ANALYSIS OF THE VARIABILITY OF SOME PROPERTIES OF A SEMI-DECIDUOUS FOREST SOIL

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Abstract

The formation of soils in any region is influenced by many factors such as the parent materials and the secondary materials derived from them, the vegetation and the history of land use. These factors vary from place to place and they contribute to the spatial variation in properties of the soil. Quantification of the magnitude, location and causes of spatial variability is an essential but insufficient ingredient of soil surveys.

We took soil samples from the 0-20 cm depth covering soils in the Asuansi-Akroso-Nta-Ofin compound association (Lixisol, Cambisol and Fluvisol association) at the study site, following the nested balanced hierarchical sampling technique. This covered distances between 100 and 0.80 m. Standard laboratory analyses were performed to quantify the selected properties, namely, pH, organic carbon, total nitrogen, total phosphorus, exchangeable potassium and content of sand, silt and clay. Classical statistics and geostatistical procedures were performed on the data and models fitted to the variability patterns.

Physical and the more stable properties such as sand, silt and clay were fitted with spherical variogram models. These models indicate a high level of spatial dependence and therefore such properties may be said to be fairly stable in the field. On the contrary, chemical properties such as exchangeable potassium, were fitted with exponential variogram models, indicating that these properties were less stable and showed dependence over longer distances. The scale of variation of the properties ranged between 35 m – 62 m.

The degree of uncertainty associated with time and space can be reduced by improved documentation of field variability using the tools of geostatistics.
INTRODUCTION

Accurate information on land resources is required for farm planning and management as management involves decision making based on facts and figures. Farm plans are designed to delineate land areas into units for specific uses.

Once a site is put into production or otherwise disturbed, the spatial variability of the soil properties may be markedly altered (Trangmar et al., 1987; Gaston et al., 1990). According to Rao and Wagenet (1985), the total spatial variability of soil properties at a managed site is a composite of intrinsic variability derived from locally variable pedological factors and extrinsic variability which is due to management. Such changes in variation of soil properties may be physical or chemical and continuous, with no well-defined inflections in the lateral rate of change, or discontinuous, as two distinct but relatively homogeneous bodies of soil adjoin. Variations tend to be highest for chemical properties and lowest for physical properties; also, variations tend to be usually higher in the topsoil than in the subsoil.

Knowledge about soil changes resulting from long term agriculture, as an extrinsic factor, is important because the influence of agricultural practices increases in extent, intensity and duration. As a result, most cultivated plots have relatively unstable soil composition. One would thus expect wide variations in the values of their soil properties and associated changes in soil quality.

In Ghana today, agricultural lands are continuously being cropped due to scarcity of land as a result of rapidly increasing population but quantitative information about the influence of management on scale of variation is lacking. The variability of soils in Ghana (differences and similarities) has been traditionally expressed by means of soil classification and map units in surveys at both regional and local scales (Dwomo and Asiamah, 1993), with no statistical presentation of variation within map units. The quantification of the changes occurring in some basic soil properties due to continuous cropping of agricultural lands is essential in order to propose land remedial measures.

As relatively little information abounds in Ghana regarding scales of variation in agricultural fields, we have investigated the scale and extent of spatial variation of some selected properties of a semi-deciduous humid tropical soils at Asuansi, and agricultural research station located in the Central Region of Ghana. Soils of the research station had been continuously cropped for the last 30 years and more. The study dwells on the theory of regionalized variables and the tools of geostatistics. We have interpreted the spatial structures emanating from the study to ascertain the sustainability and stability of soil properties studied. This information could further be used as a basis for efficient land use planning and management employing other tools of interpolation, such as kriging (Ogoe, 1999).

THEORY

Case 1: Consider a two-dimensional surface showing variation for which local estimated means are very similar to the overall mean; it is statistically homogeneous or spatially independent. Such a surface is called “pure noise” because not much extra information can be extracted from it beyond the parameters of mean and variance.
Case 2: Consider another two-dimensional surface in which points that are close together have a large degree of similarity and a strong spatial dependence. In other words, the local variation of the surface is much less than the variation of the same surface over a much larger area. Obviously, if such a surface were sampled properly the value of the soil attribute could be estimated more accurately at unsampled locations than in case 1. Also, a single sample in case 2 would be more likely to give a good idea of the value of the attribute at points in its immediate vicinity than would a single sample in case 1.

It is evident from previous studies on characterization of soil variability that the measured variance of a given property was not constant, even within a well-defined soil map unit. The variance depended greatly on the average distance between the sample points that was used to estimate it.

If variance was a function of distance then measuring how variance changed with distance could provide a useful clue to the presence of spatial structures in our soil data. Attributes that vary in this way are called regionalized variables and they satisfy the Intrinsic Hypothesis of Journal & Huijbregts (1978). Regionalized variable theory assumes that the spatial variation of any variable can be expressed as the sum of three major components, namely, a structural component, associated with a constant mean value or a polynomial trend, a spatially correlated random component, and a residual error term that is spatially uncorrelated.

Let \( x \) denote a set of spatial co-ordinates in one, two or three dimensions. Then the spatial variable \( Z \) at \( x \) is given by:

\[
Z_i(x) = m(x) + \varepsilon'(x) + \varepsilon''
\]

where \( m(x) \) is a deterministic function describing the structural component of \( Z \) at \( x \). \( \varepsilon'(x) \) is the term denoting the stochastic, locally varying spatially dependent residuals from \( m(x) \), and, \( \varepsilon'' \) is a residual spatially independent noise term having zero mean and variance \( \sigma^2 \).

For practical purposes, \( m(x) \), which is the mean of the region, is assumed to be constant. All the variation can then be represented by the stochastic term \( \varepsilon'(x) \), whose variation over space is summarized by the semi-variance, \( \gamma \). For a lag (sample separation) \( h \), the semi-variance is given by:

\[
\gamma(h) = \frac{1}{2} E(Z_{x+h} - Z_x)
\]

where \( E \) is the expected value. For a one dimensional transect of \( n \) sites, the semi-variance at lag \( h \) is estimated by:

\[
\gamma(h) = \frac{1}{2(n-h)} \sum_{i=1}^{n} (Z_{i+h} - Z_i)^2
\]
where $h$ is the distance between $(n - h)$ pairs of sample sites $Z_i$ and $Z_{i+h}$. The function can also be estimated for sample sites in two and three dimensions and for different directions to determine possible anisotropy. A plot of $\gamma(h)$ against $h$ is called an experimental variogram. Various theoretical models can then be fitted through the experimental variogram in order to describe how the semi-variance attribute values vary with increasing sample spacing.

MATERIALS AND METHODS

The study site was at the Asuansi Agricultural Research Station in the Central Region of Ghana, located within latitudes 5° and 5° 30' North and longitude 1° and 1° 30' West.

The area experiences an average annual rainfall of 1000 mm with two wet seasons and two dry seasons in each normal year. Mean monthly temperature ranges between 20°C and 33°C, with the relative humidity peaking up to 90% in the month of June.

The soils were used extensively in the past for plantations of coconut, oil palm, cocoa, citrus and rubber, but in recent past the land has given way to a secondary forest.

The area, which is drained by the Kakum River and its tributaries, is gently sloping to near flat with a common gradient of 0-2% reaching 7% at the highest points. The major geological formation of the area is the Cape Coast granite, which weather to give rise to sandy clays on the uplands and almost pure sand in the valley bottom. There are isolated granitic outcrops as well.

Three locations, each measuring 200 m x 200 m were demarcated. Soil samples were taken based on the nested hierarchical sampling procedure (Webster, 1977). The range of scales covered was 0.8 m to 30 m, in an almost three-fold geometrical progression to ensure independence of the components of variation. Nine primary centres were marked and the samples were taken from the 0-20 cm depth using a 10-cm diameter bucket auger. In all 216 lots of samples were collected, with 72 coming from each demarcated site. We air-dried these samples and sieved them to pass 2-mm mesh sieve to obtain the fine earth. Standard laboratory analyses were performed on the prepared samples for pH, organic carbon, total nitrogen, total phosphorus, exchangeable potassium and particle size distribution.

We subjected the data to both classical and geostatistical procedures using the GEO-EAS (Geostatistical Environmental Assessment Software of the United States EPA (Englund and Sparks, 1988)).

RESULTS

Classical approach

Table 1 contains the descriptive statistics of the variables measured. Skewness across board ranged from -0.05 for silt to +1.55 for clay. Due to the generally low skewness, the distributions of the variables were considered to be approximately normally distributed.
Table 1  Descriptive statistics of soil variables studied

<table>
<thead>
<tr>
<th>Variable</th>
<th>Range</th>
<th>Mean</th>
<th>CV(%)</th>
<th>Skewness</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH (pH unit)</td>
<td>4.1 - 7.5</td>
<td>5.8</td>
<td>11.7</td>
<td>0.49</td>
</tr>
<tr>
<td>Organic C</td>
<td>5.5 - 18.5</td>
<td>11.1</td>
<td>27.1</td>
<td>0.55</td>
</tr>
<tr>
<td>Total N</td>
<td>0.5 - 1.5</td>
<td>0.97</td>
<td>24.0</td>
<td>0.19</td>
</tr>
<tr>
<td>Total P</td>
<td>194.1 - 515.3</td>
<td>309.6</td>
<td>20.9</td>
<td>0.98</td>
</tr>
<tr>
<td>Exch. K</td>
<td>0.10 - 0.49</td>
<td>0.25</td>
<td>32.4</td>
<td>0.58</td>
</tr>
<tr>
<td>Sand (%)</td>
<td>53.7 - 84.3</td>
<td>73.0</td>
<td>6.9</td>
<td>-1.15</td>
</tr>
<tr>
<td>Silt (%)</td>
<td>3.7 - 9.9</td>
<td>7.4</td>
<td>17.5</td>
<td>-0.05</td>
</tr>
<tr>
<td>Clay (%)</td>
<td>12.1 - 36.3</td>
<td>19.6</td>
<td>21.6</td>
<td>1.55</td>
</tr>
</tbody>
</table>

The soils were generally slightly acid, although pH ranged from very acid (4.1) to slightly alkaline (7.5). The organic carbon content of the soils would be regarded as low with a mean of 11.1 g kg\(^{-1}\) soil. The total nitrogen was considered to range from low to slightly low, also with a range of 0.5 - 1.5 g kg\(^{-1}\) soil. Observed values of P were quite low despite the mean value of 309.6 µg g\(^{-1}\) soil. On the contrary, potassium content of the soils was generally high considering the range of 0.10 - 0.49 cmol\(_{c}\) kg\(^{-1}\) soil. The textural class range observed for the field was in the range of sandy loam to sandy clay loam.

Correlation coefficients measure the degree of association among the mean values of soil variables. These relationships have been shown in Table 2 in a triangular matrix. We observed that there was a high association between sand and clay, indicated by the \(r^2\) value of -0.98 whilst the least association was observed between pH and clay fraction \((r^2 = +0.02)\). Due to the large sample size, most correlation coefficients were significantly different from zero. However, only a few of the pairs of variables showed values greater than 0.70.

Organic carbon was positively and significantly correlated with total nitrogen, total phosphorus, exchangeable potassium and silt fraction. Total nitrogen was also positively and significantly correlated with total phosphorus, exchangeable potassium and silt fraction.
Table 2 Correlation coefficients among soils variables studied

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>-</td>
<td>0.55**</td>
<td>0.54**</td>
<td>0.42**</td>
<td>0.29**</td>
<td>-0.06</td>
<td>0.32**</td>
<td>0.02</td>
</tr>
<tr>
<td>Org. carbon</td>
<td>-</td>
<td>-</td>
<td>0.80**</td>
<td>0.75**</td>
<td>0.41**</td>
<td>-0.32</td>
<td>0.64**</td>
<td>0.18</td>
</tr>
<tr>
<td>Total N</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.61**</td>
<td>0.34**</td>
<td>-0.42**</td>
<td>0.71**</td>
<td>0.29*</td>
</tr>
<tr>
<td>Total P</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.22</td>
<td>-0.32**</td>
<td>0.54**</td>
<td>0.21</td>
</tr>
<tr>
<td>Exch. K</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-0.47**</td>
<td>0.49**</td>
<td>0.42**</td>
</tr>
<tr>
<td>Sand</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-0.72**</td>
<td>-0.98**</td>
</tr>
<tr>
<td>Silt</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.33</td>
</tr>
<tr>
<td>Clay</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

* = significantly different from zero at 95%

** = significantly different from zero at 99%
Coefficient of variation (CV) is an independent measure of relative dispersion and it is a useful tool in comparing distributions where units may be different. Describing soil variability using classical statistics has been done effectively by making use of coefficients of variation. However, there had been no table of categorization of coefficient of variation and Table 3 had been suggested to offer a basis for comparison in this study.

Table 3 Categorization of coefficients of variation

<table>
<thead>
<tr>
<th>Category of CV (%)</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;15</td>
<td>15-30</td>
<td>&gt;30</td>
</tr>
<tr>
<td>Suggested limit of spatial dependence (range) /m</td>
<td>&lt;25</td>
<td>25-50</td>
<td>&gt;50</td>
</tr>
</tbody>
</table>

The coefficients of variation of the soil variables ranged from 6.9% for sand to 32.4% for exchangeable K. The CVs of sand fraction and pH were low, whereas that of exchangeable K was high. The CVs for organic C, total N, total P, silt fraction were, however, medium.

Geostatistical approach

The soil variables studied were all spatially structured. Theoretical models that fitted the variables were either spherical or exponential.

Figure 1 shows the empirical omni-directional variograms (dots) and the fitted theoretical functions (models) for pH, organic C, total N, total P and exchangeable K, which were all modelled as exponential.
Figure 1: Empirical omni-directional variograms (dots) and fitted theoretical functions (models) of pH, organic C, total N, total P and exchangeable K.
Figure 2: Empirical omni-directional variograms (dots) and fitted theoretical functions (models) of sand, silt and clay fractions.
Figure 2 shows the empirical omni-directional variograms (dots) and the theoretical functions (models) for sand, silt and clay fractions, which were modelled as spherical.

The characteristics of the theoretical models (range, sill and nugget) as shown in Figures 1 and 2 have been presented in Table 4.

Table 4  Characteristics of variograms of soil properties studied

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>MODEL</th>
<th>RANGE (m)</th>
<th>SILL</th>
<th>NUGGET</th>
<th>S/N (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>E</td>
<td>48.0</td>
<td>0.50</td>
<td>0.02</td>
<td>4</td>
</tr>
<tr>
<td>Organic Carbon</td>
<td>E</td>
<td>62.0</td>
<td>0.10</td>
<td>0.01</td>
<td>10</td>
</tr>
<tr>
<td>Total Nitrogen</td>
<td>E</td>
<td>55.0</td>
<td>0.00045</td>
<td>0.00015</td>
<td>33</td>
</tr>
<tr>
<td>Total Phosphorus</td>
<td>E</td>
<td>60.0</td>
<td>3000</td>
<td>800</td>
<td>20</td>
</tr>
<tr>
<td>Exchangeable K</td>
<td>E</td>
<td>50.0</td>
<td>0.004</td>
<td>0.003</td>
<td>75</td>
</tr>
<tr>
<td>Sand</td>
<td>S</td>
<td>45.0</td>
<td>27.0</td>
<td>3.0</td>
<td>11</td>
</tr>
<tr>
<td>Silt</td>
<td>S</td>
<td>35.0</td>
<td>1.50</td>
<td>0.20</td>
<td>13</td>
</tr>
<tr>
<td>Clay</td>
<td>S</td>
<td>35.0</td>
<td>18.0</td>
<td>2.0</td>
<td>11</td>
</tr>
</tbody>
</table>

E  = Exponential Model  
S  = Spherical Model  
N/S  = Proportion of sill represented by the nugget

The distance over which there was spatial dependence was 35 m for both silt and clay and this shot up to 62 m for organic C. The maximum variation between any two neighbouring samples, the sill variance, was lowest in total N and highest in total P. The nugget variance, which measures the total random component or non-spatial variance, was lowest for total N and highest for total P. The proportion of the sill (or total variance) represented by the nugget was below 20% for all variables, except total N and exchangeable K which recorded 33% and 75% respectively.

DISCUSSION

The entire study area was located in a moist semi-deciduous forest zone and the conditions controlling pedogenesis, especially the macro-climate (temperature and rainfall), parent material, geomorphic surface and landform elements have had profound influence on distribution of soil properties. The study site was part of a field that had been cropped mainly with maize once in a
year during the major farming season with some fertilizer input but had been left to fallow in the minor season for the past thirty years.

The mean pH value places the soils in the category of slightly acid reaction. The range of pH, however, across the field indicates a whole range of very acid to slightly alkaline conditions. This seems to indicate varying effects of management on soil pH in this locality. Whilst crop removal and leaching of cations due to percolating rain water tend to lower soil pH, cation residues from isolated burning have been found elsewhere to raise the pH at these locations (Sanchez et al., 1983; Trangmar, et al., 1987; Andreaux and Cerri, 1989).

The levels of organic C and total N content of the soil, which bear direct relationship with the organic matter content of the soil, were low (Table 1). Long term effects of management including nutrient removal by crops, non-systematic application of organic and inorganic manures, insufficient fallow periods and the isolated burning as well as the effect of high temperatures and intense rainfall, have been blamed for the low levels of organic C and total nitrogen observed. In general, low levels of organic carbon and total N have been attributed to mineralization losses in the organic matter of the soil.

The total P content of the soils was also observed to be quite low. Phosphorus, however, correlated very well with the organic carbon content of the soils and similar reasons as long term removal of P by crops, insufficient fallow periods and non-systematic application of organic and inorganic manures can be advanced for this effect.

The levels of exchangeable K in the soil were rather on the high side. A level of 0.2 cmol kg⁻¹ soil was considered the barest amount for most crops, and most sites showed values above this value. It is possible that the K supply in the soil might have come from the weathering of primary minerals and dissociation from colloidal clay and humus, as well as the patches of ash resulting from localized burning of crop residue.

In general, content of sand in the soils studied was high followed by clay and silt. The high content of sand is consistent with values of the entire station, since this could be a direct effect of the weathering of the granitic parent rocks of the experimental station. Mechanical tillage at the study site could have caused the upward translocation of clay particles to the topsoil. There was a strong negative correlation between sand content and clay content, a feature which is typical of most tropical soils (Ovalles and Collins, 1988; Bonsu and Laryea, 1989).

The coefficients of variation in the properties seemed to compare favourably with literature, from 6.9% to 32.4% (Davis et al., 1995). This can be attributed generally to earlier propositions regarding causes of variation in the landscape. In such a high rainfall area, erosion and deposition of silt and clay could play a role in the re-distribution of some of these properties.

The study of soil variation using geostatistical tools has demonstrated a general lack of randomness in the soil properties studied. This might explain why classical statistics may not offer effective analysis of variation patterns in the variables. The general interpretation of the variograms indicated a high degree of spatial dependence expressed by the derived exponential
and spherical models. The study site shows medium to long range variation, which ranges from 35 to 62 m.

The proportion of the sill represented by the nugget ranged from 4% in pH to 75% in exchangeable K. This wide range depicts either a possible high proportion of experimental errors or that the variability pattern in exchangeable K was not captured even at the lowest scale of measurement.

CONCLUSIONS

The results have shown a general lack of randomness and that all the properties studied were spatially structured, disproving the null hypothesis. The inherent soil properties, namely, sand, silt and clay, showed more stable spatial structures, with the spherical variogram models. This was an indication that the influence of management on them was less pronounced than that of acquired soil properties such as pH, organic C, total N, total P and exchangeable K, which showed less stable spatial structures with the exponential models.

It is important to quantify spatial variability of properties of a field when developing strategies for soil and land use management. Site-specific decisions on rates of application of agro-chemicals, for example, will be most relevant in achieving efficient and sustainable effects in the acquired properties.

The scales of spatial variation ranged between 35 m for silt and 62 m for organic C.

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