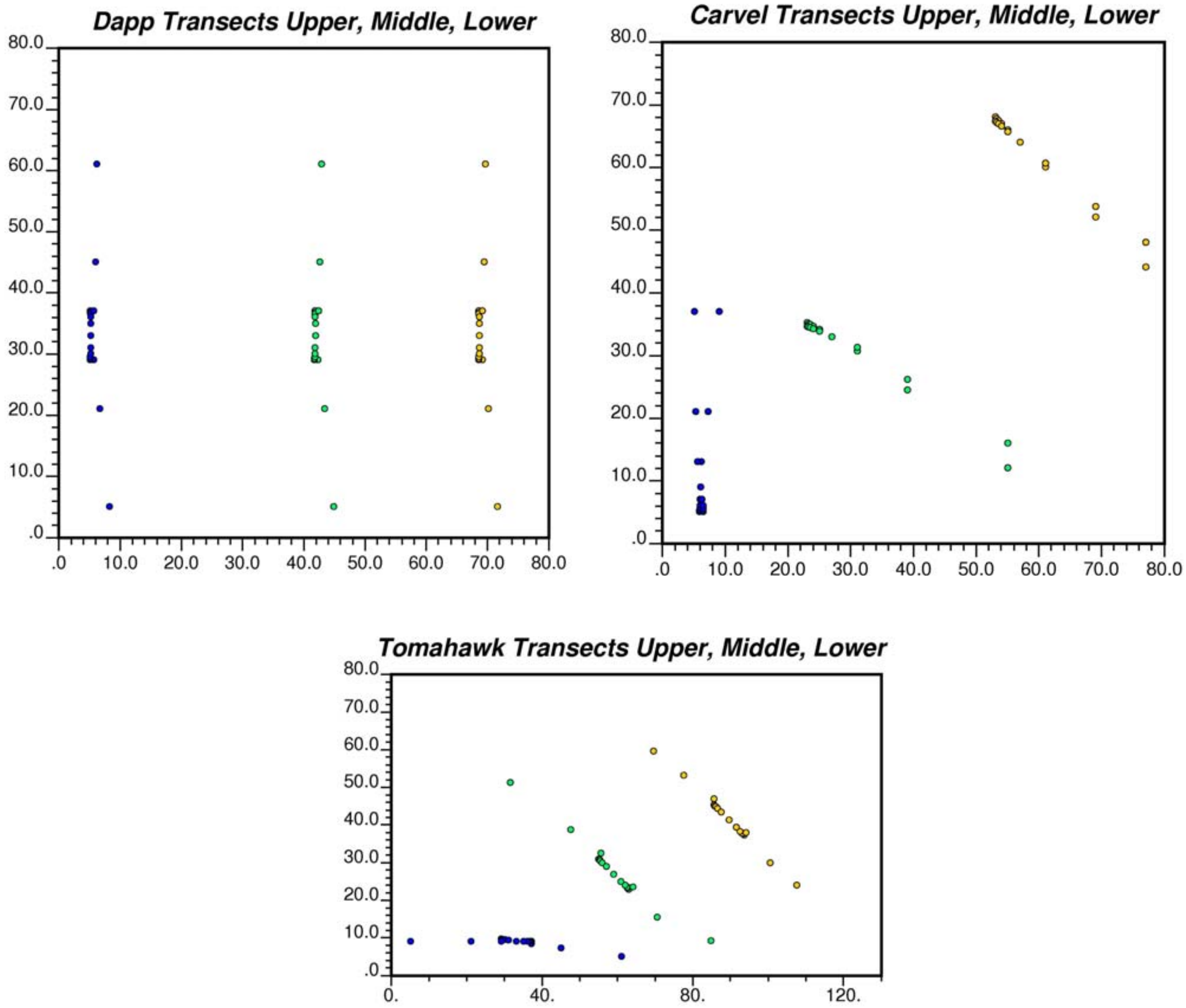


Figure 4. Relative soil sampling locations of the upper, mid and lower slope transects at each of the selected Benchmark Sites, Carvel (684), Dapp (681) and Tomahawk (692). The yellow colored dots represent transects from the upper slope position, green colored dots transects from the mid slope position and blue colored dots transects from the lower slope position.

The relative locations of the 162 sampling points for the sites 681 (Dapp), 684 (Carvel), and 692 (Tomahawk) are displayed in Figure 4. The sampling design is different for the Carvel site due to the topography at the three slope positions. The upper, mid and lower slope positions are represented by yellow, green and blue colors, respectively. The distance for the last sampling point at the Carvel and Tomahawk sites for the upper transects is 24 m rather than 32 m due to the topography at these sites. Results of the soil chemical analysis from each of the AESA sites are listed in Appendix 1, 2 and 3.

Declustering revealed no appreciable difference between the declustered mean of the soil nutrient data and the original, equal weighted mean since the data are aligned in transects as opposed to a grid. Declustering is a weighting technique that adjusts data to be representative of the entire area of interest.

Data transformation is commonly used to reduce the influence of extreme values and make the sample histogram symmetric. However, there are associated problems in performing a back-transform of the data for interpolation (Goovaerts, 1997). In addition, there are redundant data for the soil nutrients nitrogen and phosphorus that increased skewness. Consequently, no transformations are implemented for this data set.

3.2 Descriptive Statistics

The results for the soil nutrients sampled at 162 points from three AESA Benchmark Sites in central Alberta (Dapp (681), Carvel (684), and Tomahawk (692)) are presented in Table 2.

Table 2. Descriptive statistics for selected soil nutrients sampled at three AESA Benchmark Sites in central Alberta.

	OM (%)[a]	N (mg/kg)	P (mg/kg)	K (mg/kg)	EC (dS/m)[b]	pH
Mean	4.78	1.09	19.60	221.80	0.30	6.26
Variance	4.84	0.20	590.49	13665.61	0.02	0.21
CV	46.4	41.2	123.9	52.7	47.2	7.4
Skewness	0.63	5.07	1.51	0.23	2.10	0.44
Kurtosis	-0.39	27.03	1.00	-1.34	5.97	-1.28

[a] at 25° C

[b] by weight

The variability in soil nutrients is highest for potassium and lowest for EC based on the variance. The coefficient of variation is highest for phosphorus and lowest for pH. There is a high amount of variation in all soil nutrients except pH based on the CV. Similarly, all soil nutrient data are positively skewed with nitrogen being the most positive. This indicates that the distributions are nearly symmetrical around the mean with the right tail of the distribution heavier than the left tail. Most of the soil nutrients have a negative kurtosis indicating a flatter distribution except for nitrogen which is positive and very peaked. This is due to the low levels of nitrogen recorded at all the sampling locations.

The spatial distribution of OM, N, P, K, EC and pH averaged over both transects is presented in Figures 5, 6 and 7. Spatial trends are displayed along the transect with respect to variability for all soil variables except N which shows no clear trend. The standard error of the mean is small for pH while it is large for P and moderate for OM, N, K, and EC. This indicates there is large variation in the measurements for P while for pH there is a small amount of variation and consequently, more confidence in the data.

The histograms for each of the soil nutrients are displayed in Figure 8. This confirms the skewness and kurtosis values obtained for each distribution. The nitrogen kurtosis value is positive and the histogram illustrates that most values in the data set are 1 or 0.99.

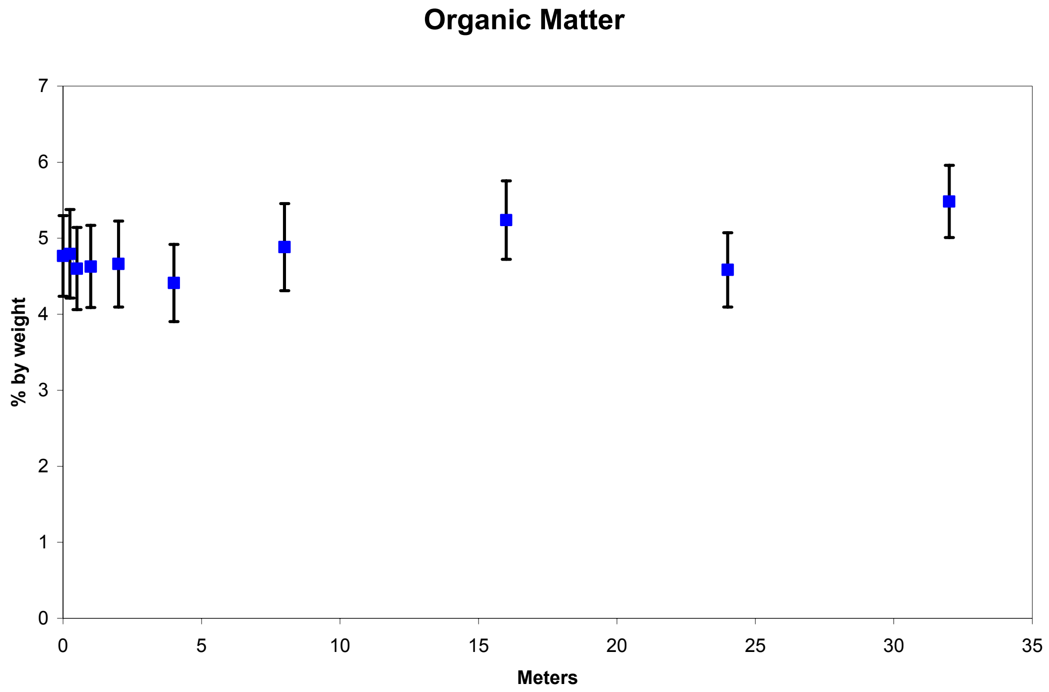
The data for each of the AESA Benchmark Sites, 681, 682 and 694 are tabulated in Table 3 based on 54 sampling locations per site. Soil nutrient means are highest at the Tomahawk site except for phosphorus which is highest at Carvel. The pH is least acidic at the Dapp site. Variability is high for potassium at all three benchmark site based on the variance.

Table 3. Descriptive statistics for selected soil nutrients sampled at AESA Benchmark Sites (Dapp (681), Carvel (684), and Tomahawk (692)) in central Alberta.

	OM (%)[a]	N (mg/kg)	P (mg/kg)	K (mg/kg)	EC (dS/m)[b]	pH
681 Dapp						
Mean	4.04	1.18	4.92	103.52	0.36	6.86
Variance	1.44	0.50	0.01	1849.00	0.03	0.02
CV	30.5	59.3	3.0	41.6	48.0	2.1
Skewness	0.85	4.22	6.86	1.79	1.75	-0.09
Kurtosis	-0.49	17.93	46.29	2.97	2.77	-0.47
684 Carvel						
Mean	3.07	1.10	48.93	217.41	0.32	6.00
Variance	1.69	0.10	488.41	8172.16	0.01	0.06
CV	40.9	28.7	45.1	41.6	32.2	4.0
Skewness	0.22	2.41	0.46	1.09	1.01	0.05
Kurtosis	-1.45	3.86	-1.34	-0.11	1.10	-0.89
692 Tomahawk						
Mean	7.28	0.99	5.06	344.44	0.20	5.93
Variance	1.96	0.00	0.25	1883.56	0.00	0.02
CV	19.6	0.0	10.9	12.6	27.9	2.4
Skewness	0.10	0.00	3.81	0.51	0.38	-0.16
Kurtosis	-1.05	0.00	14.91	0.42	-1.19	-0.71

[a] at 25° C

[b] by weight



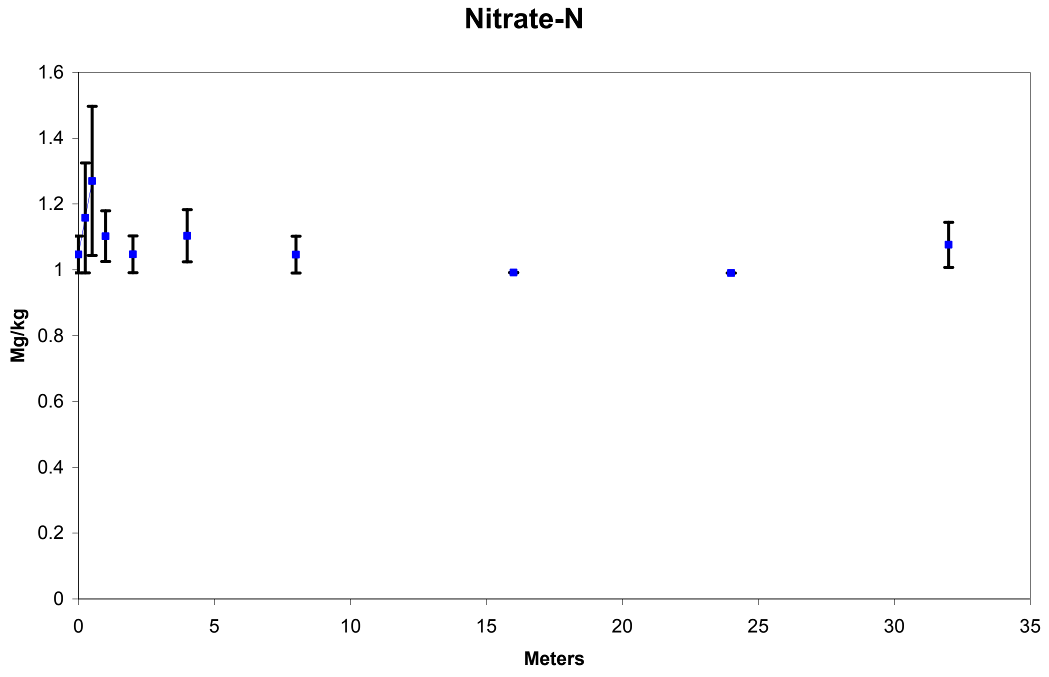


Figure 5. Spatial distribution of average values of organic matter and nitrogen along two transects sampled at 18 locations from three AESA Benchmark Sites in central Alberta. Error bars are standard error of the mean.

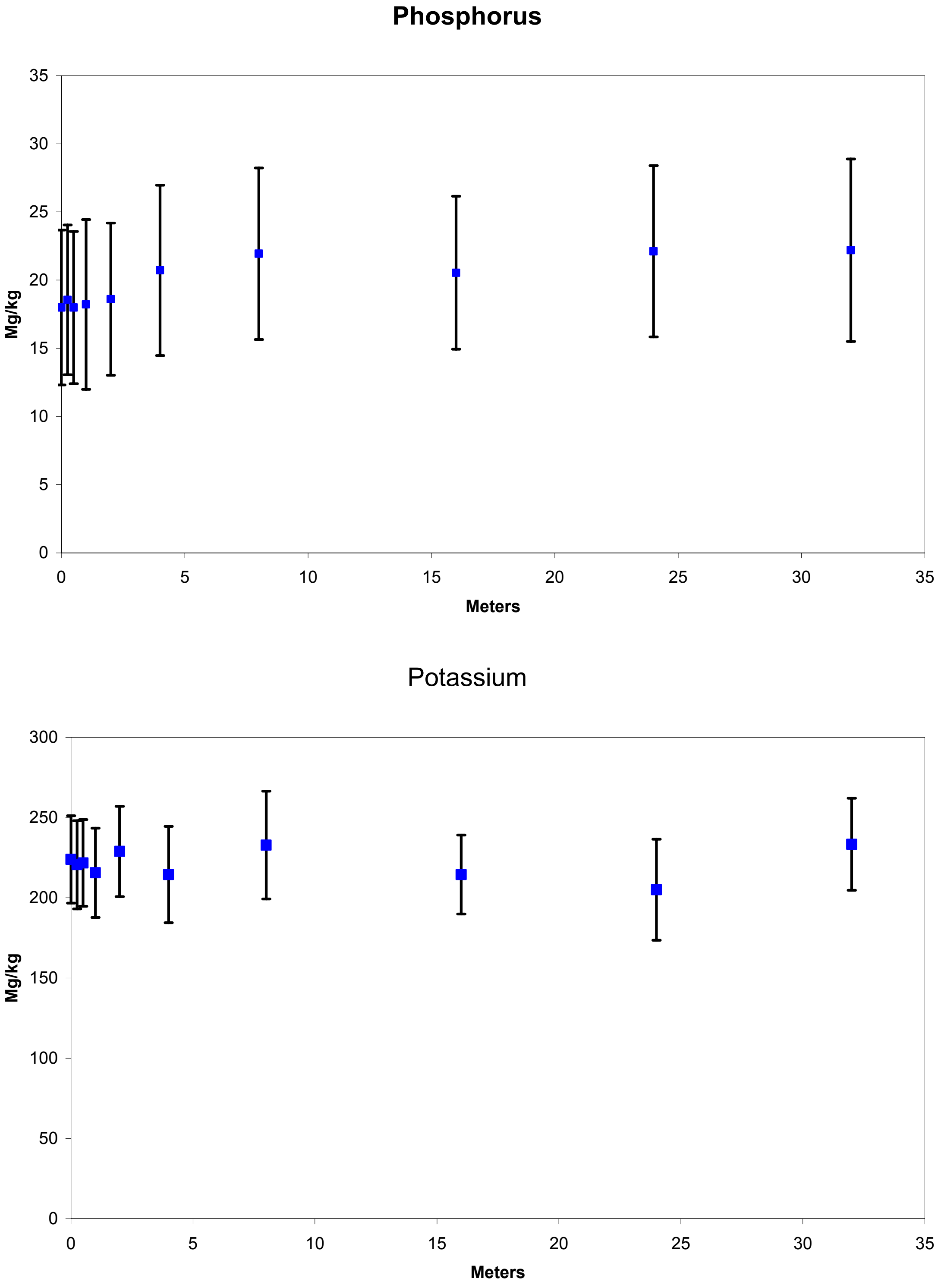


Figure 6. Spatial distribution of average values of phosphorus and potassium along two transects sampled at 18 locations from three AESA Benchmark Sites in central Alberta. Error bars are standard error of the mean.

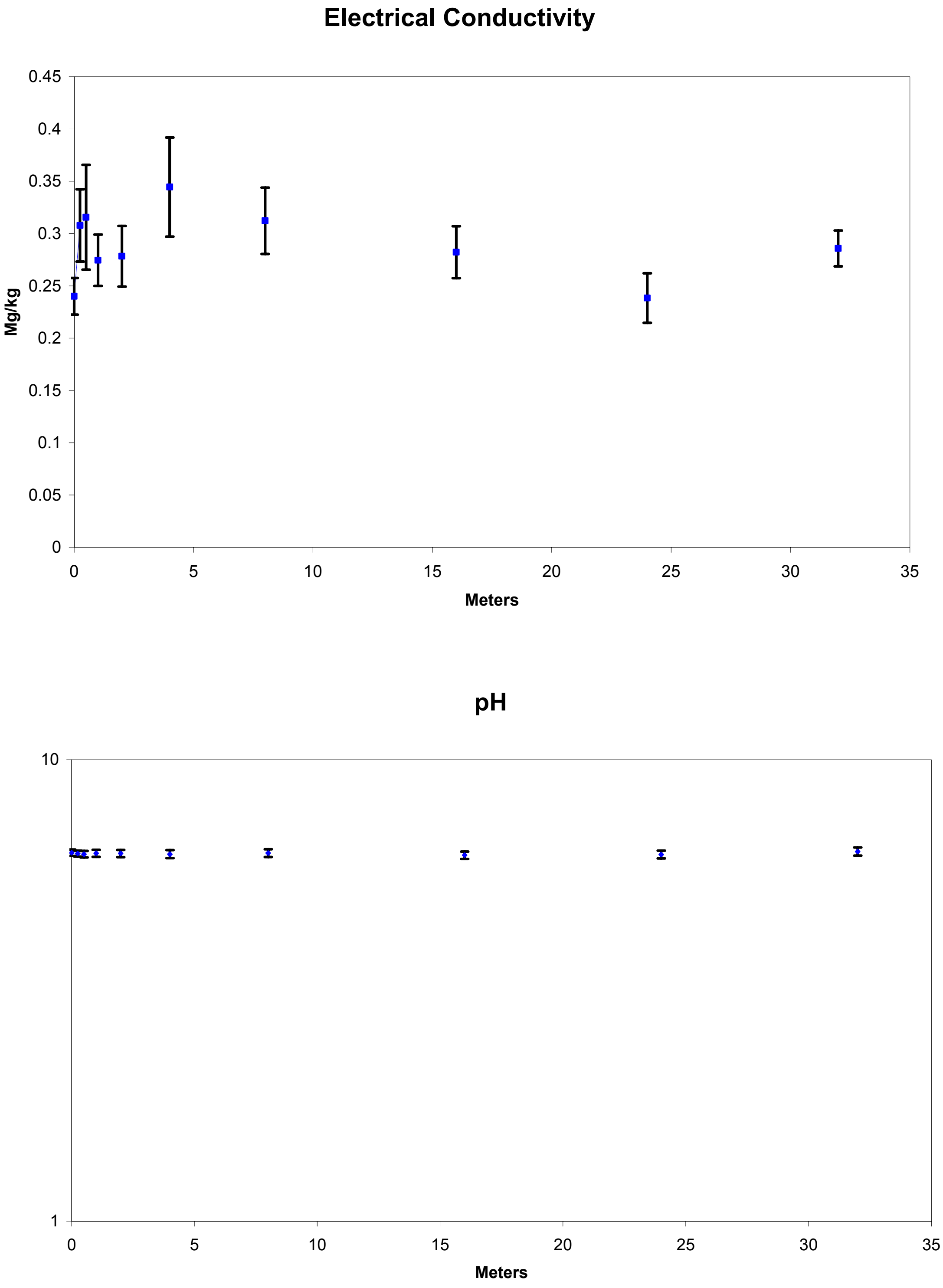


Figure 7. Spatial distribution of average values of electrical conductivity and pH along two transects sampled at 18 locations from three AESA Benchmark Sites in central Alberta. Error bars are standard error of the mean.

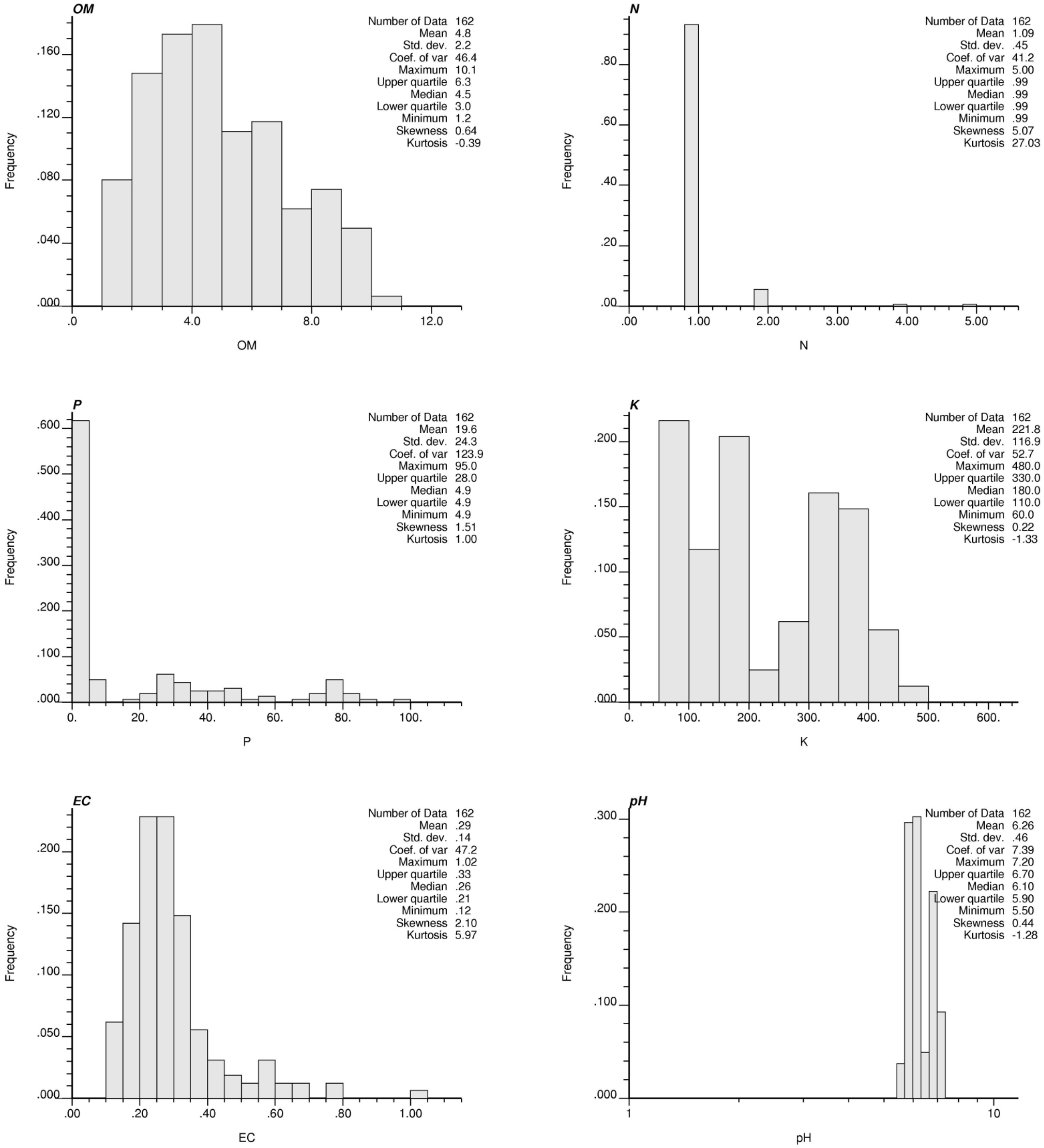


Figure 8. Histograms for the six selected soil nutrients sampled at 162 locations from three AESA Benchmark Sites in central Alberta.

Variation in soil nutrients is similar and high at all three sites based on the CV but between the sites, the variation is lower at the Tomahawk site compared to the Carvel and Dapp sites. The CV is low for phosphorus at the Dapp and Tomahawk sites compared to the Carvel site. Kurtosis is highly positive for nitrogen and phosphorus at Dapp. It is highly positive at Tomahawk for phosphorus. The other soil nutrients are symmetrical and flat peaked for skewness and kurtosis, respectively.

Histograms of soil nutrients for each of the Alberta Benchmark Sites are displayed in Figures 9, 10 and 11. The distributions for nitrogen and phosphorus at Dapp (Figure 9) are peaked validating the kurtosis value for each soil nutrient. The distribution is similar for phosphorus at Tomahawk. The range of the soil nutrients at each benchmark site (Figures 9, 10, and 11) is narrower compared to those obtained for all sites (Figure 11).

Descriptive statistics for the slope positions at the selected Benchmark Sites is provided in Table 4. The soil nutrient means are similar among all slopes except OM, P and K which are highest at the lower slope. Variability is highest in P and K for all slopes based on the variance. Phosphorus variation is highest among the soil nutrients when comparing the CV's. Skewness values indicate most distributions are symmetrical around the mean except for nitrogen while kurtosis values are low indicating a flat distribution. The only exception for kurtosis is nitrogen at all slope positions and EC at the lower slope.

Table 4. Descriptive statistics for selected soil nutrients sampled at 3 slopes over three AESA Benchmark Sites in central Alberta.

	OM (%)[a]	N (mg/kg)	P (mg/kg)	K (mg/kg)	EC (dS/m)[b]	pH
Upper Slope						
Mean	3.68	1.05	15.34	195.93	0.26	6.21
Variance	3.61	0.17	246.49	13363.36	0.02	0.24
CV	50.6	38.8	102.3	59.0	56.1	7.8
Skewness	0.47	6.95	1.16	0.55	1.43	0.41
Kurtosis	-1.19	47.11	-0.05	-1.27	1.13	-1.36
Mid Slope						
Mean	4.50	1.07	16.03	204.07	0.31	6.23
Variance	4.00	0.07	331.24	12678.76	0.02	0.18
CV	43.7	24.8	113.7	55.2	45.0	6.8
Skewness	0.53	3.16	1.68	0.49	1.43	0.50
Kurtosis	-1.25	8.15	2.39	-1.23	2.13	-1.40
Lower Slope						
Mean	6.21	1.16	27.54	265.37	0.30	6.35
Variance	4.41	0.37	1102.24	12034.09	0.02	0.22
CV	33.0	52.0	120.5	41.4	39.8	7.4
Skewness	0.48	4.88	0.85	-0.28	4.06	0.41
Kurtosis	-1.33	26.70	-1.19	-1.05	19.63	-1.39

[a] at 25° C

[b] by weight

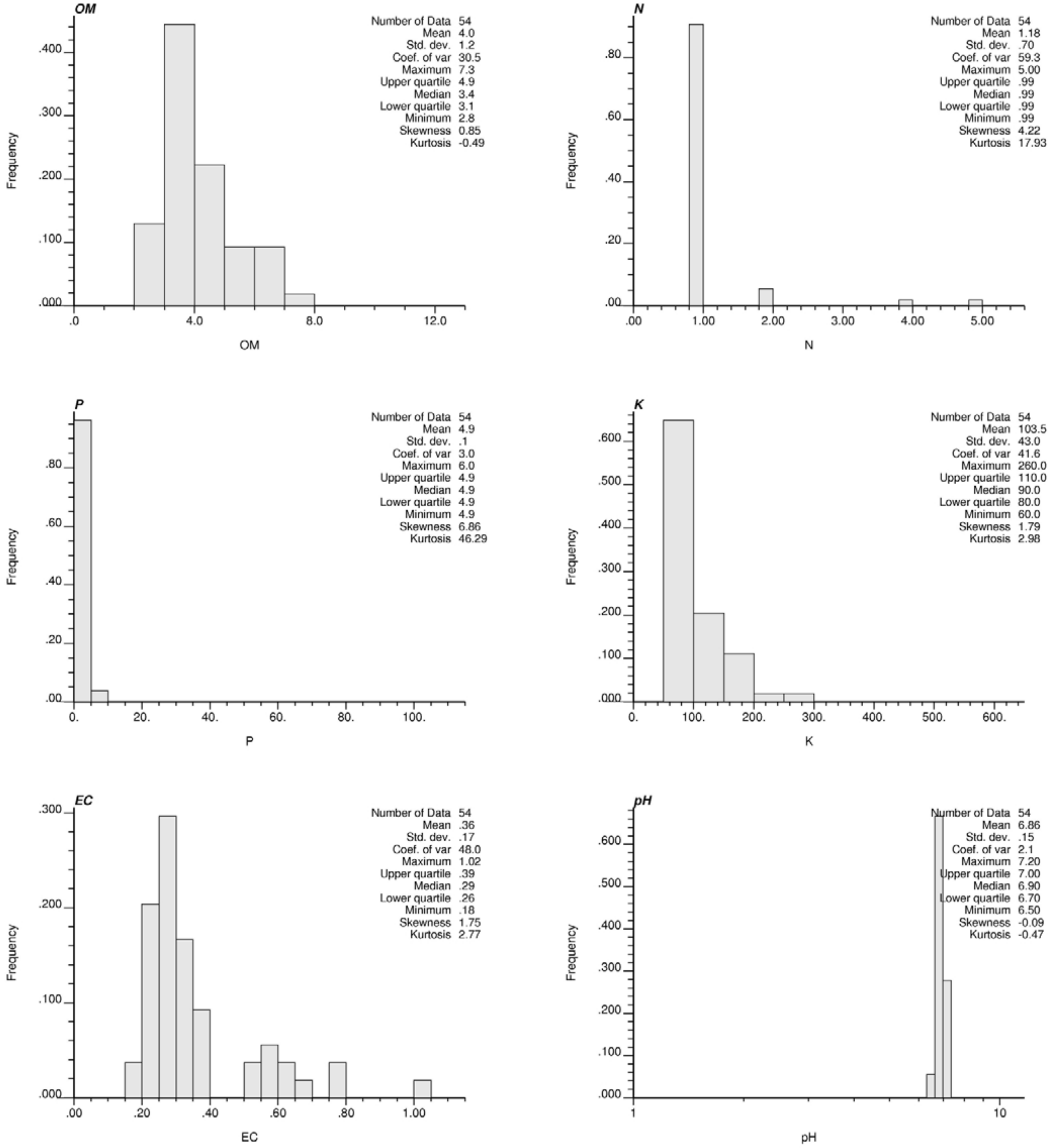


Figure 9. Histograms for the six selected soil nutrients sampled at 54 locations for AESA benchmark site 681 (Dapp) in central Alberta.

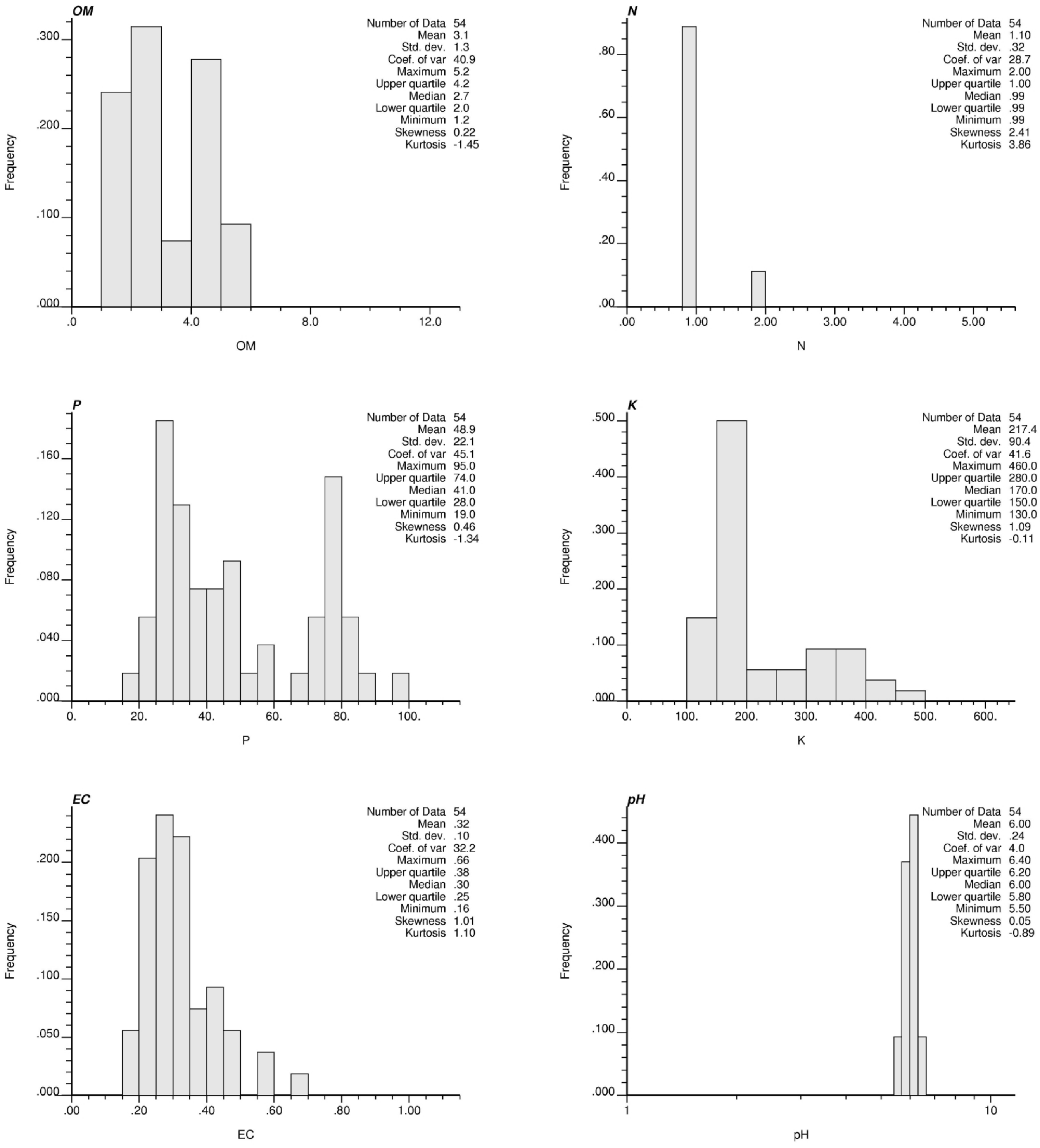


Figure 10. Histograms for the six selected soil nutrients sampled at 54 locations for AESA benchmark site 682 (Carvel) in central Alberta.

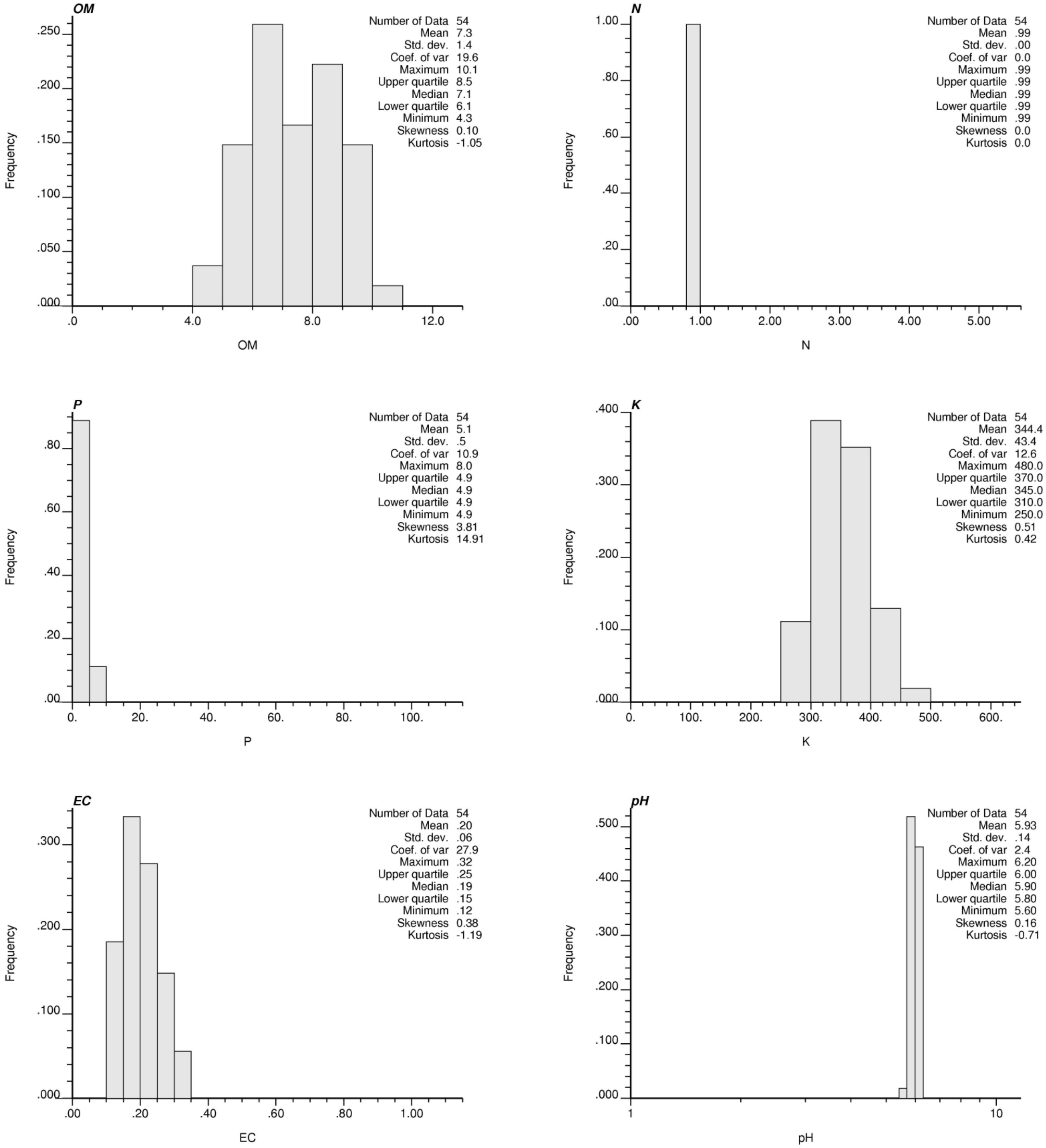


Figure 11. Histograms for the six selected soil nutrients sampled at 54 locations for AESA benchmark site 692 (Tomahawk) in central Alberta.

Table 5. Descriptive statistics for selected soil nutrients sampled at 2 transects over three AESA Benchmark Sites in central Alberta.

	OM (%)[a]	N (mg/kg)	P (mg/kg)	K (mg/kg)	EC (dS/m)[b]	pH
Transect 1						
Mean	4.69	1.12	19.60	223.70	0.30	6.27
Variance	4.41	0.26	571.21	13386.49	0.02	0.21
CV	45.6	45.6	23.9	51.7	49.5	7.3
Skewness	0.52	5.78	1.47	0.25	2.16	0.40
Kurtosis	0.51	38.74	0.90	-1.33	6.59	-1.32
Transect 2						
Mean	4.91	1.07	19.67	219.88	0.29	6.26
Variance	5.29	0.14	610.09	13900.41	0.02	0.22
CV	47.0	35.6	125.5	53.6	44.5	7.5
Skewness	0.40	6.14	1.56	0.22	1.61	0.47
Kurtosis	0.96	41.42	1.14	-1.46	2.68	-1.27

[a.] at 25° C
[b.] by weight

Histograms of soil nutrients for each slope position are illustrated in Figures 12, 13, and 14. The distributions for nitrogen at all slopes (Figures 12, 13, and 14) and EC at the lower slope (Figure 14) are peaked confirming their kurtosis value. The range for each soil nutrient at each slope position (Figures 12, 13, and 14) is narrower compared to those obtained for all sites (Figure 8).

When comparing the mean, variance, CV, skewness and kurtosis of Transect 1 to 2, the values are very similar (Table 5). Transect 1 is perpendicular to the slope position while Transect 2 is 8.1941° angle upslope from Transect 1 (Figure 3). Histograms of the soil nutrient distributions are displayed in Figures 15 and 16.

Table 6. Correlation coefficients for selected soil nutrients sampled at three AESA Benchmark Sites in central Alberta, $P < 0.05$(*).

	OM (%)[a]	N (mg/kg)	P (mg/kg)	K (mg/kg)	EC (dS/m)[b]	pH
OM	1	-0.08	-0.32*	0.67*	-0.33*	-0.18*
N		1	0.12	-0.06	0.40*	0.15
P			1	0.17*	0.11	-0.31*
K				1	-0.38*	-0.67*
EC					1	0.29*
pH						1

[a.] at 25° C
[b.] by weight

The strength of linear dependence among soil nutrients is provided in Table 6. The Pearson correlation coefficients are significant at the 5% level of probability when OM is associated with P, K, EC and pH. Potassium is significantly, negatively correlated with EC and pH.

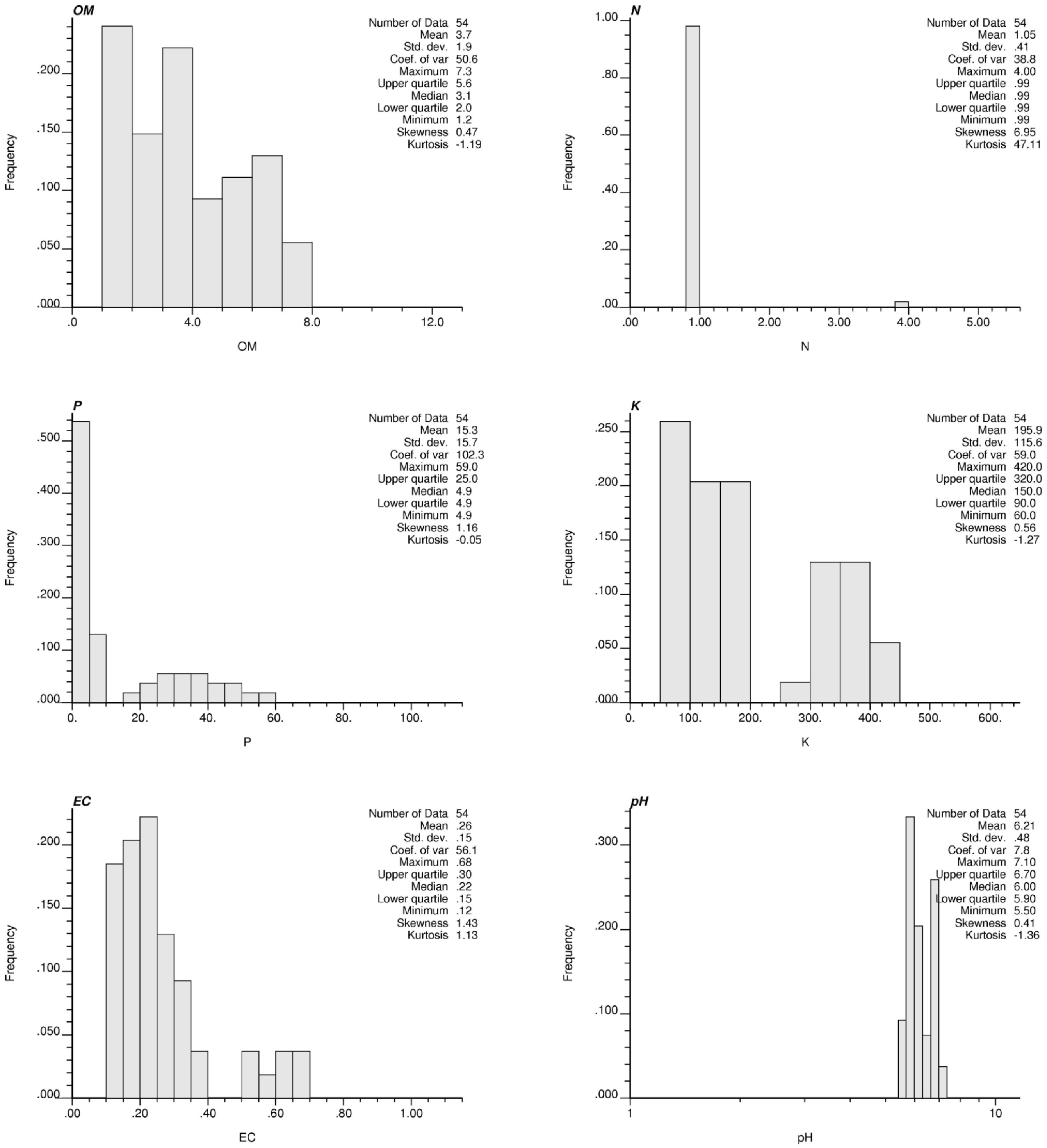


Figure 12. Histograms for the six selected soil nutrients sampled at 54 locations for the upper slope from all AESA Benchmark Sites in central Alberta.

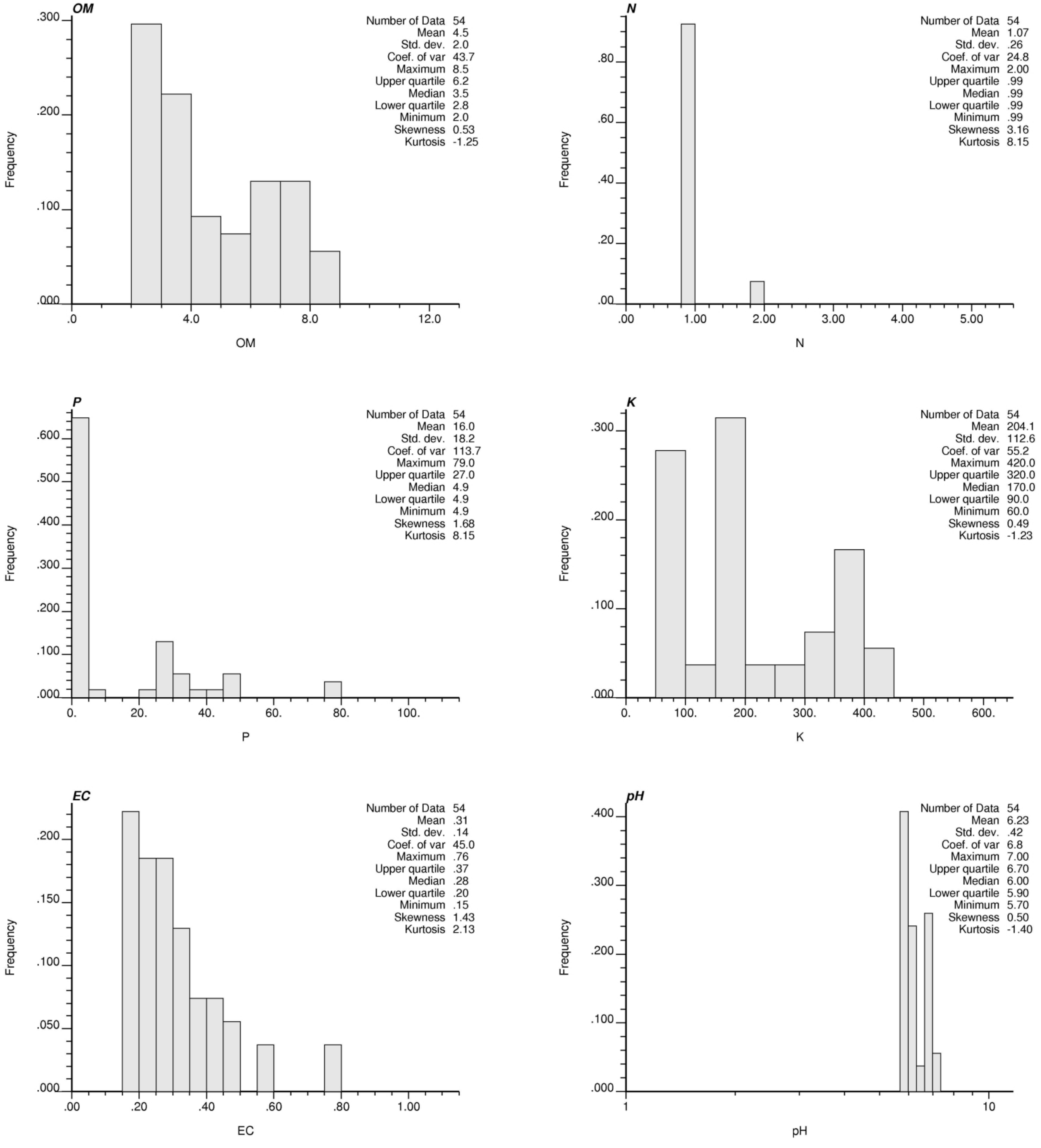


Figure 13. Histograms for the six selected soil nutrients sampled at 54 locations for the mid slope from all AESA Benchmark Sites in central Alberta.

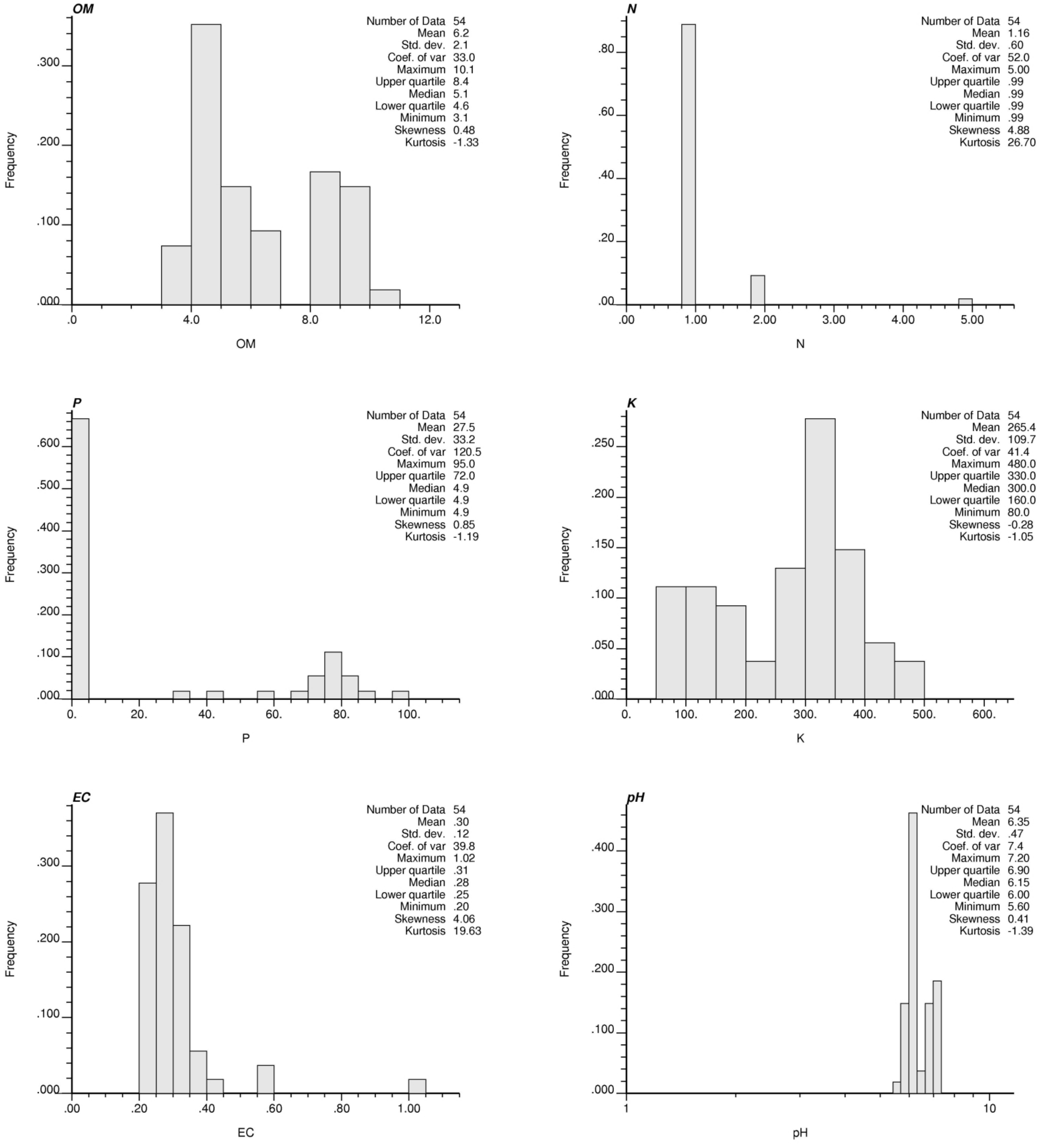


Figure 14. Histograms for the six selected soil nutrients sampled at 54 locations for the lower slope from all AESA Benchmark Sites in central Alberta.

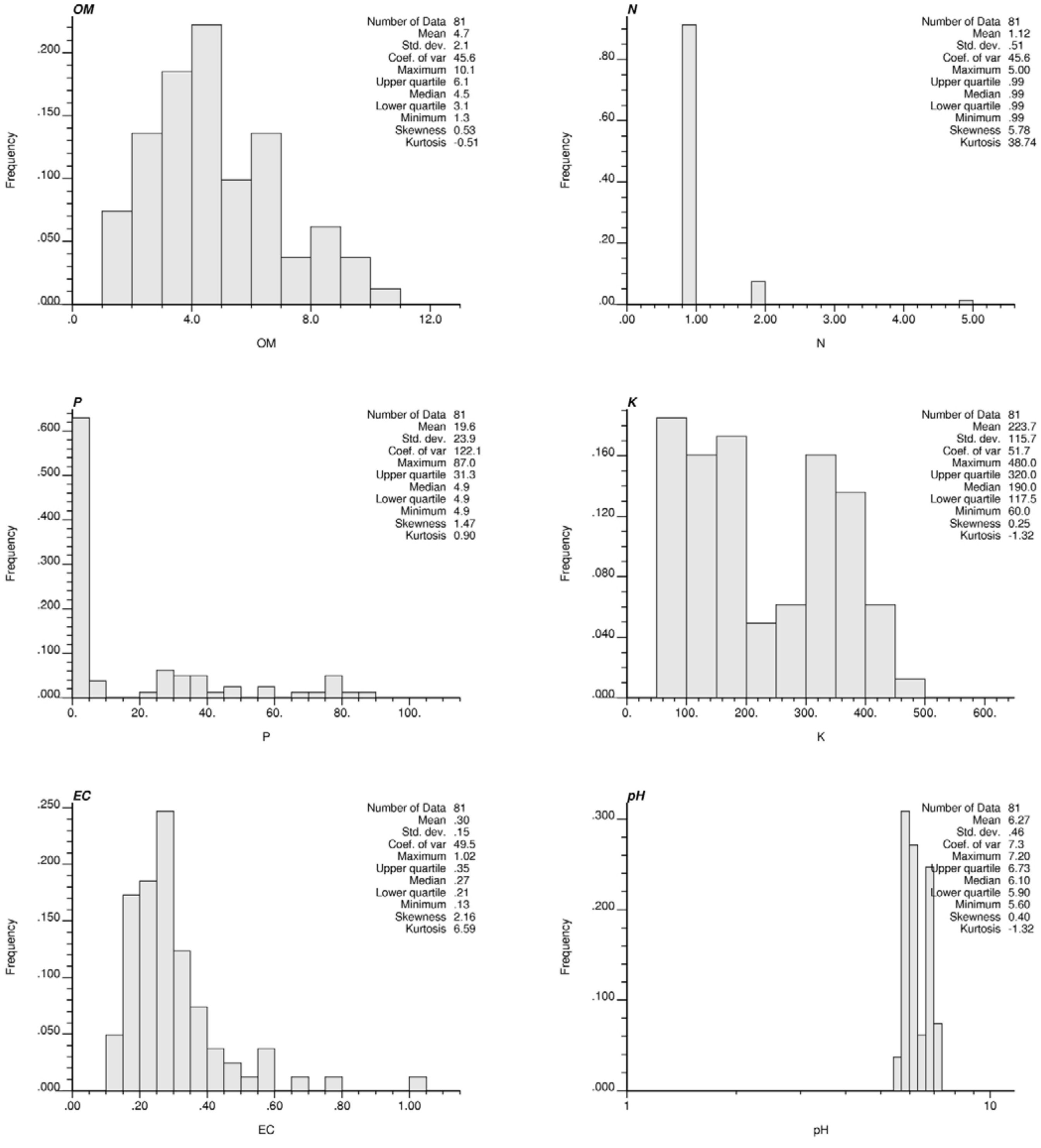


Figure 15. Histograms for the six selected soil nutrients sampled at 81 locations for Transect 1 from all AESA Benchmark Sites in central Alberta.

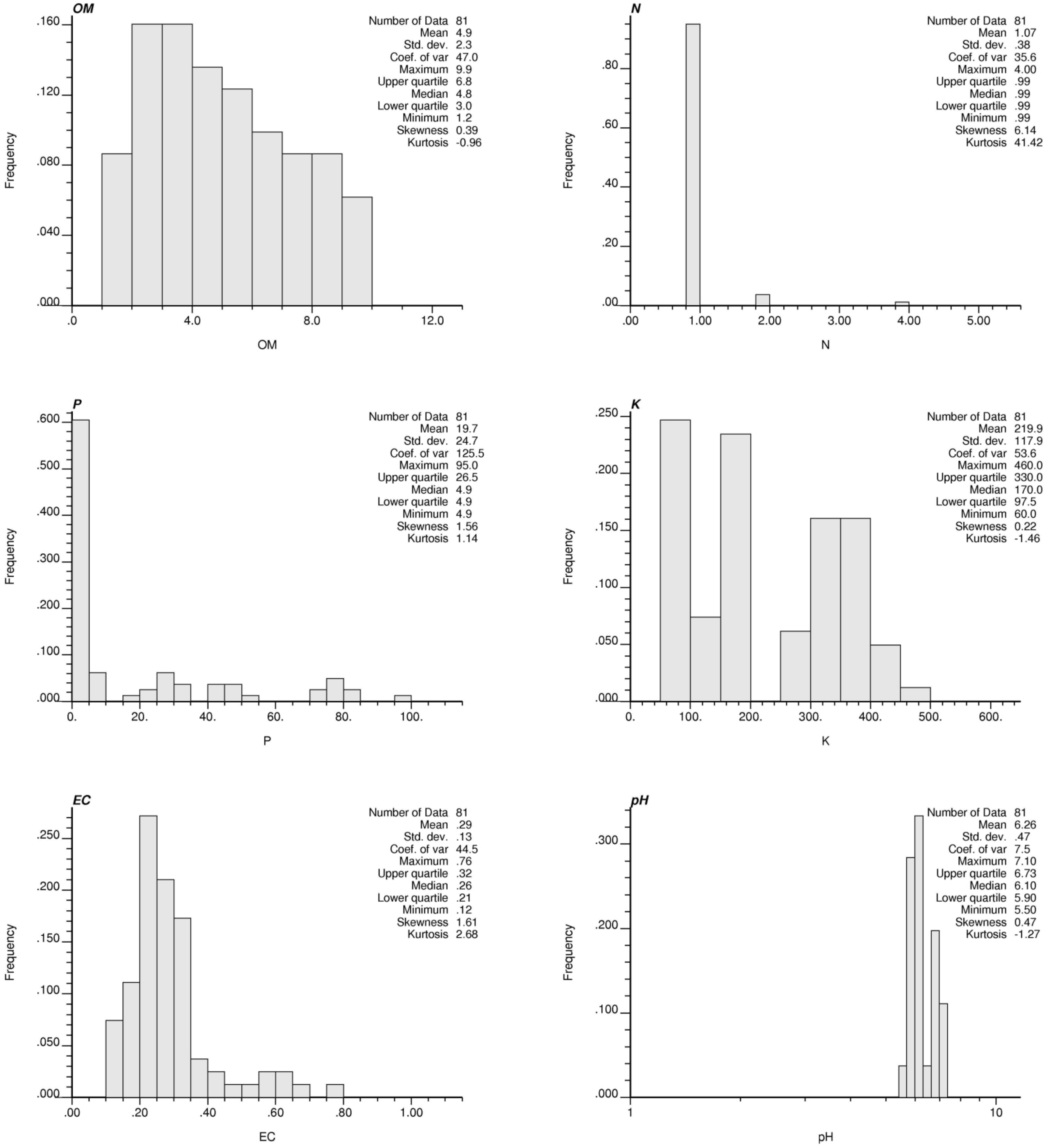


Figure 16. Histograms for the six selected soil nutrients sampled at 81 locations for Transect 2 from all AESA Benchmark Sites in central Alberta.

Table 7. Correlation coefficients for selected soil nutrients sampled at 2 transects over three AESA Benchmark Sites in central Alberta, $P < 0.05$(*).

	OM (%)[a]	N (mg/kg)	P (mg/kg)	K (mg/kg)	EC (dS/m)[b]	pH
Transect 1						
OM	1	-0.05	-0.36*	0.67*	-0.31*	-0.20
N		1	0.16	0.01	0.52*	0.18
P			1	0.11	0.07	-0.20
K				1	-0.40*	-0.64*
EC					1	0.37*
pH						1
Transect 2						
OM	1	-0.12	-0.29*	0.67*	-0.35*	-0.17
N		1	0.08	-0.14	0.23*	0.12
P			1	0.22*	0.14	-0.41*
K				1	-0.37*	-0.71*
EC					1	0.19
pH						1

[a] at 25° C

[b] by weight

Table 8. Correlation coefficients for selected soil nutrients sampled at three AESA Benchmark Sites in central Alberta (Dapp (681), Carvel (684), and Tomahawk (692)), $P < 0.05$(*).

	OM (%)[a]	N (mg/kg)	P (mg/kg)	K (mg/kg)	EC (dS/m)[b]	pH
681 Dapp						
OM	1	-0.05	0.35*	0.47*	-0.19	0.56*
N		1	-0.04	0.11	0.54*	-0.17
P			1	0.27*	-0.02	0.13
K				1	0.09	0.09
EC					1	-0.22
pH						1
684 Carvel						
OM	1	0.37*	0.84*	0.76*	0.01	0.19
N		1	0.48*	0.36*	-0.16	0.40*
P			1	0.79*	-0.04	0.24
K				1	0.02	0.10
EC					1	-0.31*
pH						1
692 Tomahawk						
OM	1	0.00	-0.15	0.16	0.82*	0.48*
N		1	0.00	0.00	0.00	0.00
P			1	0.23	-0.14	0.00
K				1	-0.05	-0.12
EC					1	0.53*
pH						1

[a.] at 25º C

[b.] by weight

Table 9. Correlation coefficients for selected soil nutrients sampled at 3 slopes over three AESA Benchmark Sites in central Alberta, $P < 0.05$(*).

	OM (%)[a]	**N (mg/kg)**	**P (mg/kg)**	**K (mg/kg)**	**EC (dS/m)[b]**	**pH**
Upper Slope						
OM	1	-0.04	-0.63*	0.81*	-0.45*	-0.22
N		1	-0.09	-0.14	0.32*	0.11
P			1	-0.24	0.10	-0.39*
K				1	-0.58*	-0.68*
EC					1	0.41*
pH						1
Mid Slope						
OM	1	-0.12	-0.40*	0.81*	-0.56*	-0.31*
N		1	0.11	-0.26	0.09	0.36*
P			1	-0.16	0.20	-0.23
K				1	-0.53*	-0.72*
EC					1	0.27
pH						1
Lower Slope						
OM	1	-0.24	-0.54*	0.33*	-0.29*	-0.31*
N		1	0.16	0.01	0.69*	0.08
P			1	0.46*	0.04	-0.44*
K				1	-0.10	-0.81*
EC					1	0.14
pH						1

[a] at 25° C

[b] by weight

For correlation coefficients based on location (Table 8), the most significant number of correlations occurs at the Dapp site while the least number occurs at Tomahawk. Almost half of the correlations among soil nutrients are significant when considering different slopes (Table 9) and there are 7 to 8 significant correlations at the upper, mid and lower slope positions. There is consistency in correlations that are significant between soil nutrients from the two transects (Table 7). For example, P, K, and EC are significantly correlated with OM between Transect 1 and 2.

The significant correlation coefficient between various soil nutrients implies that one variable may be used to model another variable due to its dependence. Similarly, for soil nutrients that had non-significant correlations, this implies they need to be modeled independently.

3.3 Spatial Continuity – Soil Properties

The spatial continuity of soil properties at three AESA Benchmark Sites in central Alberta are presented in Table 10. The experimental data for OM is modeled with a variogram having a nugget of 0.03 and two nested Gaussian structures with a contribution of 0.1 and range of 12 m for the first structure and a contribution of 0.87 with a range of 17 m for the second structure. There is no model variogram calculated for nitrogen since the experimental data are independent and not spatially correlated. For the P variogram model, the nugget effect is 0.02 and there are two nested spherical structures with a variance of 0.25 at a range of 3 m and 0.73 at a range of 21 m. The potassium variogram model has a nugget of 0.04 and one nested, Gaussian structure with a contribution of 0.96 at a range of 12 m. EC and pH have spherical models and a range of 3.5 and 13 m, respectively.

Figure 17 displays the model and experimental omni directional variograms for each soil nutrient. The red dashed line represents the experimental variogram while the dark solid line represents the model variogram. There are no trends present in the experimental variograms for each of the soil nutrients. A trend is identified when the experimental variogram keeps increasing above the sill. This means that each soil nutrient variable is stationary or its mean is independent of location and relevant to the entire study area.

The zone of influence or range of spatial correlation varies among the soil nutrients from 3.5 m for EC to 21 m for P. Depending on the soil nutrient being evaluated, this suggests that OM, P, K, and pH could be sampled beyond the 2 m radius currently set for Benchmark Sites.

The range of spatial correlation for model isotropic variograms generally appears to be longest for phosphorus followed by organic matter, potassium and pH, EC and nitrogen. Mobility of these elements in the soil may explain why they are uncorrelated at short distances for nitrogen or correlated at longer distances for phosphorus. Electrical conductivity is spatially variable and is controlled by ionic concentration, clay, soil moisture, calcium and magnesium in the soil (Hartsock et al., 2000) and these factors may explain its variability in this study.

Table 10. Spatial parameters for isotropic variograms of selected soil nutrients sampled at three AESA Benchmark Sites in central Alberta. Continuity refers to the variance contribution of each nested structure. The variograms are modeled with 1 or 2 nested spherical or Gaussian structures.

Soil Nutrient	Model	Nugget	Continuity 1	Range 1 (m)	Continuity 2	Range 2 (m)
OM	Gaussian	0.03	0.1	12	0.87	17
N		0	0	0	0	0
P	Spherical	0.02	0.25	3	0.73	21
K	Gaussian	0.04	0.96	12	---	---
EC	Spherical	0.35	0.65	3.5	---	---
pH	Spherical	0.18	0.82	13	---	---

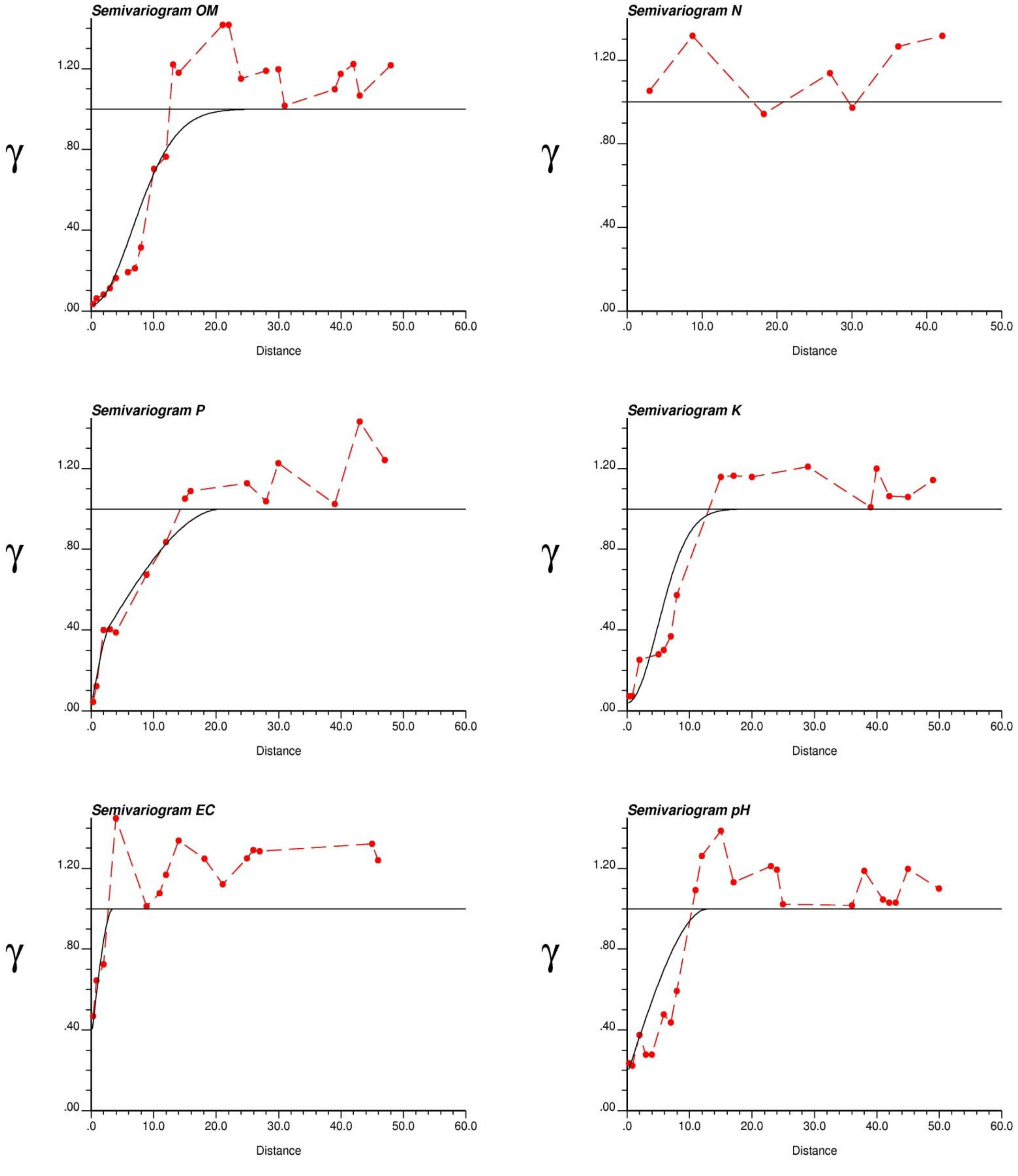


Figure 17. Model and experimental variograms for six selected soil nutrients sampled at 162 locations at selected AESA Benchmark Sites in central Alberta. The dark, solid line is the model variogram and the red, dashed line represents the experimental variogram.

Directional variogram parameters in Table 11 indicate that 2 nested structures are modeled with Gaussian structures for OM. The direction of maximal continuity is east-west (E-W) while the direction of minimal continuity is north-south (N-S). The corresponding variograms are shown in Figure 18. The dark dashed and solid lines show the experimental and model variograms for the direction of maximal continuity. The red and dark dashed lines are model variograms while the red and dark solid lines represent experimental variograms.

Similarly, model variogram parameters used for P, K, EC and pH are listed in Table 11. The nugget effect is 0.02 and 2 nested spherical structures are used for phosphorus. Direction of maximal continuity is E-W and N-S is the direction of minimal continuity. The exception to this geometric anisotropy is pH which has N-S as the direction of maximal continuity and the direction of minimal continuity is E-W. Model and experimental variograms for P, K, EC and pH are displayed in Figure 18. The dark dashed and solid lines represent variograms in the direction of maximal continuity, and the red dashed and solid lines are variograms in the direction of least continuity. The red and dark dashed lines are model variograms while the red and dark dashed lines represent experimental variograms. The experimental variograms in Figure 18 illustrate geometric anisotropy of soil nutrients which is spatial dependence with different ranges and directions.

Table 11. Directional parameters for of selected soil nutrients sampled at three AESA Benchmark Sites in central Alberta. Continuity refers to the variance contribution of each nested structure. The direction of maximal continuity is the E-W direction except pH which is N-S and variograms are modeled with 1 or 2 nested spherical or Gaussian structures.

Soil Nutrient	Model	Nugget	Continuity 1	Range 1 (m)	Continuity 2	Range 2 (m)
OM (max)	Gaussian	0.005	0.08	3	0.915	40
OM (min)	Gaussian	0.005	0.08	0.5	0.915	20
P (max)	Spherical	0.02	0.25	3	0.73	23
P (min)	Spherical	0.02	0.25	1	0.73	11
K (max)	Gaussian	0.04	0.96	16	---	---
K (min)	Gaussian	0.04	0.96	4	---	---
EC (max)	Spherical	0.1	0.9	10	---	---
EC (min)	Spherical	0.1	0.9	1	---	---
pH (max)	Spherical	0.18	0.82	21	---	---
pH (min)	Spherical	0.18	0.82	6	---	---

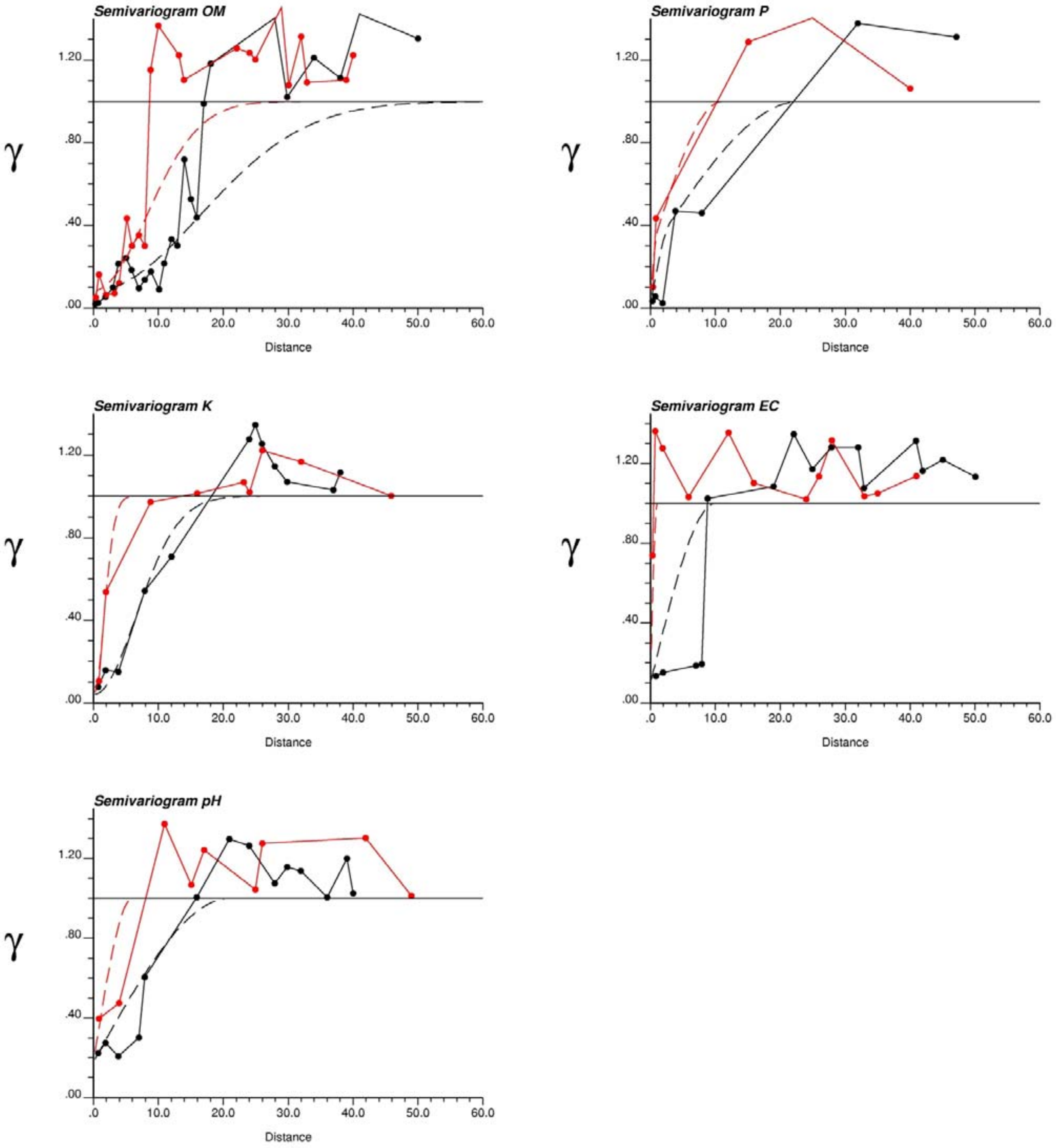


Figure 18. Directional variograms for five selected soil nutrients sampled at 162 locations at selected AESA Benchmark Sites in central Alberta. The red and black dashed lines are the model variograms and the red and dark solid lines represent the experimental variograms. The dark dashed and solid lines are the experimental and model variograms in the direction of maximal continuity (N90^{0}E), and the red dashed and solid lines represent the experimental variogram for the direction of least continuity (N0^{0}E) with the exception of pH which is N0^{0}E for maximal continuity and N90^{0}E for minimal continuity.

3.4 Spatial Continuity – Location, Slope, Transect

The spatial correlation of soil nutrients at three AESA sites, Dapp, Carvel and Tomahawk are presented in Table 12. There are no variogram models calculated for nitrogen and EC at Dapp, and nitrogen and phosphorus at Tomahawk since the experimental data are uncorrelated. The experimental data for the other soil nutrients are modeled with a Gaussian structure except potassium at Dapp and nitrogen at Carvel. All model, omni directional variograms have a range of 4 to 51 m with a nugget effect of 0.02 to 0.79. Nitrogen is modeled with one variogram structure with a variance contribution of 0.21 at Carvel which indicates a high amount of unexplained error. For all of these sites, with the exception of nitrogen, the distance at which there is spatial independence of data pairs is beyond the 2 m zone of sampling presently being used. This zone of influence could be confirmed with additional sampling of more sites in different ecoregions of Alberta.

Table 12. Spatial parameters for isotropic variograms for selected soil nutrients sampled at AESA Benchmark Sites (Dapp (681), Carvel (684), and Tomahawk (692)) in central Alberta. Continuity refers to the variance contribution of each nested structure. The variograms are modeled with one nested spherical or Gaussian structure.

Soil Nutrient	Model	Nugget	Continuity 1	Range 1 (m)
681 Dapp				
OM	Gaussian	0.04	0.96	22
N	---	0	0	0
P	Gaussian	0.02	0.98	22
K	Spherical	0.35	0.65	7
EC	---	0	0	0
pH	Gaussian	0.25	0.75	4
684 Carvel				
OM	Gaussian	0.04	0.96	45
N	Spherical	0.79	0.21	15
P	Gaussian	0.06	0.94	42
K	Gaussian	0.09	0.91	51
EC	Gaussian	0.4	0.6	11
pH	Gaussian	0.56	0.44	14
692 Tomahawk				
OM	Gaussian	0.23	0.77	34
N	---	0	0	0
P	---	0	0	0
K	Gaussian	0.4	0.6	16
EC	Gaussian	0.1	0.9	29
pH	Gaussian	0.2	0.8	15

There are no directional or anisotropic model variograms calculated from the experimental soil nutrient data for the AESA Benchmark Sites, Dapp, Carvel and Tomahawk. This indicates that no directional continuity is present at these sites at this sample spacing. More transects at different angles would assist in confirming this finding.

Experimental and model omni directional variograms for soil nutrients at the three AESA Benchmark Sites are illustrated in Figures 19, 20 and 21. The dark solid line represents the model variogram and the red dashed line is the experimental variogram. No model variograms are determined for N and EC at Dapp or N and P at Tomahawk since the experimental variogram is pure nugget.

The spatial correlation of soil nutrients at three slopes is presented in Table 13. There is a pure nugget effect for nitrogen at the upper and lower slopes and thus, no variogram models are calculated. The smallest sampling distance is 0.25 m and the reason such a correlation structure cannot be determined for nitrogen is that the range of correlation maybe smaller than this sample spacing. The experimental data for the other soil nutrients are modeled with a Gaussian structure except EC and pH on the upper slope and nitrogen and phosphorus on the mid slope. All model omni directional variograms have a range of 0.5 to 27 m with a nugget effect of 0.01 to 0.70.

Table 13. Spatial parameters for isotropic variograms for selected soil nutrients sampled at 3 slopes over three AESA Benchmark Sites in central Alberta. Continuity refers to the variance contribution of each nested structure. The variograms are modeled with one nested spherical or Gaussian structure.

Soil Nutrient	Model	Nugget	Continuity 1	Range 1 (m)
Upper Slope				
OM	Gaussian	0.05	0.95	21
N	---	0	0	0
P	Gaussian	0.04	0.96	18
K	Gaussian	0.04	0.96	27
EC	Spherical	0.35	0.65	9
pH	Spherical	0.03	0.97	18
Mid Slope				
OM	Gaussian	0.1	0.9	28
N	Spherical	0.7	0.3	5
P	Spherical	0.01	0.99	17.8
K	Gaussian	0.01	0.99	21.5
EC	Gaussian	0.3	0.7	3.6
pH	Gaussian	0.11	0.89	17.9
Lower Slope				
OM	Gaussian	0.11	0.89	35
N	---	0	0	0
P	Gaussian	0.15	0.85	18
K	Gaussian	0.15	0.85	11.6
EC	Gaussian	0.5	0.5	0.5
pH	Gaussian	0.41	0.59	12.9

Figures 22, 23 and 24 display the model and experimental omni directional variograms for each soil nutrient at upper, mid and lower slope positions. The red dashed line represents the experimental variogram while the dark solid line represents the model variogram. There are no trends present in the experimental variograms for each of the soil nutrients.

There are no anisotropic model variograms calculated from the experimental soil nutrient data for the upper, mid and lower slope positions. This indicates that directional continuity is not present at these sites with this sample spacing. More transects at different angles would assist in confirming this finding.

The zone of influence or range of spatial correlation varies among the soil nutrients from 0.5 m for EC to 27 m for P. Depending on the soil nutrient being considered, OM, P, K, and pH could be sampled beyond the 2 m radius currently set for Benchmark Sites. Nitrogen is mobile in the soil and that may explain why its range of correlation is unexplained even at the smallest spacing of 0.25 m. EC has a short spatial dependence of 0.5 at the lower slope position while at the mid and upper slopes, the range of correlation is 3.6 to 9 m. EC is measure of salt concentration in the soil and the lower slope is a discharge area with wider range of values compared to the mid or upper slope.

Table 14. Spatial parameters for isotropic variograms for selected soil nutrients sampled at 2 transects over three AESA Benchmark Sites in central Alberta. Continuity refers to the variance contribution of each nested structure. The variograms are modeled with one nested spherical or Gaussian structure.

Soil Nutrient	Model	Nugget	Continuity 1	Range 1 (m)
Transect 1				
OM	Gaussian	0.03	0.97	24
N	---	0	0	0
P	Spherical	0.05	0.95	12
K	Spherical	0.03	0.97	12
EC	Spherical	0.4	0.6	1
pH	Spherical	0.15	0.85	11
Transect 2				
OM	Gaussian	0.1	0.9	15
N	---	0	0	0
P	Spherical	0.05	0.95	12
K	Spherical	0.01	0.99	12
EC	Spherical	0.35	0.65	4
pH	Spherical	0.01	0.99	9

Omni directional variogram parameters for soil nutrients at two transects for the AESA Benchmark Sites is presented in Table 14. There is no spatial correlation for N in both transects and no model variograms are calculated. The nugget effect varies from 0.01 to 0.4 and the range of correlation is 1 to 24 m. All model structures are spherical except OM. Figures 25 and 26 display the model and experimental omni directional variograms for each soil nutrient at transect 1 and 2. The red dashed line represents the experimental variogram while the dark solid line represents the model variogram. There are no trends present in the experimental variograms for each of the soil nutrients.

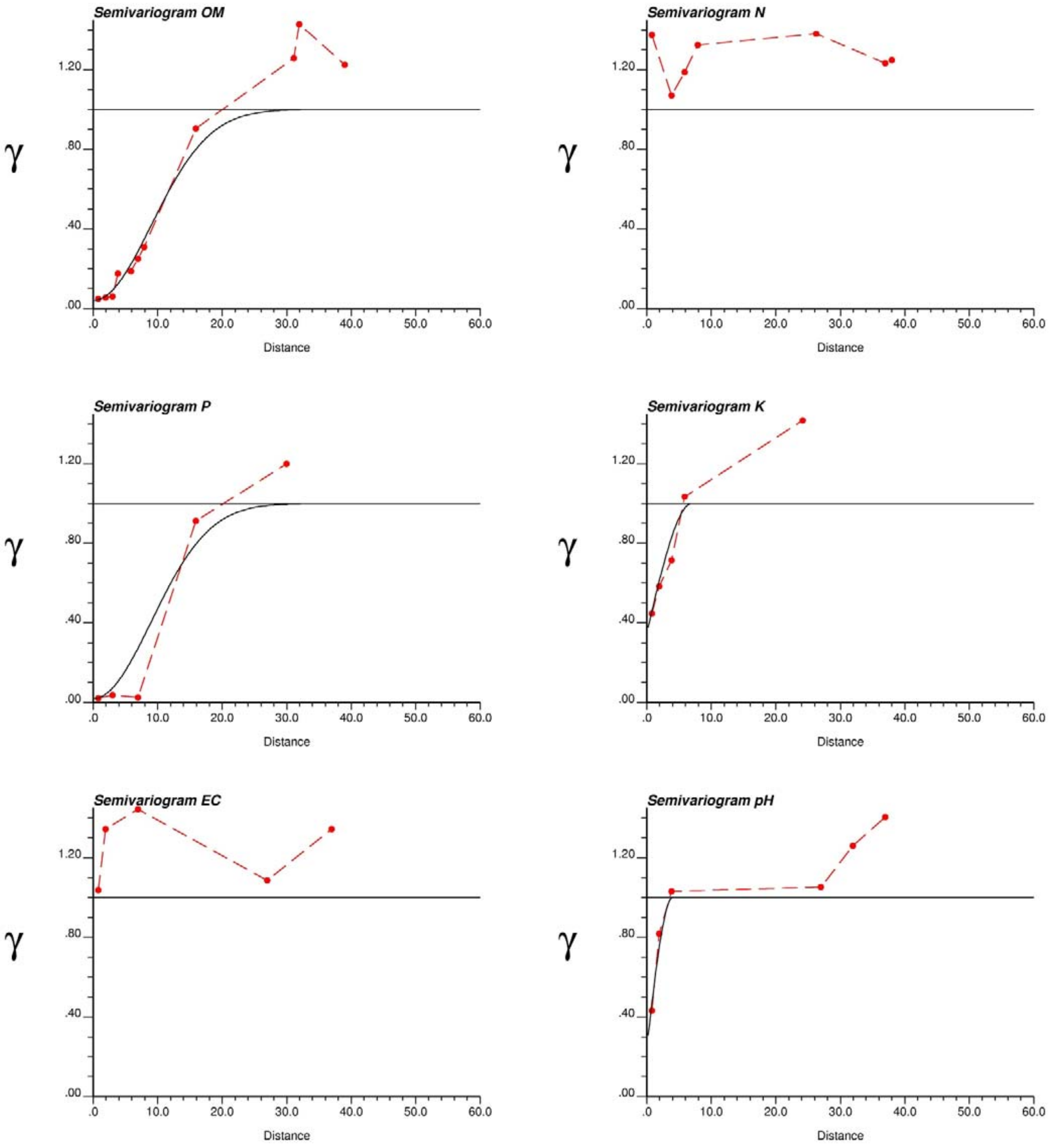


Figure 19. Model and experimental variograms for six selected soil nutrients sampled at 54 locations for AESA benchmark site 681 (Dapp) in central Alberta. The dark, solid line is the model variogram and the red, dashed line represents the experimental variogram.

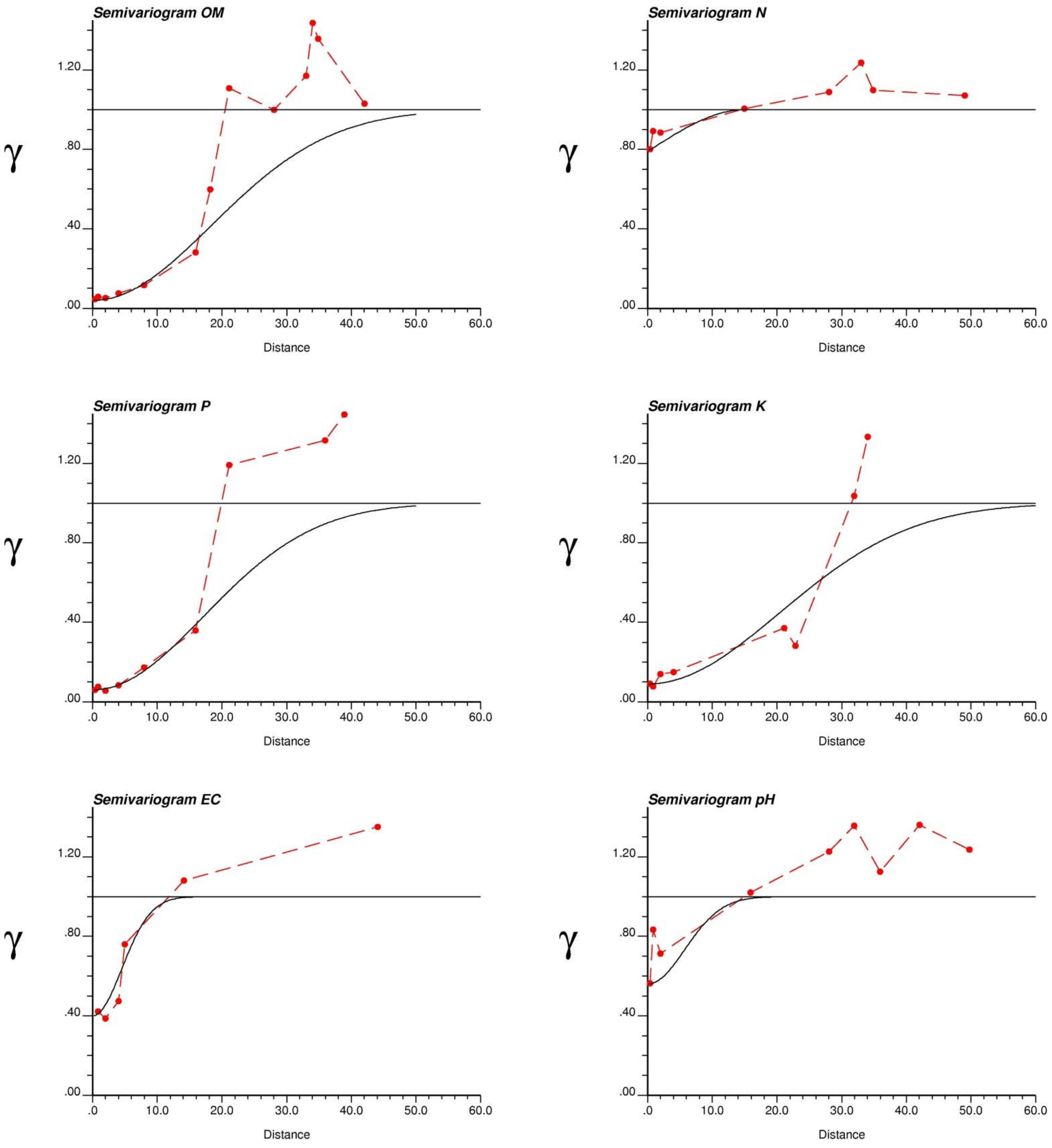
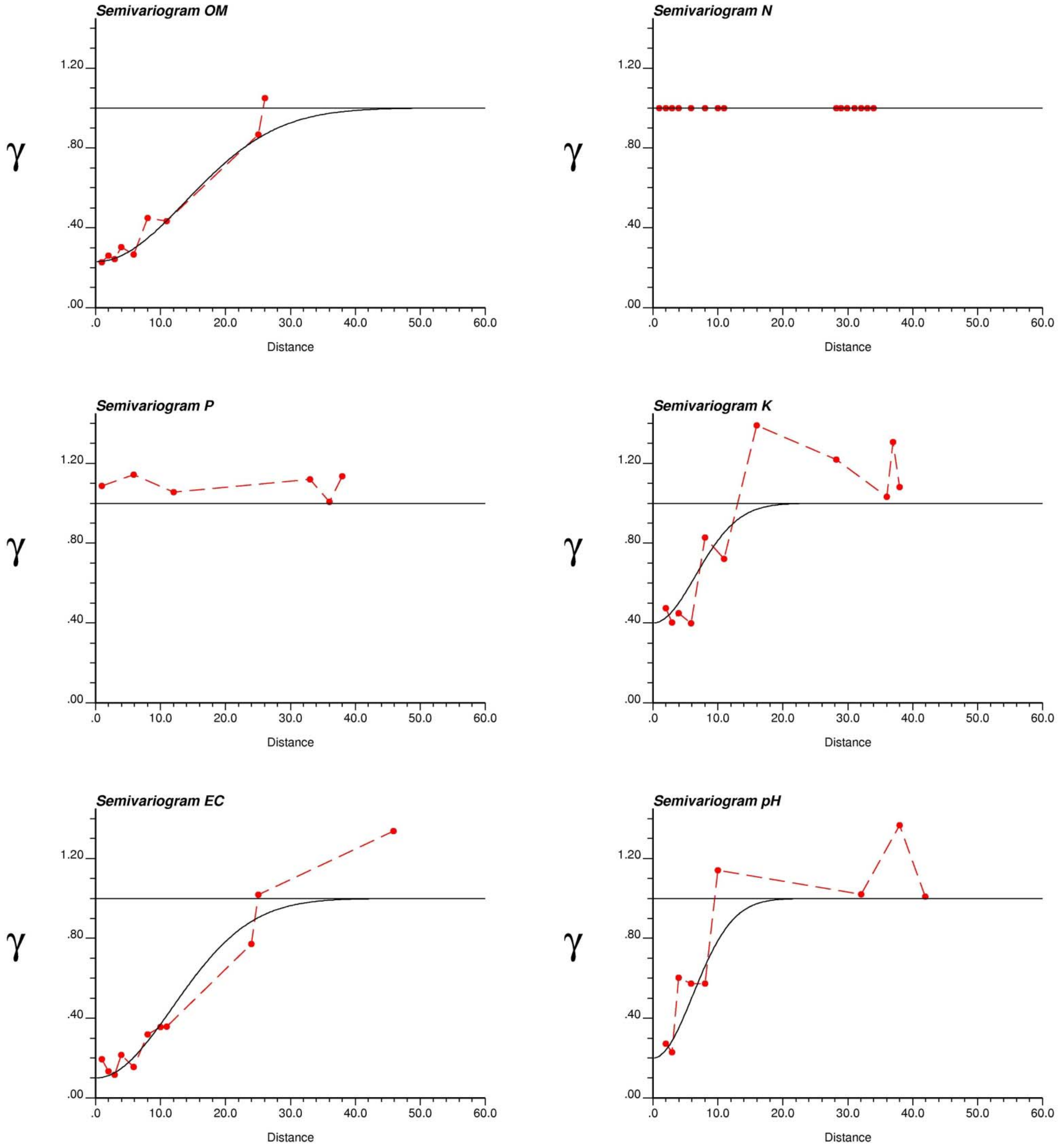


Figure 20. Model and experimental variograms for six selected soil nutrients sampled at 54 locations for AESA benchmark site 682 (Carvel) in central Alberta. The dark, solid line is the model variogram and the red, dashed line represents the experimental variogram.


Semivariogram OM

Semivariogram N

Semivariogram P

Semivariogram K

Semivariogram EC

Semivariogram pH

Figure 21. Model and experimental variograms for six selected soil nutrients sampled at 54 locations for AESA benchmark site 692 (Tomahawk) in central Alberta. The dark, solid line is the model variogram and the red, dashed line represents the experimental variogram.

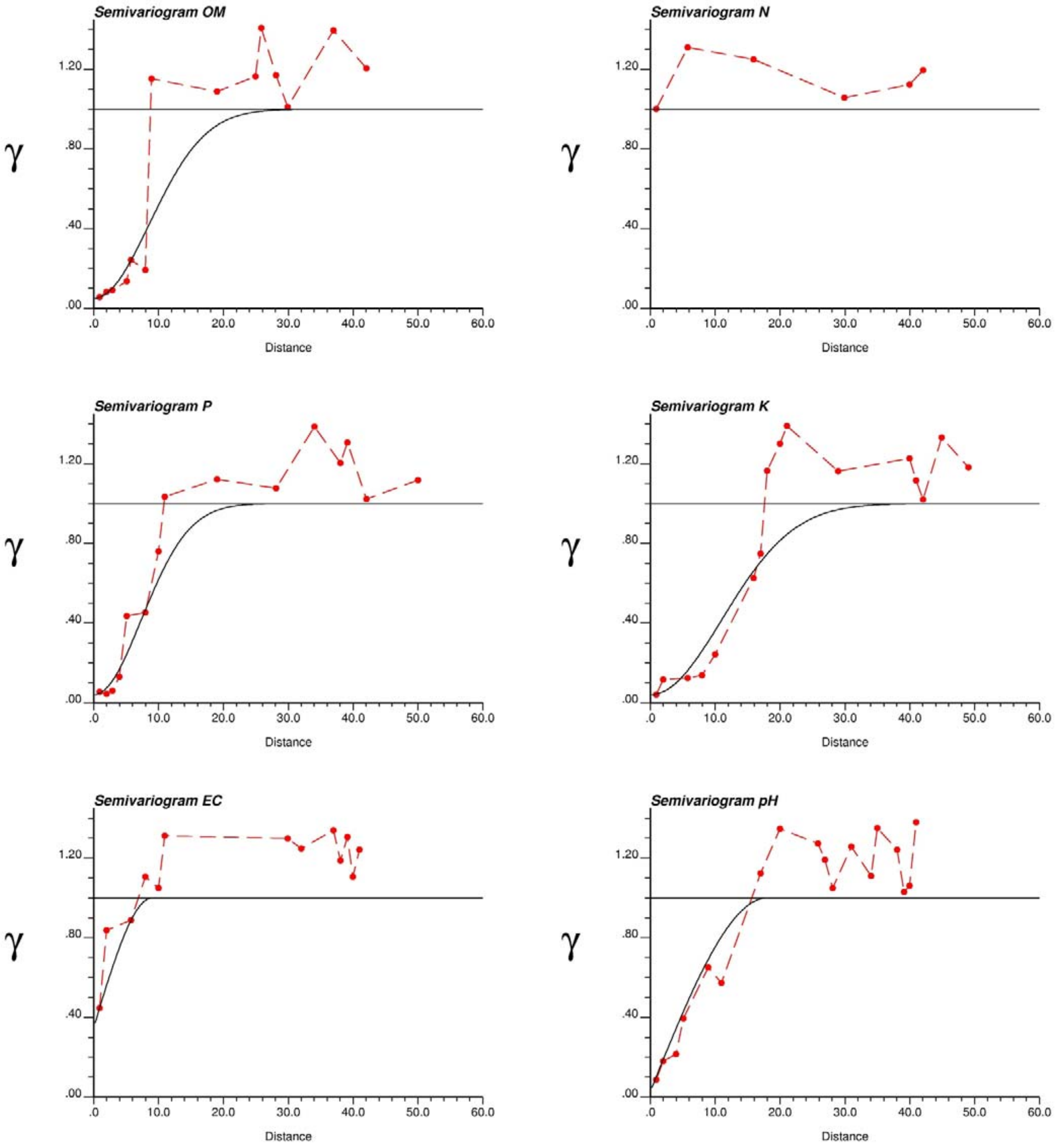


Figure 22. Model and experimental variograms for six selected soil nutrients sampled at 54 locations for the upper slope at selected AESA Benchmark Sites in central Alberta. The dark, solid line is the model variogram and the red, dashed line represents the experimental variogram.

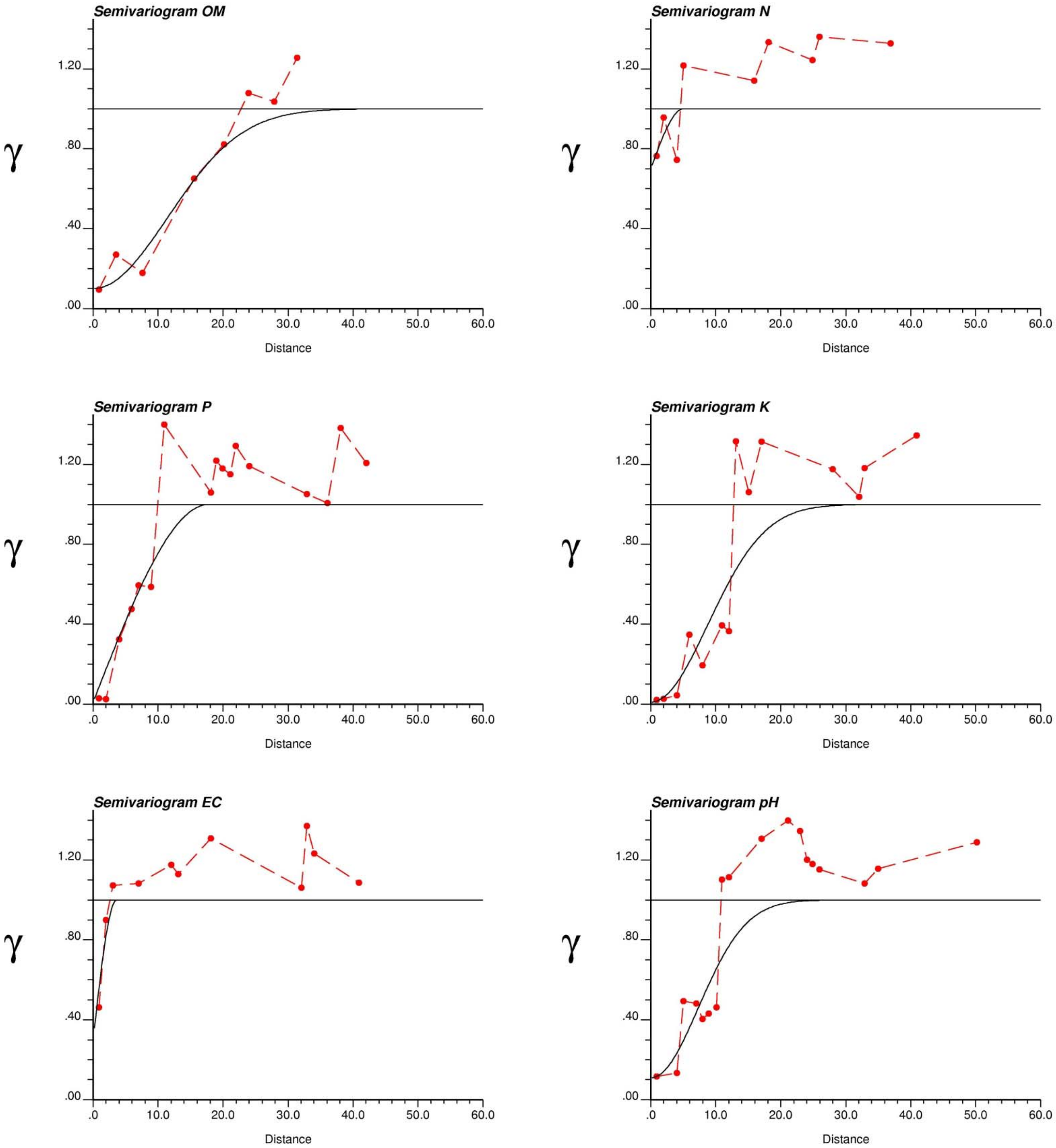


Figure 23. Model and experimental variograms for six selected soil nutrients sampled at 54 locations for the mid slope at selected AESA Benchmark Sites in central Alberta. The dark, solid line is the model variogram and the red, dashed line represents the experimental variogram.

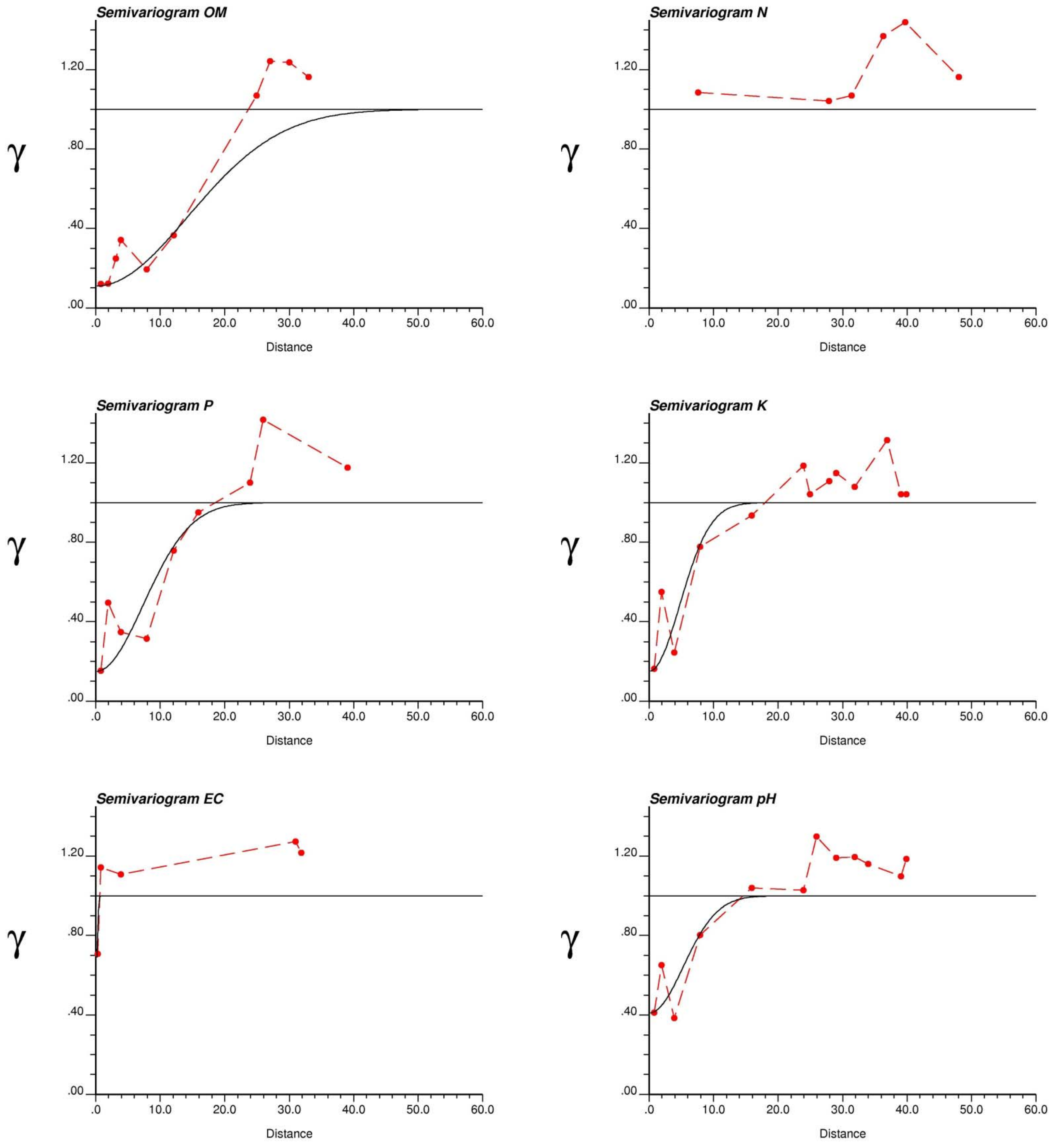


Figure 24. Model and experimental variograms for six selected soil nutrients sampled at 54 locations for the lower slope at selected AESA Benchmark Sites in central Alberta. The dark, solid line is the model variogram and the red, dashed line represents the experimental variogram.

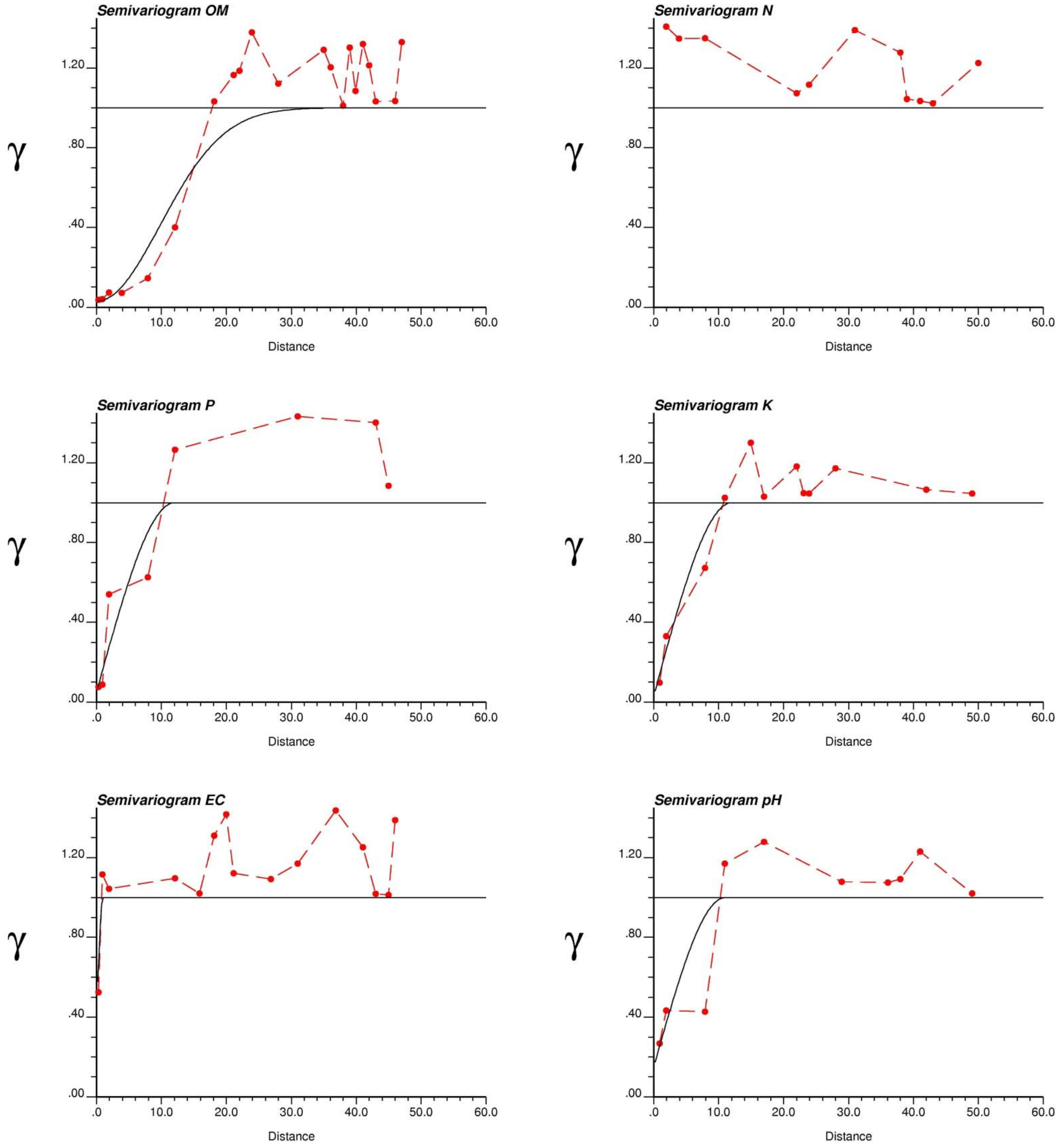


Figure 25. Model and experimental variograms for six selected soil nutrients sampled at 81 locations for Transect 1 at selected AESA Benchmark Sites in central Alberta. The dark, solid line is the model variogram and the red, dashed line represents the experimental variogram.

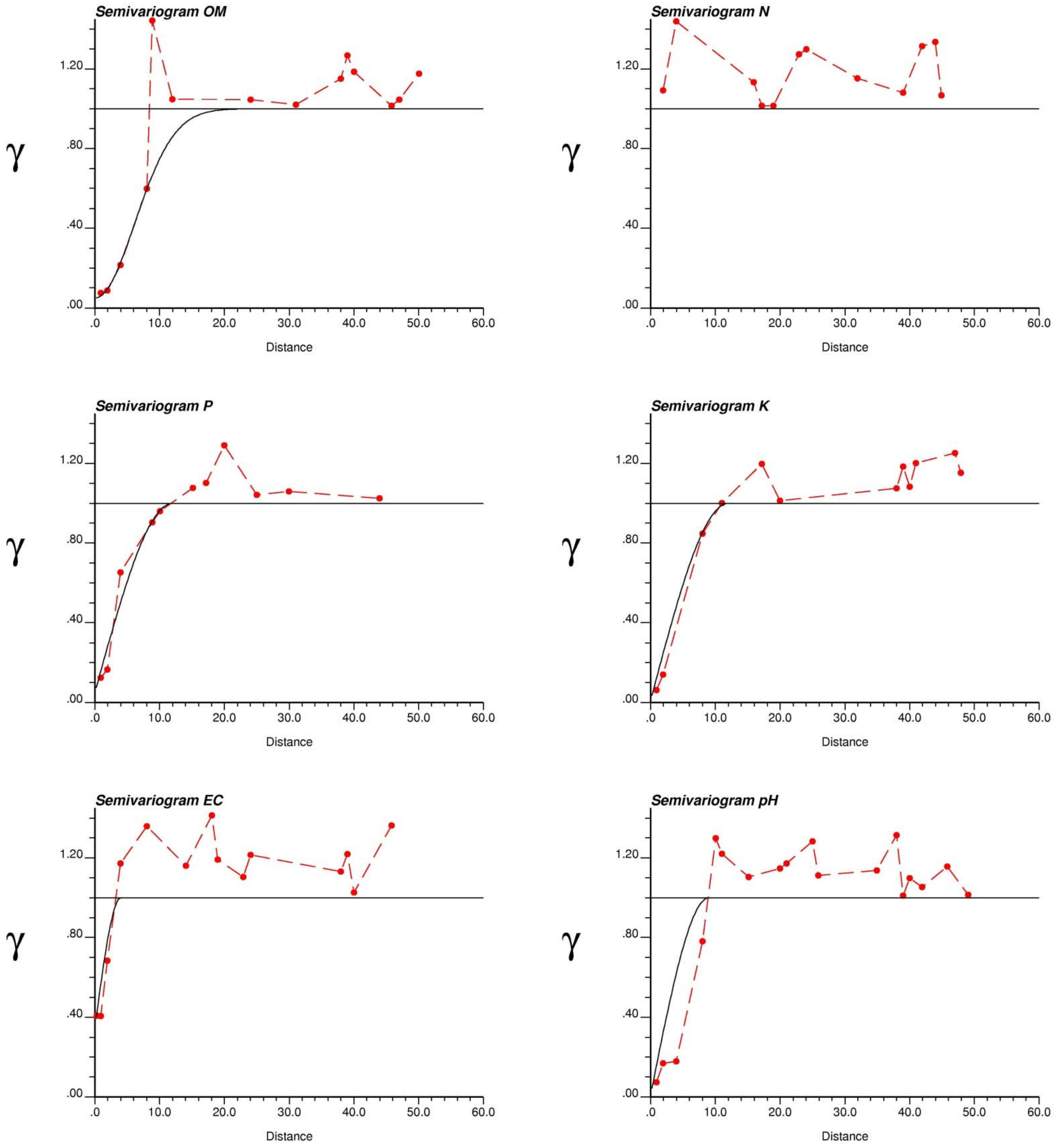


Figure 26. Model and experimental variograms for six selected soil nutrients sampled at 81 locations for Transect 2 at selected AESA Benchmark Sites in central Alberta. The dark, solid line is the model variogram and the red, dashed line represents the experimental variogram.

4.0 Conclusions

Spatial variability is controlled by the processes of soil formation which are affected by lithology, climate, biology, and relief through geologic time (Wilding et al., 1994). Long range spatial variability is a gradual change in soil properties as a function of physiography, geomorphology and interactions of soil-forming factors. Fine scale variability occurs in aggregate ped units such as coatings of clay along void surfaces, zonation of oxyhydroxides, and concentrations of carbonates within the soil matrix. These spatial patterns reflect hydraulic flow, diffusion, immobilization and microbial colonization processes at micron and submicron scales in soil systems.

Soil properties that are sampled in this study include OM, N, P, K, EC, and pH at three AESA Benchmark Sites in central Alberta. There is spatial variability detected for each of the soil properties and the range of correlation varied depending on the particular property. Utilizing experimental and model variograms, spatial dependence is quantified with phosphorus generally having the longest range followed by organic matter, potassium and pH, EC and nitrogen. Spatial correlation from the 3 Benchmark Sites varied from 3.5 m for EC to 21 m for P. Lauzon et al., (2005) indicated that P, K and pH were spatially correlated at less than 30 m in an analysis of 23 Ontario farm fields. In most cases, no spatial correlation is detected for nitrogen at the smallest sample spacing of 0.25 m. These results also agree with those of Solie et al., (1999) who found ranges of correlation from 1 to 6 m for P, K, pH and N based on a 0.3 m grid sampling.

Morton et al., (2000) used sample spacing similar to this study and found a sharp increase in variation for P within 10 m with no further, added variation after 20 m. For K there is a high level of variation over very short distances (<1 m) and a consistent climb over the 100 m measured. The sulphate S tests showed a slight increase with increasing distance that tails off toward the 100 m point. The variation in organic C follows a similar pattern to that of P.

Causes of anisotropy that result in spatial variability over short distances include: differential lithology, intensity of pedogenic weathering processes, hydrology, biological activity, erosion, deposition and perturbation; temporal effects of soil management; sampling and analytical errors (Wilding et al., 1994).

Directional experimental and model variograms for OM, P, K, EC, and pH confirmed anisotropy over short and long ranges at the three AESA Benchmark Sites. The short range correlation is 1 to 20 m while long range correlation varied from 10 to 40 m. The strongest direction of correlation is in an east –west direction that follows the slope (i.e., up and down) except for pH, which is north-south (i.e., perpendicular to the slope). Thus, sampling may be expanded up to 6 m from the central marker parallel to the slope and 4 m perpendicular to the slope except for N which has no correlation and EC which has a 1 m range opposite the slope.

No directional trends were determined at the slope position or individual AESA site. There is a need to validate this finding with additional sample locations at all slope positions within an AESA site.

Depending on the soil nutrient being evaluated, this suggests that OM, P, K, and pH could be measured beyond the 2 m radius currently set for AESA Benchmark Sites. However, only 3 of 42 sites are sampled in this project and more sample locations at individual sites is required before recommending a change in sampling protocol for the AESA Soil Quality Resource Monitoring Program.

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6.0 Appendices

Appendix 1. *Selected soil nutrient values at the Dapp (681) AESA benchmark site in central Alberta.*

Appendix 2. *Selected soil nutrient values at the Carvel (684) AESA benchmark site in central Alberta.*

Appendix 3. *Selected soil nutrient values at the Tomahawk (692) AESA benchmark site in central Alberta.*

Appendix 1. Attribute values for selected soil nutrients sampled at the Dapp (681) AESA benchmark site in central Alberta.

Slope	Transect	Distance	Organic Matter	Nitrate-N	Phosphorus	Potassium	Electrical Conductivity	pH
		meters	% by weight	% by weight	mg/kg	mg/kg	dS/m at 25^{0}C	
Upper	1	0	3.2	<1	<5	110	0.25	6.7
Upper	1	0.25	3.1	<1	<5	90	0.3	6.9
Upper	1	0.5	3.1	<1	<5	90	0.27	6.9
Upper	1	1	3.1	<1	<5	70	0.27	6.8
Upper	1	2	3	<1	<5	100	0.68	6.7
Upper	1	4	2.8	1	<5	60	0.53	7.1
Upper	1	8	3	<1	<5	60	0.25	6.9
Upper	1	16	3	<1	<5	190	0.39	6.6
Upper	1	32	4.1	<1	<5	120	0.29	6.7
Upper	2	0	3	<1	<5	60	0.18	6.8
Upper	2	0.25	3.1	4	<5	80	0.61	6.6
Upper	2	0.5	2.9	<1	<5	70	0.65	6.7
Upper	2	1	3.2	<1	5	90	0.31	6.9
Upper	2	2	3	<1	<5	80	0.33	6.9
Upper	2	8	3.2	<1	<5	70	0.21	6.9
Upper	2	16	4	<1	<5	80	0.24	6.9
Upper	2	32	4.5	<1	<5	90	0.39	6.9
Mid	1	0	4.5	<1	<5	90	0.33	6.7
Mid	1	0.25	3.4	<1	<5	60	0.19	6.8
Mid	1	0.5	3.2	1	<5	80	0.31	6.8
Mid	1	1	3.4	2	<5	90	0.58	6.8
Mid	1	2	3.5	2	<5	80	0.28	7
Mid	1	4	2.8	<1	<5	80	0.76	6.7
Mid	1	8	3.4	<1	<5	90	0.37	6.8
Mid	1	16	3.1	<1	<5	90	0.27	6.7
Mid	1	32	5.3	<1	<5	110	0.39	6.9
Mid	2	0	3	<1	<5	80	0.28	6.8
Mid	2	0.25	3.1	<1	<5	80	0.26	6.5
Mid	2	0.5	3.1	<1	<5	70	0.25	6.7
Mid	2	1	2.8	<1	<5	80	0.25	6.7
Mid	2	2	2.9	<1	<5	80	0.23	6.7
Mid	2	8	3.4	2	<5	80	0.29	6.9
Mid	2	16	5.4	<1	<5	130	0.36	7
Mid	2	32	7.3	1	6	190	0.34	7

Slope	**Transect**	**Distance**	**Organic Matter**	**Nitrate-N**	**Phosphorus**	**Potassium**	**Electrical Conductivity**	**pH**
		meters	% by weight	% by weight	mg/kg	mg/kg	dS/m at 25^0C	
Lower	1	0	4.7	1	<5	260	0.26	6.9
Lower	1	0.25	4.9	<1	<5	160	0.56	6.9
Lower	1	0.5	4.6	5	<5	180	1.02	6.8
Lower	1	1	5	<1	<5	120	0.26	7
Lower	1	2	4.9	<1	<5	240	0.23	6.9
Lower	1	4	4.9	<1	<5	90	0.26	6.9
Lower	1	8	6.4	<1	<5	100	0.26	7
Lower	1	16	6.7	<1	<5	100	0.28	7
Lower	1	32	4.9	<1	<5	80	0.35	7.2
Lower	2	0	6.1	<1	<5	90	0.22	7
Lower	2	0.25	6.3	<1	<5	160	0.26	7
Lower	2	0.5	6.4	<1	<5	140	0.3	7
Lower	2	1	5.6	<1	<5	90	0.25	7
Lower	2	2	5.6	<1	<5	100	0.27	7.1
Lower	2	8	4.9	<1	<5	140	0.3	7.1
Lower	2	16	3.7	<1	<5	150	0.59	6.8
Lower	2	32	3.1	<1	<5	90	0.2	6.9

Appendix 2. Attribute values for selected soil nutrients sampled at the Carvel (684) AESA benchmark site in central Alberta.

Slope	Transect	Distance	Organic Matter	Nitrate-N	Phosphorus	Potassium	Electrical Conductivity	pH
		meters	% by weight	% by weight	mg/kg	mg/kg	dS/m at 25^0C	
Upper	1	0	2	<1	32	160	0.3	6.4
Upper	1	0.25	1.5	<1	28	140	0.29	6
Upper	1	0.5	2.1	<1	33	140	0.25	6
Upper	1	1	1.5	<1	24	130	0.25	5.9
Upper	1	2	1.4	<1	36	150	0.2	5.9
Upper	1	4	1.8	<1	42	170	0.26	5.6
Upper	1	8	1.3	<1	39	140	0.55	5.9
Upper	1	16	1.9	<1	38	140	0.21	6.1
Upper	1	24	2.1	<1	59	140	0.16	6.4
Upper	2	0	1.2	<1	25	130	0.16	6.1
Upper	2	0.25	1.4	<1	25	150	0.16	6.1
Upper	2	0.5	1.8	<1	24	170	0.21	6
Upper	2	1	1.8	<1	19	150	0.23	5.9
Upper	2	2	1.6	<1	32	160	0.2	5.9
Upper	2	8	1.4	<1	45	150	0.66	5.5
Upper	2	16	2.4	<1	46	190	0.34	5.6
Upper	2	24	2.8	<1	54	130	0.29	6
Mid	1	0	2.7	<1	28	180	0.3	6
Mid	1	0.25	2.3	<1	38	180	0.42	5.8
Mid	1	0.5	2	<1	27	170	0.22	5.8
Mid	1	1	2.1	<1	27	190	0.41	5.9
Mid	1	2	2.5	<1	26	200	0.38	5.9
Mid	1	4	2.6	<1	34	160	0.47	6
Mid	1	8	3.5	<1	49	160	0.46	5.7
Mid	1	16	4.1	1	46	150	0.35	5.9
Mid	1	32	4	1	79	240	0.27	6.3
Mid	2	0	2.6	<1	22	170	0.43	5.8
Mid	2	0.25	2.6	<1	34	180	0.57	6
Mid	2	0.5	2.3	<1	26	170	0.43	5.9
Mid	2	1	2.5	<1	25	180	0.31	6.3
Mid	2	2	2.7	<1	28	160	0.33	6.2
Mid	2	8	3	<1	40	150	0.28	6.3
Mid	2	16	4	1	49	150	0.28	6.2
Mid	2	32	4.4	2	76	150	0.24	6.4

Slope	**Transect**	**Distance**	**Organic Matter**	**Nitrate-N**	**Phosphorus**	**Potassium**	**Electrical Conductivity**	**pH**
		meters	% by weight	% by weight	mg/kg	mg/kg	dS/m at 25^0C	
Lower	1	0	4.5	2	79	370	0.28	6.3
Lower	1	0.25	4.2	1	72	260	0.35	6.4
Lower	1	0.5	4.5	2	79	300	0.31	6.2
Lower	1	1	4.5	2	79	320	0.28	6.3
Lower	1	2	4.1	1	69	300	0.36	6.4
Lower	1	4	4.1	2	80	360	0.26	6.2
Lower	1	8	4.5	<1	87	440	0.4	6.3
Lower	1	16	5.2	1	58	180	0.23	6
Lower	1	32	3.6	<1	31	240	0.38	5.6
Lower	2	0	5.1	<1	79	380	0.24	6
Lower	2	0.25	5.1	<1	77	320	0.35	5.9
Lower	2	0.5	4.7	1	76	310	0.28	5.8
Lower	2	1	5	<1	95	360	0.38	5.7
Lower	2	2	4.8	1	83	410	0.32	5.8
Lower	2	8	4.6	<1	73	460	0.34	5.9
Lower	2	16	5.1	<1	74	280	0.3	5.7
Lower	2	32	3.6	<1	40	280	0.28	5.8

Appendix 3. Attribute values for selected soil nutrients sampled at the Tomahawk (692) AESA benchmark site in central Alberta.

Slope	Transect	Distance	Organic Matter	Nitrate-N	Phosphorus	Potassium	Electrical Conductivity	pH
		meters	% by weight	% by weight	mg/kg	mg/kg	dS/m at 25^0C	
Upper	1	0	5.8	<1	<5	310	0.14	5.9
Upper	1	0.25	5.8	<1	<5	380	0.15	5.9
Upper	1	0.5	5.6	<1	<5	350	0.13	5.7
Upper	1	1	6	<1	<5	340	0.14	5.7
Upper	1	2	4.3	<1	<5	320	0.13	5.7
Upper	1	4	5.6	<1	6	330	0.15	5.7
Upper	1	8	6.7	<1	8	370	0.21	6.1
Upper	1	16	6.8	<1	<5	360	0.15	5.9
Upper	1	24	7.3	<1	5	400	0.16	5.6
Upper	2	0	6.2	<1	<5	360	0.16	5.9
Upper	2	0.25	7	<1	6	420	0.14	6
Upper	2	0.5	4.9	<1	<5	310	0.12	6.2
Upper	2	1	5.1	<1	<5	310	0.14	6.2
Upper	2	2	7.1	<1	7	420	0.16	5.9
Upper	2	8	6.1	<1	<5	350	0.13	5.8
Upper	2	16	6	<1	<5	290	0.12	5.7
Upper	2	24	6.7	<1	<5	350	0.14	5.8
Mid	1	0	5.6	<1	<5	320	0.16	5.9
Mid	1	0.25	6.2	<1	<5	270	0.15	5.9
Mid	1	0.5	6.1	<1	<5	360	0.16	5.8
Mid	1	1	6.2	<1	<5	320	0.15	5.8
Mid	1	2	6.6	<1	<5	310	0.16	5.9
Mid	1	4	7.1	<1	<5	370	0.18	5.9
Mid	1	8	6.1	<1	<5	380	0.2	6
Mid	1	16	7.4	<1	<5	420	0.19	5.9
Mid	1	32	6.3	<1	<5	400	0.15	5.9
Mid	2	0	8.5	<1	<5	350	0.17	6
Mid	2	0.25	8	<1	<5	350	0.26	6
Mid	2	0.5	7.5	<1	<5	350	0.2	6
Mid	2	1	8.2	<1	<5	420	0.24	5.8
Mid	2	2	7.9	<1	<5	370	0.22	5.9
Mid	2	8	7.2	<1	<5	360	0.18	5.8
Mid	2	16	6.9	<1	<5	310	0.2	5.7
Mid	2	32	5.4	<1	<5	250	0.26	5.8

Slope	**Transect**	**Distance**	**Organic Matter**	**Nitrate-N**	**Phosphorus**	**Potassium**	**Electrical Conductivity**	**pH**
		meters	% by weight	% by weight	mg/kg	mg/kg	dS/m at 25^{0}C	
Lower	1	0	8.4	<1	<5	280	0.23	6
Lower	1	0.25	8.4	<1	<5	360	0.29	6
Lower	1	0.5	9.4	<1	<5	400	0.3	6.1
Lower	1	1	8.2	<1	<5	320	0.25	6.1
Lower	1	2	9	<1	<5	320	0.28	6
Lower	1	4	8	<1	<5	310	0.23	6.1
Lower	1	8	10.1	<1	<5	360	0.27	6
Lower	1	16	8.8	<1	<5	280	0.28	6
Lower	1	32	9.2	<1	<5	480	0.25	5.9
Lower	2	0	8.7	<1	<5	330	0.23	6
Lower	2	0.25	9.9	<1	<5	330	0.23	6
Lower	2	0.5	8.6	<1	<5	330	0.27	6
Lower	2	1	9.1	<1	<5	300	0.24	6.1
Lower	2	2	9	<1	<5	320	0.25	6
Lower	2	8	9.1	<1	<5	330	0.26	6.1
Lower	2	16	9.8	<1	<5	370	0.3	6.1
Lower	2	32	8.7	<1	<5	290	0.32	6.2

NOTES