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Soil geography and geostatistics

Concepts and Applications

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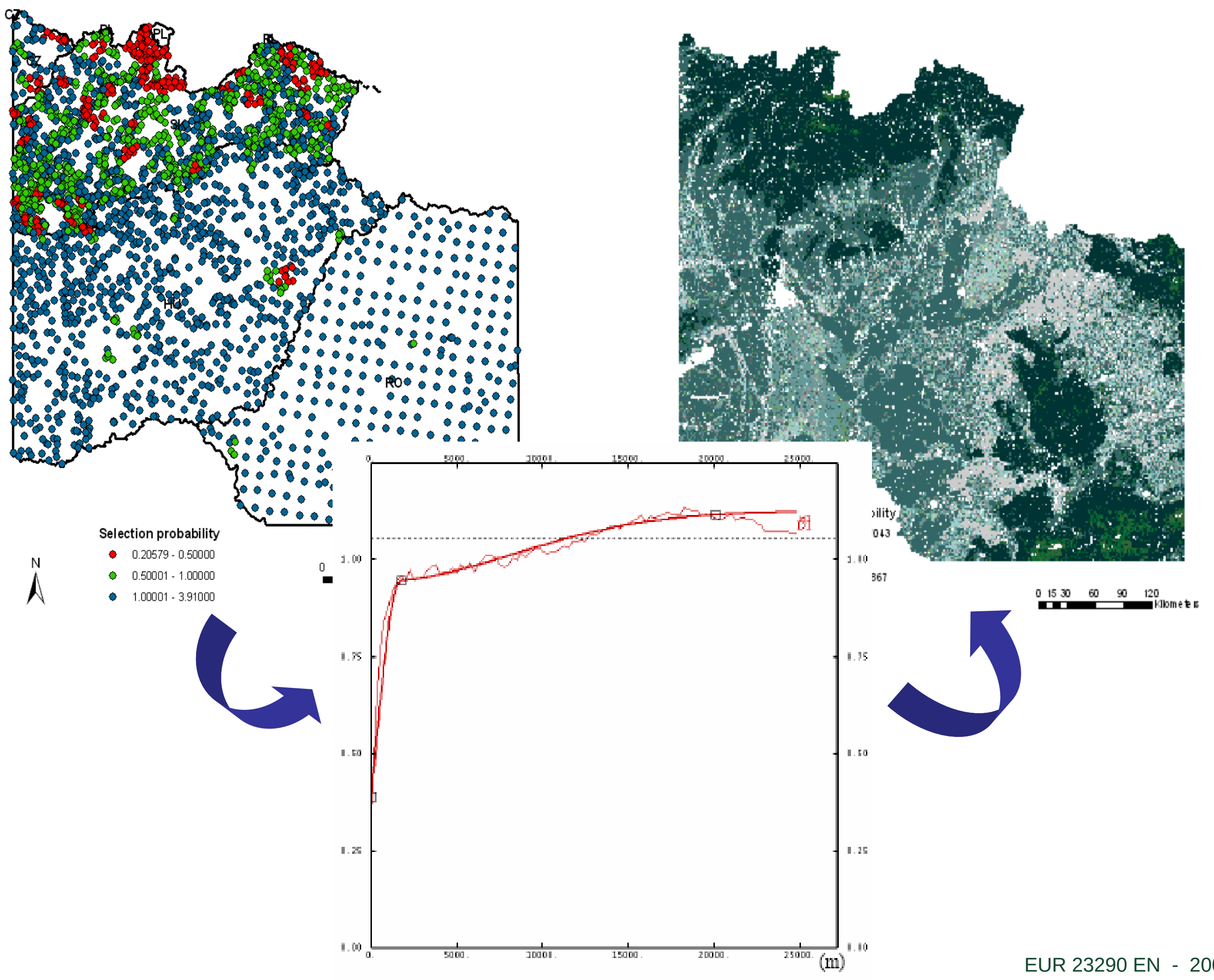

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Introduction

Geostatistics, which can be defined as the tools for studying and predicting the spatial structure of georeferenced variables, have been mainly used in soil science during the past two decades. Since now, hundreds of geostatistical papers have been published on soil science issues (see bibliography ibid., this volume). The use of geostatistical tools in soil science is diverse and extensive. It can be for studying and predicting soil contamination in industrial areas, for building agrochemical maps at the field level, or even to map physical and chemical soil properties for a global extent. The users of the output maps are going from soil scientists to environmental modelers. One of the specificity of geostatistical outputs is the assessment of the spatial accuracy associated to the spatial prediction of the targeted variable. The results which are quantitative are then associated to a level of confidence which is spatially variable. The spatial accuracy can then be integrated into environmental models, allowing for a quantitative assessment of soil scenarios.

Geostatistics are one of the most popular tools of pedometrics (the application of mathematical and statistical methods for the study of the distribution and genesis of soils), as well as digital soil mapping which is defined as the creation and the population of geographically referenced soil databases generated at a given spatial resolution by using field and laboratory observation methods coupled with environmental data through quantitative relationships. In pedometrics, geostatistics are then exploratory tool for understanding the distribution and the genesis of soil whereas in digital soil mapping they have mapping as finality. Geostatistics are also valuable supplement to classical soil mapping since they allow for recovering data knowledge hidden in traditional soil maps.

In this book, we call 'soil geography' the study of the spatial distribution of the soil cover which concerns physical, chemical and biological soil properties, their vertical and lateral variability (the spatial variability), and their description through the use of taxonomic tools. The spatial variation of soil properties can be defined as a function of three parameters: (1) the average value determined by the soil forming factors (the corpan factors or climate, organisms, relief, parent material, time and location), (2) its local variation (function of scale and extent), (3) the stochastic or pseudo-stochastic variation (Chapter 1). The geostatistics are then applied in this context. So that to illustrate the spatial variation factors and strength the advantages of using geostatistics, we can use the following example. Let say that the target issue is to map values of humus content of a specific area. The first spatial soil variation parameter can be determined by a certain amount of samples. The humus content values may vary regularly, e.g., along the slope or any other gradient of local factors. In most cases, this variation is not found at first glance, because the values increase or decrease irregularly; in other situations, the changes can be along a more complex surface. In that case, one should search for a trend, a regression dependence on the coordinates. Medium value and local trend constitute a deterministic component of soil variability. The second parameter of spatial variation does not depend on coordinates, but only on the distance between the sampling units (sampling resolution). This component can be analysed with geostatistics. Finally, the third parameter of spatial soil variation is completely random, and practically cannot be interpreted; in geostatistical models, it is expressed by the "nugget" – variability that does not depend either on coordinates or on the lag distance. These notions and concepts are further detailed by Webster (chapter 1 of this book).

This book aims then first to present the different concepts of geostatistics with an introductory chapter of Prof. Richard Webster, one of the fathers of geostatistics in soil science, and thus, to illustrate the use of geostatistical methods in different geomorphological contexts (Chapters 2, 3, 4, 5, 6, 7, 8). The aim is also to present the limits of geostatistics by opening the discussion on the use of soil diversity indices (Chapter 9 by Dr. Juan-José Ibáñez and Dr. Asunción Saldaña). The vocation of this book is then not to be a theoretical handbook on geostatistics but only to provide some examples of applications of geostatistics in soil geography followed by a discussion on the limits of geostatistics.

The basis for this monograph is the collection of studies conducted by the Laboratory of Soil Ecology and Soil Geography of the Institute of Biology, Karelian Research Centre of the Russian Academy of Science (KarRC RAS) within the research project supported by the Russian Foundation for Basic Research "Soil geographical interpretation of spatial variation of soil properties" (N 03-04-48089). The monograph is also supplemented with the results of the bilateral project "Spatial variation of chemical and agrophysical soil properties" of the Institute of Biology, KarRC RAS and the Research Institute of Soil Science and Agrochemistry of the Hungarian Academy of Sciences, and of a number of other projects supported by the Ministry of Education of Hungary (NKFP6/0079/2005 and NKFP 4/064/2004), the Hungarian Scientific and Technological Foundation (OTKA T062436, T042996 and T048302), and the National Council for Science and Technology of Mexico (SEP–CONACyT 43702 and 55718).

Some research activities were conducted in the territory of the Karelian Republic, where geostatistical methods were used for mapping particular soil horizons (Chapter 7), for studying spatial variation of the soil floor (Chapter 3), and for characterization of changes in the spatial structure of soils due to beavers' activity (Chapter 6). Another chapter attempts to evaluate the spatial structure of some soil properties using geostatistical methods on the zonal sequence of soils in the Great Russian Plain (Chapter 5). One chapter deals with Hungarian soils and shows the possibility of spatial interpolation of water transport models (Chapter 8). Another chapter studies the spatial distribution of the soil properties controlling soil aggregate stability in coffee-growing areas of Mexico (Chapter 4). The volume also includes a brief bibliography of research papers where geostatistics were used in soil research.

Finally, we would like to thank the authors of the different chapters who contributed to the book with a lot of successful efforts and we are also very grateful to the different foundations which gave financial support to the research studies.

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Chapter 1

Soil science and geostatistics

R. Webster

Abstract [1]

Pedologists want sound quantitative measures of spatial variation in soil, and they are turning increasingly to geostatistics to provide them. They are treating the soil's properties as the outcomes of random processes and characterizing their variation by variograms. Ordinary kriging is proving sufficiently robust for estimating values at unsampled places in most cases. More sophisticated technique is needed where there is evident trend; it includes universal kriging and restricted maximum likelihood (REML) to estimate the parameters of the underlying models. Simulation is needed to portray the full magnitude of the variation and to generate distributions in assessing risk and sampling effects. There is a correspondence between the geostatistical expression of variation and fractals, but whether variation in the landscape is fractal remains moot.

Background

Farmers have for centuries recognized variation in the soil and taken it into account in their management. They have divided their land into fields within any one of which they could treat the soil as if it were uniform. In recent times they have come to realize that the fields that they or their predecessors created are not uniform, that in many instances the variation within them is substantial, and that with modern technology they can increase yields and make better use of fertilizers and other agrochemicals by taking that variation into account in their management. This realization has led to the current interest in precision agriculture and the need to map the variation. At the same time people and their governments, at least in the richer countries, have grown increasingly concerned about soil pollution and even naturally occurring toxins, whether salts or trace elements, in the soil. They too now want maps of individual soil properties, in these instances showing where the pollutants are and how much of them there is. Both they and the precision farmers want

[1] This chapter is an extended and improved translation of the text published in Russian in "Geostatistics and Soil Geography", Moscow, Nauka Publ., P. 8-18.

quantitative information on the substances of concern. There are similar demands being made by scientists in closely related disciplines, such as geochemistry and hydrology.

Quantitative information must derive from measurement, and we cannot measure the soil everywhere; we can at best measure the soil on samples. So accurate information for any region is available only at isolated points or for small bodies of soil. Whatever we state for intermediate positions or larger blocks of land involves some kind of interpolation or estimation from the measurements. That in turn carries with it uncertainty, and so we want some measure of that uncertainty too.

Engineers first tried to predict values of soil properties from sample data by combining classical statistics with soil classification. They sampled classes delineated on soil maps at random. Then, for each soil property of interest, they computed from their data the means for the classes and used those means as predictors for the classes. They also computed the associated prediction variances, which gave them measures of uncertainty. The method proved a success for several engineering properties of the soil, such as Atterberg limits and particle size fractions. It did not work for the plant nutrients in the soil, which are strongly affected by farm management, nor could it be expected to work for pollutants, which bear no relation to the geology or physiography. Further, the results depended on the skill and predilections of the individual soil surveyors who made the maps in the first place. Some other approach was needed.

Early attempts to break from soil classification treated soil properties as mathematical functions of the spatial coordinates. The functions were fitted by least squares approximation to give regression surfaces or trend surfaces. Typically they were polynomials in the coordinates. The technique had been applied with considerable success in petroleum geology. However, it soon became apparent that polynomials of very high orders were needed to represent actual variation in soil and that they could have no generality. Soil properties appeared as if they were random rather than deterministic, and it was this recognition that provided the break-through: if the soil appeared to be random then why not treat it as if it were random?

The question was rhetorical; pedologists did treat the soil as if its spatial variation were random, as miners had treated ores and rocks shortly before them in the birth of geostatistics. Pedologists discovered that the techniques developed for mining and the underlying theory could be applied equally to soil. And so began a new era in quantitative pedology. Initially, in the 1970s, pedologists had to master the mathematics, to program computers and to explore the potential of their new-found theory. Then, as results of their work were reported in research journals from 1980 onwards, the techniques were increasingly applied in practice in such fields as precision agriculture, pollution assessment and remediation.

The geostatistical approach

What characterizes the geostatistical approach?, we may ask. A brief answer is that it views the soil is as suites of variables that are continuous in space, and it describes their variation in terms of spatial dependence. Specifically it treats those variables as though they were the outcomes of random processes, and it uses geostatistics to estimate both plausible generating functions of the processes and values of the realizations at unsampled places.

It will help to formalize mathematically the basic ideas here as a prelude to the contributions that follow.

Random variables and random functions

In geostatistics we regard any region of interest as comprising an infinite number of points $\mathbf{x}_i, i = 1, 2, \ldots, \infty$. At each point $\mathbf{x}$ we regard the soil property as a random variable, $Z(\mathbf{x})$, which can take many values. For a continuous variable such as the soil's strength or pH this number is infinite, and the whole process may be regarded as a doubly infinite super-population. The variable at $\mathbf{x}$ has a distribution with a mean and variance and higher-order moments, and the actual value there, $z(\mathbf{x})$, is just one drawn at random from that distribution. Other variables may occur in only a finite number of discrete states, and the actual value at any place is one of these states drawn at random.

In these circumstances the quantitative description of the variation involves estimating the characteristics of what are assumed to be the underlying random processes. The characteristics include the means and variances, and perhaps higher-order moments, as above, and, most important, the spatial covariances.

The spatial covariance between the variables at two places $\mathbf{x}_i$ and $\mathbf{x}_i + \mathbf{h}$, separated by the vector $\mathbf{h}$, is given by

$$C(\mathbf{x}_i, \mathbf{x}_i + \mathbf{h}) = \mathrm{E}\left[\{Z(\mathbf{x}_i) - \mu(\mathbf{x}_i)\}\{Z(\mathbf{x}_i + \mathbf{h}) - \mu(\mathbf{x}_i + \mathbf{h})\}\right] , \qquad (1.1)$$

where $\mu(\mathbf{x}_i)$ and $\mu(\mathbf{x}_i + \mathbf{h})$ are the means at $\mathbf{x}_i$ and $\mathbf{x}_i + \mathbf{h}$, and E denotes the expected value. If the mean is constant then Equation (1.1) generalizes to

$$\begin{aligned} C(\mathbf{h}) &= \mathrm{E}\left[\{Z(\mathbf{x}) - \mu\}\{Z(\mathbf{x}) - \mu\}\right] \\ &= \mathrm{E}\left[\{Z(\mathbf{x})\}\{Z(\mathbf{x} + \mathbf{h})\} - \mu^2\right] , \end{aligned} \qquad (1.2)$$

which is constant for any given $\mathbf{h}$. This constancy of the mean and variance and of a covariance that depends only on separation and not on absolute position constitutes *second-order stationarity.*

So the covariance is a function of the lag and only of the lag. It is readily converted to the dimensionless *autocorrelation* by

$$\rho(\mathbf{h}) = C(\mathbf{h})/C(\mathbf{0}) , \qquad (1.3)$$

where $C(\mathbf{0}) = \sigma^2$ is the covariance at lag $\mathbf{0}$. This too is a function of $\mathbf{h}$, namely the spatial correlogram.

In many instances it is unreasonable to assume that the mean is the same everywhere in a region. In these circumstances covariances cannot be defined because there is no value for μ to insert in Equation (1.2). Georges Matheron (1965), the founder of modern geostatistics, recognized the situation and proposed a less demanding statistic to describe variation. He defined the expected squared difference between $Z(\mathbf{x})$ at any two points separated by $\mathbf{h}$, thus:

$$\begin{aligned} \mathrm{E}\left[\{Z(\mathbf{x}) - Z(\mathbf{x}+\mathbf{h})\}^2\right] &= \mathrm{var}\left[Z(\mathbf{x}) - Z(\mathbf{x}+\mathbf{h})\right] \\ &= 2\gamma(\mathbf{h}) \ . \end{aligned} \tag{1.4}$$

The variance per point is half of this, i.e. $\gamma(\mathbf{h})$, which Matheron called the 'semivariance'. Like the covariance, it depends only on the separation of the points and not on their absolute positions. As a function $\gamma(\mathbf{h})$ is the variogram, often still called the 'semivariogram'. Russians should be glad to know that Kolmogorov (1939) had already defined the same function and called it the 'structure function'.

If the process $Z(\mathbf{x})$ is second-order stationary then the semivariance and the covariance are equivalent:

$$\begin{aligned} \gamma(\mathbf{h}) &= C(\mathbf{0}) - C(\mathbf{h}) \\ &= \sigma^2\{1 - \rho(\mathbf{h})\} \ . \end{aligned} \tag{1.5}$$

If it is intrinsic only then the covariance does not exist, but the semivariance remains.

The validity of Equation (1.4) in a wide range of circumstances makes the variogram very useful, so much so that it has become the central tool of geostatistics. It summarizes quantitatively spatial variation in terms of dependence, and it is the essential intermediary for spatial prediction with minimum variance by kriging. It features prominently in several of the chapters that follow, and it will be helpful here to display some of its common characteristics. These appear in Figure 1.1 in their isotropic form, i.e. with lag in distance only: $h = |\mathbf{h}|$.

Figure 1.1 (a) shows a variogram rising from its origin with ever decreasing gradient towards an asymptote, its upper bound, also known as its 'sill'. Its equation is a simple negative exponential:

$$\gamma(h) = c\left\{1 - \exp\left(-\frac{h}{a}\right)\right\} \ , \tag{1.6}$$

where c is the sill, the *a priori* variance of the random process, and a is a distance parameter. It describes a second-order stationary process, and so has a corresponding covariance function, which is also shown. The latter is simply a mirror image of the variogram with equation

$$C(h) = c\left\{\exp\left(-\frac{h}{a}\right)\right\} \ . \tag{1.7}$$

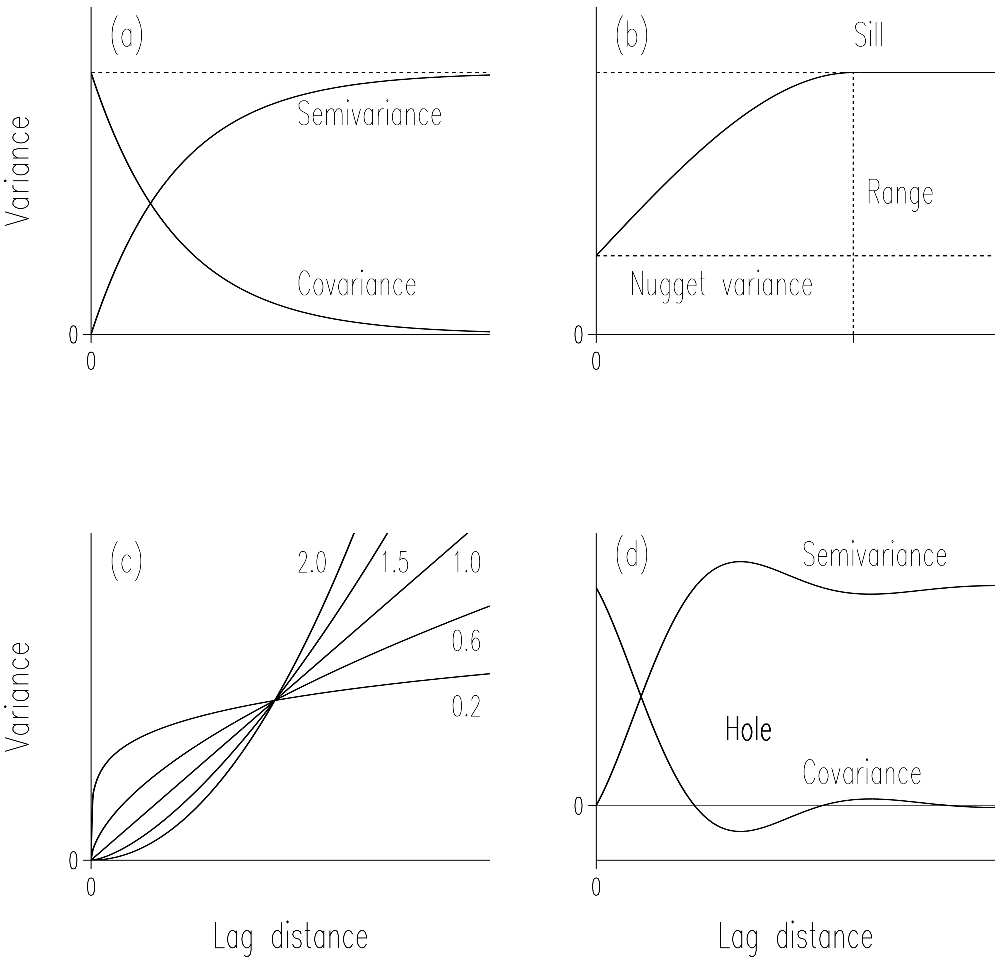

Figure 1.1: Some common kinds of variogram and their corresponding covariance functions: (a) negative exponential variogram and covariance function; (b) spherical function with nugget; (c) five power functions, which have no corresponding covariance functions; (d) 'hole effect' variogram and covariance function

These functions arise frequently in spatial statistics and are the basis of much theoretical work in spatial statistics.

A function that more often describes reality in soil is the spherical function, shown in Figure 1.1(b). It increases to its maximum, its sill, at a finite range, beyond which it remains constant. Its formula is

$$\begin{aligned}
\gamma(h) &= c_0 + c\left\{\frac{3h}{2r} - \left(\frac{h}{r}\right)^3\right\} \text{ for } \ 0 < h \leq r \\
&= c_0 + c \quad \text{for } \ h > r \\
&= 0 \quad \text{for } \ h = 0 \ ,
\end{aligned} \tag{1.8}$$

where r is the range, or 'correlation range' as it is often called. It represents repetitive patches of soil of roughly similar size, sometimes called 'transition' features.

Figure 1.1(b) shows another feature of variograms: models fitted from data often appear to have positive intercepts on the ordinate, whereas theoretically the variance a zero lag should itself be zero. This intercept has the symbol c_0 in Equation (1.8) and is known as the 'nugget variance'. The term derives from gold mining where gold nuggets occur apparently at random and without any relation to one another in low-grade ores. In soil survey the cause is usually unaccountable variation within the shortest sampling interval in surveys, though measurement error also contributes. The nugget variance is constant for all lags and swells the variogram everywhere, as you can see in Figure 1.1(b).

As above, the mean might not be constant, and in those circumstances the variance is unbounded, at least within the regions that pedologists study. A simple power model will often describe such variation:

$$\gamma(h) = \beta h^{\alpha} \ , \tag{1.9}$$

in which the parameter β is a measure of the rate of change, a scaling factor. The exponent α, which must lie within the range 0 to 2, defines the shape of the curve. When $\alpha = 1$ we have a straight line. If $0 < \alpha < 1$ then the curves are convex upwards; if $1 < \alpha < 2$ the curves are concave upwards. Figure 1.1(c) shows several curves with their exponents printed alongside. There are nor corresponding covariance functions. Note also that the limits 0 and 2 are excluded; $\alpha = 2$ defines a parabola and is not legitimate to describe random variation. At the other extreme, when $\alpha = 0$, the variogram would be flat.

Figure 1.1(d) shows another kind of variogram, one in which there is fluctuation with a peak. The corresponding covariance function has a depression, or 'hole', and is often called a 'hole effect' function. It describes variation in the underlying random process that has some degree of periodicity. In one dimension the variogram may fluctuate repeatedly with a constant amplitude. In two dimensions the function must damp as in Figure 1.1(d).

These features appear in several of the chapters below, and you can find fuller descriptions of them in Webster and Oliver (2007).

Elaboration

The above equations form the basis of geostatistics. But notice that they describe models of reality; they are not themselves the reality. Rather, they are products of our imaginations (see Webster, 2000). No real soil behaves exactly as our mental models would predict.

At its simplest we can write our mental model mathematically as

$$Z(\mathbf{x}) \;=\; \mu + \varepsilon(\mathbf{x}) \,, \tag{1.10}$$

in which μ is constant, at least locally, and the residual $\varepsilon(\mathbf{x})$ has a mean of zero and the covariance structure described above.

As several contributors to this volume show, such a model is in many instances too simple. If there is trend across the region then μ in Equation (1.10) cannot be treated as constant; it must be replaced by a term that depends on position. And so we elaborate our model to

$$Z(\mathbf{x}) \;=\; \sum_{k=0}^{K} a_k f_k(\mathbf{x}) + \varepsilon(\mathbf{x}) \,, \tag{1.11}$$

in which the $f_k(\mathbf{x})$ are known functions of $\mathbf{x}$ and the a_k are coefficients determined by the particular situation. Typically the trend term, the first term on the right-hand side of Equation (1.11), can be represented by a polynomial in the spatial coordinates. The second term is as before a random residual with variogram, $\gamma(\mathbf{h})$

This more elaborate model is the basis of universal kriging, so named by Matheron (1969) and now more accurately termed 'kriging with trend'. The trend need not be in $Z(\mathbf{x})$ but in some related variable, say $Y(\mathbf{x})$, and provided that the relation between the two is linear the kriging can incorporate it.

There is a difficulty in applying the model. It lies in estimating the variogram of $\varepsilon(\mathbf{h})$, the residuals from the trend, because the trend cannot be estimated properly without knowledge of the variogram. Olea (1975) showed how to obtain an estimate from data on a regular grid or transect, but his technique cannot be used where sampling has been irregular, which is usual in soil survey. Another method that is sometimes tried where the trend is linear (an inclined plane) is to estimate the direction of the inclination, compute a sample variogram in the perpendicular direction, and use a model of that sample variogram as the variogram of the residuals. It too has its limitations, especially if there are few valid paired comparisons from which to estimate in that direction. Zimmerman (1989) proposed the theoretically more attractive method, namely restricted maximum likelihood (REML) and set out the mathematics. There are still technical difficulties to be overcome before the method can be used widely, largely because some of the popular variogram models do not have smooth likelihood functions. Nevertheless, the approach is promising. Lark and Cullis (2004) have adapted the method for separating the contributions from deterministic and random components, and Lark and Webster (2006) and Webster and Oliver (2007) illustrate its application in geomorphology and precision agriculture, respectively.

Kriging—geostatistics in practice

I have mentioned kriging above, almost as an aside. We should remember, however, that the force driving the development of geostatistics was practical and economic. In Russia meteorologists wanted to interpolate atmospheric variables from sparse recording stations; in South Africa miners wanted to estimate the gold contents of ores locally from measurements on drill cores (Krige, 1966); elsewhere petroleum engineers wished to estimate oil reserves from logged boreholes; and all wanted their estimates to be unbiased with minimum variance. Local estimation, i.e. spatial prediction, was the ultimate goal of geostatistics, and kriging was the means of achieving that goal. Kolmogorov (1939) had written out the equations for the purpose in the 1930s, but without computers no one could solve them. The advent of computers gave mining and petroleum engineers the opportunity. Now computers enable us pedologists to predict soil conditions at unsampled places from more or less sparse data and to make maps at the press of a few buttons. Kriging is almost automatic.

What is not automatic is the design of efficient sampling to obtain data; that requires serious thought. Even less automatic is the modelling of variograms, which remains perhaps the most contentious topic in geostatistics. There are still practitioners who fit models to sample variograms by eye, but their number is dwindling as software for statistical estimation becomes increasingly powerful, with better diagnostic facilities, and congenial and affordable packaging. The greater flexibility and larger numbers of options in the packages, however, means that we must understand more widely than before what we are doing so as to choose sensibly.

Interpretation

One reason for the cavalier attitude to the choice of variogram and its modelling is that kriging is robust; its outcome is not very sensitive to the variogram. So, why worry unduly about getting the 'right' model? If all we want to do is to interpolate to make a map then perhaps we need not worry.

In many instances, however, investigators want quantitative expressions of variation that they can interpret. There are several examples in the contributions that follow. In particular, they often want estimates of the range of spatial dependence, and in those circumstances it is important that they understand the nature of bounded variation, the characteristics of the models, such as the popular spherical and exponential models, to describe it, and technicalities of estimating variograms. Other characteristics of interest are the ratio of ‘nugget’ to ‘sill’ variances, which indicates the degree of local smoothness of variation, and apparent lack of an upper bound, which some investigators interpret as signifying fractal behaviour. I return to that below.

Geostatistical simulation

A kriged estimate is an example of a best linear unbiased predictor, a ‘BLUP’. It is, as the U in its acronym denotes, unbiased, and it is best in the sense of minimizing the variance of the prediction. If you krige at a place where you have a measurement then kriging returns the measured value there with zero variance. Elsewhere it returns a weighted average of the data. The result is a statistical surface in which there is less variance than in the original data; kriging loses variance, it smoothes, and the further are estimates from data the more it smoothes. A map made by ‘contouring’ from a grid of kriged values, which is often the final outcome of a geostatistical exercise, gives a more or less smoothed picture of reality. This is not always what is wanted.

Often an investigator would like a more realistic picture of the truth in the sense that all the roughness that he or she believes to be present in the soil on the land appears in the map. The investigator wants to retain the variance and perhaps even more importantly the spatial covariance. In these circumstances he or she should simulate, and geostatistics provides the means.

Simulation is based on the same underlying models of random processes, e.g. Equations (1.10) and (1.11), as is kriging. It takes the variogram or covariance function as a necessary and sufficient summary of the spatial variation; and it generates values, often referred to as ‘data’, that have in principle the same variogram as the generator. Typically the values are simulated at the nodes of a grid, from which a map can be made. Simulation can be conditional on data, meaning that it is constrained by known values, and in that mode it returns those known values at the sampling points. Maps made from such grids show the main pattern of variation determined by the data with intermediate detail predicted from the variogram model. The technique is also used repetitively to build empirical distributions of values at unsampled places and assess risks of pollution, toxicity and deficiency. Alternatively, simulation can be unconditional, disregarding any data or producing fields of values where there are no data. The latter is often done in studies of sampling (see, for example, Webster and Oliver, 1992). There are several well-tried algorithms for the simulation, and these have been programmed in Fortran and made available in the *Geostatistical Software Library* by Deutsch and Journel (1998). Goovaerts (1997) describes them in detail and illustrates their use.

Fractals

The spherical and exponential functions I mention above describe patterns of variation that, though irregular, are essentially repetitive so that their variances are bounded. In some instances the variance seems to increase without bound as the lag distance increases. At its simplest the variogram in its one-dimensional form has the equation

$$\frac{1}{2}\mathrm{E}\left[\{Z(x) - Z(x+h)\}^2\right] \;=\; \gamma(h) \;=\; \frac{1}{2}\beta h^{2H} \;, \tag{1.12}$$

which is a reformulation of equation (1.9). If $H = 0.5$ then the variogram is linear. This is the variogram of one-dimensional Brownian motion,

$$Z(x) \;=\; Z(x+h) + \varepsilon \;, \tag{1.13}$$

in which ε is a Normal (Gaussian) random deviate.

If the lag interval is divided by any arbitrary positive value, ω, and the resulting semivariances of Equation (1.12) rescaled in the ratio ω^H then the new variogram will be identical to the original one. Brownian motion is thus seen to be a self-similar or fractal process.

In ordinary Brownian motion the successive values of ε are independent, and we can create traces using Equation (1.12) as generator with H set to 0.5. If, however, we increase H in the range 0.5 to 1 we can generate traces that are smoother than those of ordinary Brownian motion and in which successive values of ε are positively correlated. Conversely, if we diminish H to between 0.5 and 0 we shall obtain rougher traces in which successive values of ε are negatively correlated. If $H = 1$ then the variogram is a parabola, describing smooth differentiable variation that is not random. At the other extreme, $H = 0$ describes white noise, which is impossible for a continuous variable in continuous space. So, the values 1 and 0 are precluded.

Within the limits $0 < H < 1$ H is related to the Hausdorff–Besicovitch dimension, or fractal dimension, D, by

$$H \;=\; 2 - D \;. \tag{1.14}$$

Further, if the experimental variogram is expressed in double logarithmic form, i.e. $\log\gamma(h)$ against $\log(h)$, then D is obtained from the slope, m, of the relation by

$$D \;=\; 2 - m/2 \;. \tag{1.15}$$

In this way we see the connection between geostatistics and fractals.

Many pedometricians have computed the fractal dimension from soil survey data in this way, found values of D greater than 1, and sought to interpret the soil as fractal therefore, at least over the range of distances they considered. Whether the soil really is fractal at the field scale is moot. Burrough (1983), who was one of the first pedologists to investigate the matter, concluded that apparently unbounded variation was more likely to have arisen from nested processes rather than Brownian ones. We should bear his conclusions in mind when we seek to understand the meaning of unbounded variograms.

Conclusion

Pedologists have made very substantial progress in applying geostatistics and in understanding the nature of soil variation. They now have the confidence to explore new situations and hitherto little known regions. The contributions that follow, largely describing the results of case studies, show that the spirit of adventure that got us started is alive and well. Let us also realize also, however, that we do not have technical answers to every question and that there are still problems to solve. Practice and theory need to advance together.

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Chapter 2

Variography of discrete soil properties

P. Krasilnikov

Abstract

The chapter deals with simple models of regular spatial distribution of data: “chessboard”, “spot-effect model”, and “Sierpinski carpet”. We show that a mosaic distribution of data (“chessboard”) can be described by a periodic model, if the lag in the variogram is equal to the size of the square of the board. Otherwise, the experimental variogram is fuzzy, and can de described by the “pure nugget” model. If the range of semivariance values for different lags is wide, we recommend trying to vary the minimum lag to find out a periodic structure. If an area with significantly different properties (a “spot”) exists in the site, the variogram has a pseudoperiodic form. In that case, we recommend finding a square trend in data distribution. When an incomplete self-similar structure was studied, we found out that the variogram had a form close to a pseudoperiodic structure with elements of a periodic distribution. We do not recommend interpreting such a distribution as a fractal one since the evidences of self-similarity are fuzzy even in an ideal model.

Introduction

Initially, the main objective of geostatistics in soil science was to enhance the quality of spatial prediction of soil properties (Kuzyakova et al., 2001). However, it is not the only possible application of geostatistical analysis: it is known that, while managing the data, one can get important additional information on spatial distribution of the studied values, particularly for variography (Demianov et al., 1999). The aim of this study is then to explore the role of the spatial structure for expressing different types of variography above all periodicity and mosaics (mainly found for soil data distribution) by using commonly used models of variograms. We first review the geostatistical methods which can help finding and interpreting these periodical structures, including latent ones. Then, we propose a list of reference models, which might be interpreted as evidence of certain structures in soil properties spatial distributions.

Background

In most cases, soil properties with an expressed mosaic structure are characterized by high variability, and the quality of variograms is lower than for the soils with a smooth distribution of properties (Jongman et al., 1995). For the properties, regularly repeating in space, the variogram would be approximated by a periodic model, and the period would correspond to the medium size of the structural unit. Webster (1977) studied the distribution of spectral reflectance of Vertisols in Australia and found out periodicity of reflectance connected with gilgai microrelief. Hummatov et al. (1992) studied the bulk density, moisture content, and cation exchange capacity of gray forest soils (Greyic Phaeozems), and found periodicity in the distribution of the studied properties; the authors explained the phenomena by the presence of paleocryogenic polygonal structure in the soils. Similar results were obtained by Litvak et al. (1997). These authors studied the acidity and exchangeable bases content in the same soils, and also concluded that the periodicity was a result of ancient block structure. In all the cases mentioned above the researchers used a periodic (sinusoidal) model of variogram. In contrast, Bruckner et al. (1999), who found periodicity with a period of 1–1.5 m for humidity, acidity, and respiration and N mineralization rates in forest litter, used a spherical model of variogram.

Apart from periodicity, several researches also discussed pseudoperiodicity, which was realized in a variogram as an incomplete cycle of oscillation, i.e. the variogram had a reverse slope (semivariance decreased with an increase in lag distance) (Burgess and Webster, 1980; McBratney and Webster, 1981), or inverse parabolic form (semivariance increased, and then decreased with an increase in lag distance) (Shein et al., 2001). In most cases, such a behavior of a variogram is regarded as an indicator of a square trend. In a real soil cover, a square trend means there is a big “spot” with significantly different properties, typically a regular change of soils within a study plot (Shein et al., 2001). However, Oliver (1987) regarded a reverse slope of a variogram as an evidence of irregular periodicity of soil properties.

Still, it is not completely clear what kind of spatial structure of properties corresponds to a linear model of a variogram with no sill. There are simple cases, when an unlimited growth of semivariance occurs along a gradient, i.e. there is a linear trend in the distribution of properties (Jongman et al., 1995). Samsonova et al. (1999) gave an example of such a distribution of acidity and K content in sod-podzolic soils (Albeluvisols) over a field where fertilizers were applied irregularly. A linear trend can be found in directional variograms if the direction is perpendicular to a sharp boundary of two different blocks of the same plot. Goovaerts (1998) found a linear form of one of the directional variograms, because one of the fields within the study plot was limed, and the other one was not. Elimination of the trend can help in the cases mentioned. However, more complex situations have also been described. Burgess and Webster (1980) found a linear form of directional variograms for soil stoniness, and elimination of trends did not change the form of the variograms. An interesting interpretation of linear variograms was proposed by Burrough (1983; also discussed in Webster, this volume). He suggested that soil variation had the same nature as Brownian movement and, thus, could be described as a fractal. Linear model of variogram reflects a particular case of soil properties' distribution (Fig. 2.1) with a fractal dimension D=1.5. Higher or lower values of the fractal dimension result in a power function for a model variogram, at D=1 it transformers into a line parallel to the X axe ("pure nugget"), and at D=2 it has a parabolic form.

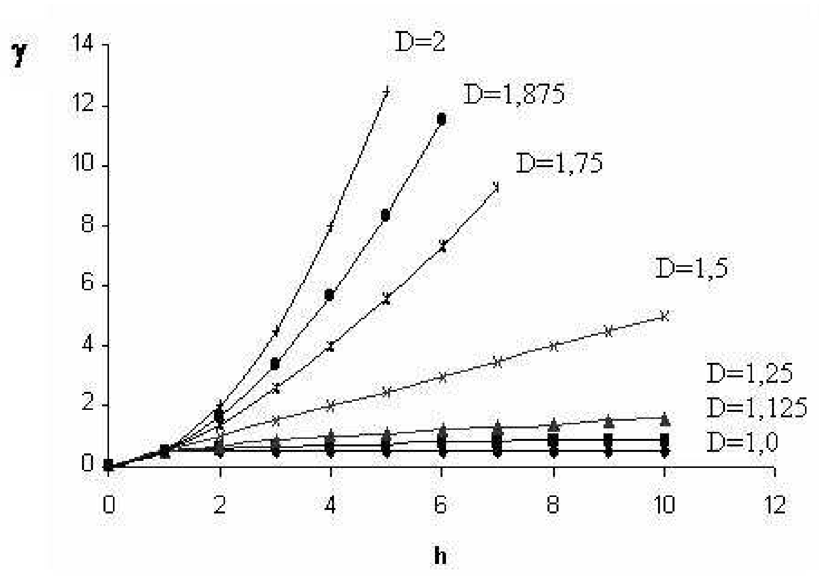

Figure 2.1: Variograms for data with a fractal distribution (one-dimensional case) depending on the value of the fractal dimension (h – lag distance in provisional units)

However, there are serious doubts that the distribution of soil properties really has fractal nature (Webster, this volume). Burrough (1983) himself noted that infinite increase of variance indicates a nested structure rather than fractal behaviour.

Jongman et al. (1995) gave a review of variogram model interpretations based on various spatially distributed data sets. They showed that a signal with sharp boundaries at regular distances in a one-dimensional case (e.g., a transect) might be better approximated by a linear model with a sill, the same regular signal in a two-dimensional case, or an irregular signal – by a spherical model, a signal with sharp boundaries at all distances – by an exponential model, a signal with a linear trend – by a linear model without sill, a periodic signal – by a periodic (sinusoidal) model, white noise – by a "pure nugget" model, and gradually varying signal – by a Gaussian model. It remains unclear in this grouping what the difference is between a signal at regular distances, and a periodic signal. The authors (Jongman et al., 1995) regard signals of various intensities as regular, and signals with fixed amplitude – as periodic ones. It is important to note that the authors worked with model variograms, which were smoothed down in comparison with experimental ones. In most cases, model approximation leads to partial loss of data, especially if the geostatistical software employed lacks some possible models (e.g. Pannatier, 1996).

Methods

In order to represent different spatial distributions, we applied three models: 1) the "chessboard", 2) the "spot", and 3) the "Sierpinski carpet". For geostatistical treatments and for constructing experimental and (in several cases) model variograms we used Variowin (Pannatier, 1996) and Genstat (2002 – evaluation version) software.

"Chessboard"

Let us model a simple "chessboard" type of periodic alternation of properties on a surface. This two-component model reflects a hypothetical soil cover, where some soil property takes fixed values $\boldsymbol{x}$ and $\boldsymbol{y}$ at a certain regular distance. To facilitate modeling let us consider $\mathbf{x}$=1 and $\mathbf{y}$=2. The soil cover is considered isotropic, i.e. the property alternates at the same distances in all directions. This model corresponds to a number of real soil properties' distributions with an expressed periodicity in the soil properties, e.g. in polygonal tundra, in zones where salts, moisture or any other components are distributed according to the microrelief. Also at other scales, many landscapes have a periodic structure related to mesorelief and erosional processes. Of course, real soil seldom has regular periodic distribution, and it seems improbable that any property can take fixed values in alternating areas. However, all these deviations from an ideal model would only be less expressed variants of the presented model.

Let us consider the variant where "samples" were collected from the center of each polygon on a "chessboard" 15x15 with a lag corresponding to the periodicity of alternation of soil properties (225 experimental points). It is known that for an experimental variogram it is enough to have 150 sampling points (Wackernagel, 2003). For modeling, let us use various lags: equal to, less and more than the sampling resolution.

If we use the lag 0.5, the experimental variogram looks like a cloud of points with variance ranging from 0 to 0.4 (Fig. 2.2 a). Facing such a distribution of experimental points on a variogram, a researcher usually concludes that the data are distributed irregularly ("white noise"). The only possible model to approximate data in this case is a line parallel to the X axis – a "pure nugget" model. Even if we can find any periodicity, no valuable information can be derived from it. One can speak of periodicity when the points are interconnected, but a periodic model is difficult to apply. If the lag is equal to 1.0 (Fig. 2.2 b), the variance decreases to a range of 0.15 to 0.35, and periodicity can be found and modeled. Increasing the lag to 2.0 (Fig. 2.2 c) one can observe further smoothing of the data. A linear model with a reverse slope in that case may approximate experimental points.

Thus, in the case of a significant range of variance of experimental points we should permit a hypothesis that the data have a periodic structure. Modeling using standard software products yields a linear model with a reverse slope or the "pure nugget" model. A periodic model can be successfully applied only if the lag corresponds to the characteristic distance of alternation of a given property. Thus, for interpretation of the data characterized by a linear model with reverse or zero slope it seems useful to try to change the lag for the experimental variogram. If some lag allows us to use a periodic model, we should conclude that the spatial distribution of the data is regular, and the period approximately corresponds to the lag distance.

As mentioned above, in a real soil cover sharp changes in the values of any parameters are seldom, in most cases they are smooth. Thus, we also modeled such a situation. The model is a slightly complicated, tri-component version of the same "chessboard", where the values in squares are distributed in the order 1–2–3–2–1 etc.

As we expected, the experimental variograms for "smoothed chessboard" were similar to those obtained for the bi-component "chessboard" periodic distribution of data (Fig. 2.3). Absolute variance values are higher in the case of the tri-component distribution due to a bigger difference between the lowest and the highest values, but the range of variance values is narrower than for the bi-component "chessboard". In the same manner, a periodic model may approximate a variogram if the lag distance corresponds to the characteristic size of a single polygon. For other lags, the only possibility is to use a linear model with reverse slope or the "pure nugget" model.

Spot effect

The spot effect, often called a "hole effect" in the literature (Oliver, 1987), describes a relatively uniform surface with an area (or areas) with contrasting properties. We do not use the term 'hole effect' because it is confusing: some authors understand the term as referring to sharp periodic changes in soil properties in space (e.g. Jongman et al., 1995). In the latter case, a linear or periodic model may describe the spatial distribution of soil properties, while the presence of a spot is usually called "quasiperiodicity".

We described a simple model of a bi-component system of a uniform plot 15x15, where there is a spot sized 9x9. The values of the background were taken as equal to 1, and the values within the spot – equal to 2.

As it has been previously described for quasiperiodic models, the distribution of experimental points indicates the presence of a square trend: the variance first increases with an increase in the lag distance, and then decreases (Fig. 2.4). The

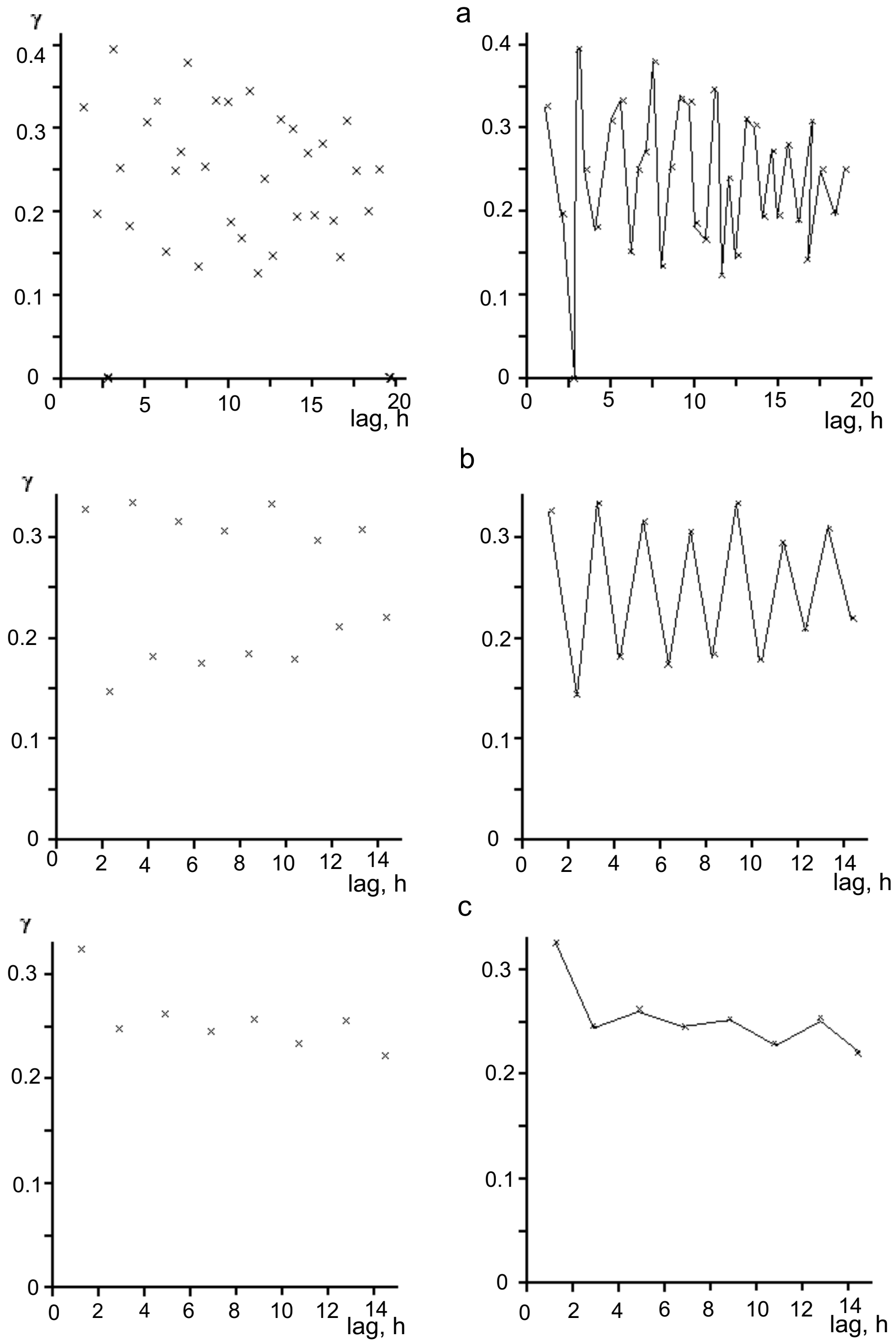

Figure 2.2: Experimental variograms for the "chessboard" model (in the right-hand column the points are connected for visibility purposes): a – lag 0.5; b – lag 1.0; c – lag 2.0

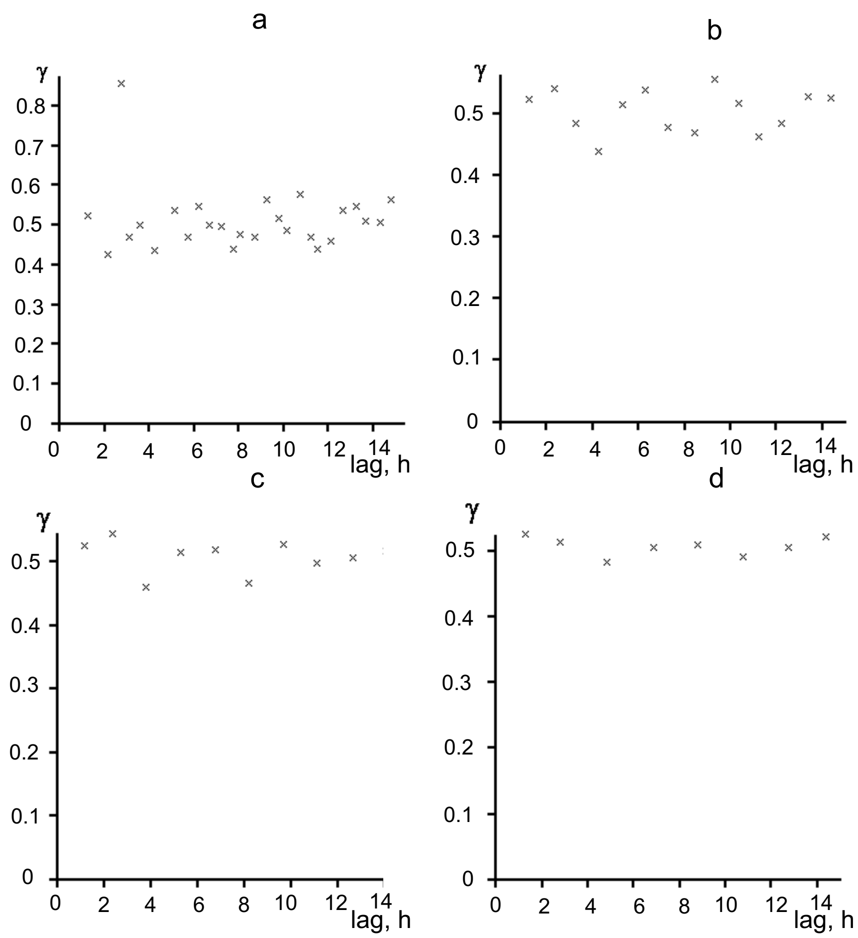

Figure 2.3: Experimental variograms for the “smoothed chessboard” model: a – lag 0.5; b – lag 1.0; c – lag 1.5; d – lag 2.0

shape of the variogram practically does not depend on the lag distance. The experimental variograms fit well to standard functions, such as Gaussian one (Fig. 2.4 d). It is important to note that such a form of the variogram curve might also result from a linear change of values (e.g., a change of soil groups), if we deal with a directional variogram in the direction perpendicular to the borders between two distinct objects.

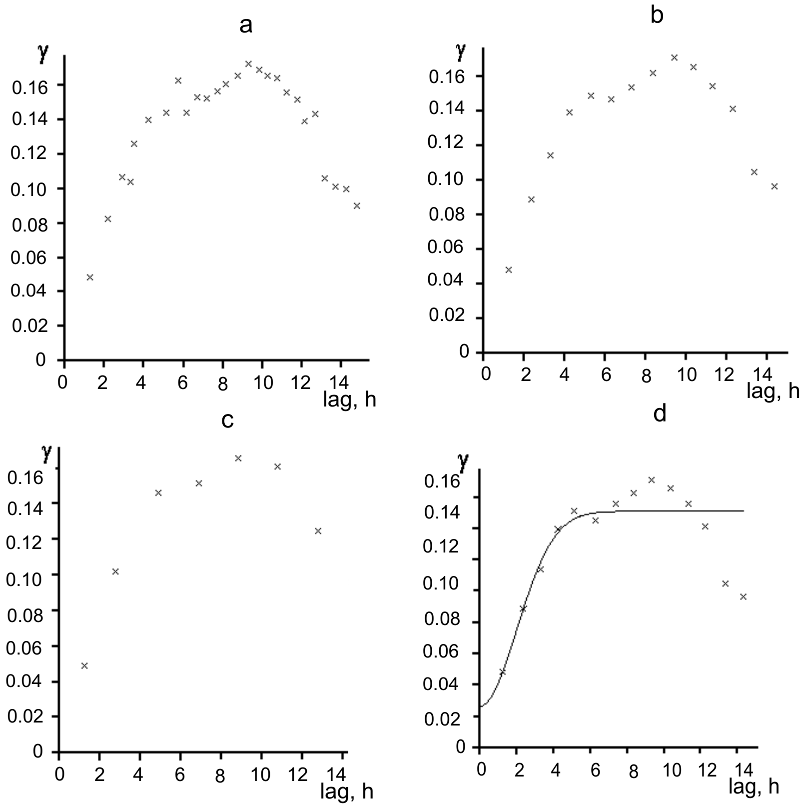

Figure 2.4: Experimental variograms for the distribution of data with the spot effect: a –lag 0.5; b – lag 1.0; c – lag 2.0; d – Gaussian model for the experimental variogram with lag 1.0

If such a distribution is found, the best way to deal with the data is to find out and describe a square trend, and then use it for interpreting the spatial distribution of the data.

Fractal model

The use of fractal models for interpretation of data on structural organization of soil properties is still under discussion. Above we discussed the theoretical background for unlimited growth of variance with increasing lag distance (linear or power model) as fractal behavior. However, as was mentioned also, it is not clear yet how these mathematical models correspond to the reality. To interpret the fractal nature of the soil cover it is necessary to understand the physical meaning of fractals for soils. In fact, when we speak of fractal organization of the soil cover, we purport that the soil cover contains some structural elements of various scales, bearing evidence of self-similarity. The latter might characterize both qualitative (e.g. shape) and quantitative soil attributes. For example, a soilscape having depressions of various sizes would show some fractal properties. Does it mean that an increase in lag distance would lead to a rise in variance? It is doubtful, because the difference in values between the "background" and "depressions" mostly does not depend on the scale. However, scale-dependent values in "depressions" are also possible, and such a situation will be discussed below.

To clear up the situation we attempted to model a partially fractal distribution of soil properties. The model was based on a simplified classical fractal surface – "Sierpinski carpet" (Fig. 2.5). Previous studies showed that the spatial distribution of some soil physical properties evidenced self-similarity, and could be successfully modeled using "Sierpinski carpet" (Perfect et al., 2006). This surface has a fractal dimension less than 2 but more than 1 (1.892...). The "background" values were considered to be uniform and equal to 1.0, the values in "depressions" – equal to 2.0.

It is obvious that the model we use is not a mathematical fractal in a strict sense: a fractal should be infinitely self-similar both at an increase and a decrease in scale. This model, however, can be used because its "incomplete fractal" behavior completely corresponds to the situation existing in nature. First, real natural objects are almost never fractals in the mathematical sense, but have only elements of fractal structure: a tree has no roots of infinitely high orders, a river does not branch out infinitely etc. Second, in a practical study of the nature we are forced to limit the scale of our study to a certain range; the upper limit depends on the grid size, and the lower limit – by the sampling resolution. Thus, such a three-level fractal can be used as a model for fractal behavior of soil properties.

As the result, we obtained experimental variograms for our incomplete fractal distribution of data. We found that experimental variograms have no tendency to unlimited growth according to linear or power law. The variance increased to some limit of the lag distance, and then decreased (Fig. 2.6). The form of the experimental variogram practically repeated that for the quasiperiodic model corresponding to the distribution of data with a "spot effect". It is not surprising since the biggest element of the fractal is a "spot" with values different from those of the "background".

1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
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1	2	1	1	2	1	1	2	1	1	2	1	1	2	1	1	2	1	1	2	1	1	2	1	1	2	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Figure 2.5: Simplified “Sierpinski carpet” model grid

Comparing with the quasiperiodic model, the “fractal” shows some secondary periodicity of distribution, which can be found after elimination of the square trend. The “spots” of secondary and tertiary order scales form this periodicity.

To check the effect of fractal distribution with the values, varying with the scale, we made a slightly complicated model. The biggest elements (the “spot” in the center) received the values equal to 4.0, the secondary “spots” – 3.0, and the tertiary “spots” – 2.0. Thus, the scale factor was included: the values in bigger elements of the plot had higher difference from the “background’ values, than smaller ones. The experimental variogram showed even more clearly quasiperiodic character (Fig. 2.6 d). It was explained by higher contrast (difference in values) between the biggest “spot” and “background”.

Experimental variograms both for “Sierpinski carpet” distribution and for its complicated model might be successfully approximated by standard models, such as Gaussian one (Fig. 2.7). Also a “layer by layer” interpretation is possible, first eliminating a square trend, and then searching for periodic components in various scales. However, we should note that in reality the latter might be difficult, because pure fractal distribution, even incomplete, is seldom found in soil cover structure. Data interpretation based on fuzzy periodicity can lead to groundless speculations.

Concluding we should stress that fractal spatial distribution of data does not lead to expected infinite growth of variance with increasing lag distance. The model proposed by Burrough (1983) implies infinite mathematical fractal distribution, while

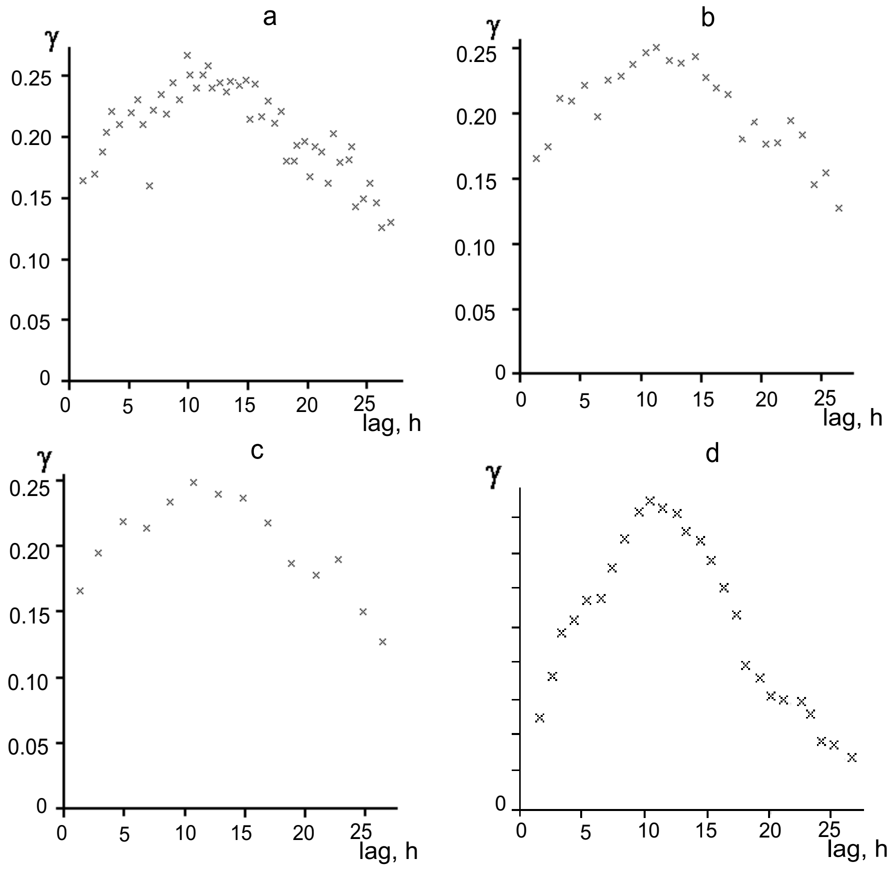

Figure 2.6: Experimental variograms for a fractal distribution of data: a – lag 0.5; b – lag 1.0; c – lag 2.0; d – "Sierpinski carpet" with a scale factor, lag 1.0

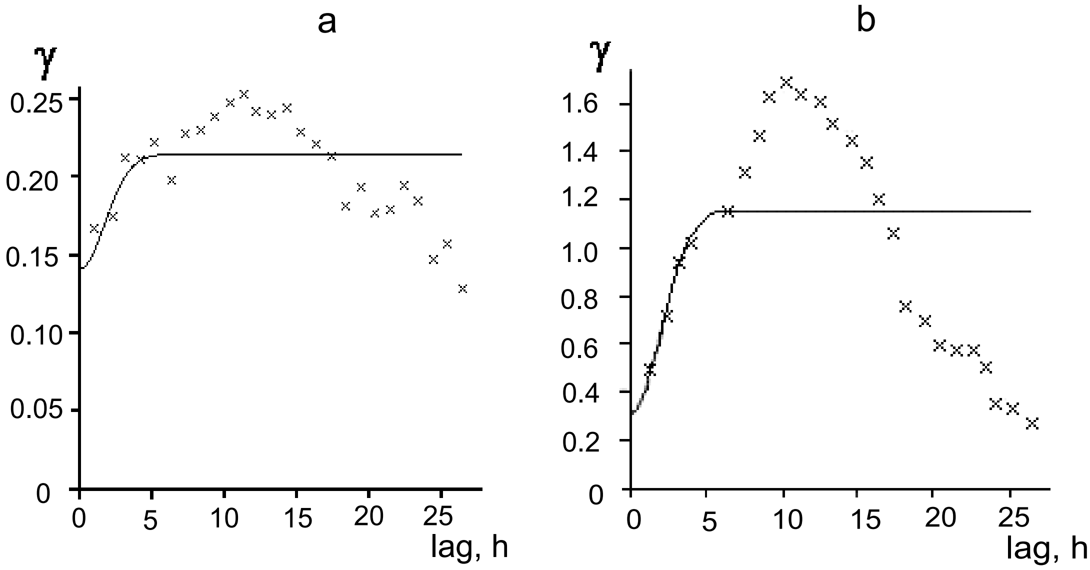

Figure 2.7: Gaussian variogram models for a fractal data distribution (lag=1.0): a – normal "Sierpinski carpet"; b – "Sierpinski carpet" with a scale factor

in reality we are limited by the scales applied. The variograms have a high nugget value (Fig. 2.6), because no data on spatial distribution on the scale finer than sampling resolution are available. At the distances bigger that ½ of the grid size, the semivariance drops down, because its growth is limited by the extension of the study plot. The behavior of the variogram resembles that in the case of the "spot effect", and the bigger "spot" determines the variogram shape.

Thus, the reported "fractal dimension" of soil cover should be regarded with caution. It would be better regarding this type of soil properties distribution as some elements of self-similar structure.

Conclusions

The modeling of spatial structures of soil properties distribution resulted in the following main results. The presence of a mosaic structure (periodicity) of soil properties of a "chessboard" type in most cases show a experimental variogram resembling "white noise", indicating the absence of spatial correlation of data. However, properly selected lag distance allows describing the spatial structure with a periodic model. If a linear model parallel to X axe or with inverse slope approximates experimental variogram we recommend searching for a minimum lag distance equal to the characteristic size of a polygon. An indirect evidence of a mosaic structure is a drastic decrease in the range of variance after increasing the minimum lag distance if a set of data is different from the "background" values ("spot effect"), or, in other words, there is quasiperiodicity in data distribution, the variance first increases with increasing lag distance, and then decreases. In that case we recommend selecting a square trend to describe the spatial distribution of data. If some elements of fractal structure are present, the experimental variogram has the form similar to that for quasiperiodic distribution of data, because the biggest element of the fractal structure is included in the model as a "spot". If after eliminating a square trend the variogram has evident periodicity, it can mean that the spatial distribution of data has elements of self-similarity.

Possible presence of spatial structure might be expected at study sites, where variograms show low spatial correlation. We propose the following steps to find out possible spatial structures in data distribution. First, linear trends should be eliminated, if present. Then, the experimental variograms should be constructed with different lag distance. The distribution, well described by a periodic or quasiperiodic model would indicate the presence of a mosaic structure or a "spot". The fractal structure, if present, is not well described by geostatistical modeling. Possible presence of self-similarity phenomena is reflected by a variogram, resembling that for quasiperiodical distribution.

However, one should be careful with the interpretation of the results of variography, since similar experimental variograms might reflect completely different spatial structures. Variography should be a tool for elaborating a working hypothesis rather than the final interpretation. Also, further research on the variography of real soil structures is needed for a better understanding of the relation between soil cover structure and geostatistic modeling.

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Chapter 3

Spatial variability of forest litters in bilberry spruce forests of Fennoscandia

E. Solomatova, V. Sidorova

Abstract [1]

Variability of the forest floor thickness was investigated in old-growth and disturbed bilberry spruce forests of Karelia and Finland. Coefficients of variation in old-growth forests reached 58–107 %, being much higher than corresponding coefficients for disturbed forests. Variography of litter depths has shown experimental variograms for old-growth forests to be best approximated by the "pure nugget" model or exponential models close thereto. The litter thickness in disturbed forests demonstrated a periodic distribution or a tendency towards one. We presume the periodicity of the litter thickness in disturbed forests is determined by its regular distribution from tree trunks to gaps. Regular distribution in old-growth forest ecosystems is veiled by a multitude of overlapping litter formation cycles, each having its own specific structure. At the same time, total variability of the litter thickness increases with age due to accumulation of random factors determining its distribution.

Introduction

Forest litters have long been an object of soil scientists' and silviculturists' close attention. There are various theoretical approaches to classification of forest litters based on traditional ideas about the object (Stepanov, 1929; Meyer, 1943; Muller, 1979; Bogatyrev, 1990, 1993). Being a biogeocoenotic formation, the litter possesses an essential property – lability (the capacity to respond quickly to changes in external factors), which is manifest in its morphology (Kylli, 1980; Chertov, 1981; Nikonov, 1988). Thickness is a basic morphological parameter of the forest litter, yet considered to be fairly subjective. Stepanov (1929) believed the bias

[1]This chapter is an extended and improved translation of the text published in Russian in "Geostatistics and Soil Geography", Moscow, Nauka Publ., P. 81-91.

could be eliminated through systematization of massive material on soil genetics and silvicultural-biogeocoenological characteristics, and suggested using this parameter as a subordinate (secondary) trait in classification of forest litters (Sapozhnikov, 1984, 1987). Indeed, litter thickness can vary widely even within the same forest type (Skorodumov, 1940; Karpachevsky, 1977; Morozova and Fedorets, 1992; etc.). A shallow floor indicates that litter decomposition rate is relatively high, a thick one – that the decomposition rate is rather slow. The floor thickness in undisturbed ecosystems is determined by quite a number of factors such as the topography, soil moisture conditions, stocking density, composition and age of the tree stand. Studies have demonstrated (Wallace Covington, 1981; Kolomyts, 2000) that the litter thickness and, hence, its stocks, are the lowest in younger, relatively sparse forest ecosystems. As the stand matures, annual amounts of litterfall stop influencing the floor thickness, and the factor of significance is the rate of decomposition and humification of dead organic matter, the floor thickness remaining relatively constant (Lull, 1959).

The present study aimed to assess and compare actual spatial variability of forest litter in bilberry spruce forests and a secondary forest type in East Fennoscandia. The litter thickness is considered here as the criterion through which spatial variability of the forest floor can be described.

Study areas and methods

Surveys were carried out in the middle and northern taiga of Karelia and South Finland, which lie on the Baltic shield. The terrain is broken, with frequent alternation of hills and ridges generated both by tectonic denudation and by aqueoglacial processes and of topographic lows. Numerous small lakes and mires are scattered over the territory (Atlas of Karelian Autonomous Soviet Socialist Republic, 1989).

The mid-taiga subzone belongs to the Central agroclimatic district. General climatic features are a short cool summer and lengthy winter (150-190 days), considerable precipitation, high cloudiness and unstable weather through most of the year. Annual precipitation is 600-700 mm, the coefficient of humidity is 1.2; temperatures above +5 °C over the growing season total 1600-1700 °C, above +10 °C – 1400-1600 °C; mean air temperature in January is –11…-11.5 °C, in June +15 …+16 °C.

The climate of the northern taiga subzone is even colder and wetter. The sum of temperatures higher than +5 °C during the growing season is 1300-1600 °C, and of temperatures higher than +10 °C is 1000-1200 °C. Mean annual precipitation is 500–650 mm, but the coefficient of humidity due to lower evaporation rate is higher (1.42).

Surveys were done in six key sites (Fig. 3.1).

Site 1 (25x30 m) is situated in the integrated monitoring area Valkea-Kotinen, Finland. The parent rock is silty-sandy bouldery till. The forest is classified as fresh

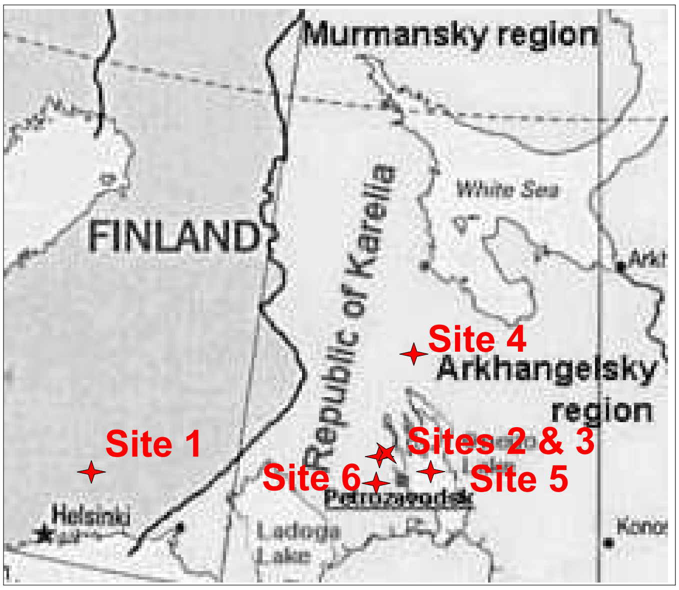

Figure 3.1: The location of the study sites

bilberry spruce forest. Trees are 155-190 years old. The stand composition is spruce mixed with birch and pine. The soils are sandy-loamy podzolized podburs (Entic Podzols). Bedrock outcrops are abundant.

Site 2 (54x54 m) is situated in the Kivach strict nature reserve, central Karelia (Kivach 1). Loamy till is the parent rock. The forest is classified as fresh bilberry spruce forest. Trees are 70 to 220 years old. The stand composition is spruce mixed with pine and birch. The soils are sandy-loamy and loamy iron, humus-iron and iron-humus podzols (Rustic and haplic Podzols).

Site 3 (54x54 m) is situated in the Kivach strict nature reserve (Kivach 2). The parent rock is banded clays. The forest is classified as fresh bilberry spruce forest. The stand age is 80 to 250 years. The stand composition is spruce mixed with birch. The soils are clayey, surface podzolic (Stagnosols).

Site 4 (2500 m^2) (Gabselga) is a remnant fragment of a spruce forest on a steep morainic ridge on Lake Kask shore, at the boundary between middle and northern taiga of Karelia. The parent rock is sandy-loamy, bouldery till. At a depth of 1.2-1.5 m, diorite bedrock underlies the till. The forest is classified as fresh bilberry spruce forest. The stand is dominated by spruce with some birch present. Trees are 100-120 years old. The soils are groundwater-gleyed loamy-sandy humus-iron podzols (Endogleyic Podzols).

Forest in **site 5** (81x81 m) (southern Bolshoi Klimetskiy Isl., Lake Onego) is classified as moist bilberry spruce forest. The parent rock is sandy till. The stand is dominated by spruce with some birch and aspen present. Trees are 100 year old. The soil cover is a variation of podzolized podburs (Entic Podzols), iron podzols (Rustic Podzols), and humus-iron podzols (Haplic Podzols) with patches of gravelly

(Leptosols) and peaty gley soils (Histic Gleysols).

The territory of **site 6** (81x81 m) (Gomselga) used to be covered by spruce forest, which was nearly totally cut down. The parent rock is silty-sandy till. The site is now under a secondary forest stand defined as a secondary type aged 50 years. The stand composition includes birch and aspen with some pine and spruce. The soil is silty-sandy iron-humus podzol (Haplic Podzol).

To determine litter thickness, the sample plots were split into 1 m^2 squares following a regular grid. Measurements were done in small soil pits. The number of litter thickness measurements done in site 1 was 400, in sites 2 & 3 – 2916 in each, in site 4 – 72, in site 5 – 6500, and in site 6 – 2500.

Spatial variability of the litter thickness was studied using geostatictical methods. Geostatistics provides a set of statistical tools for incorporating the spatial coordinates of soil observations in data processing, allowing description and modeling of spatial patterns, predictions at unsampled locations, and assessment of the uncertainty attached to these predictions (Goovaerts, 1998).

The *semivariance* is the central tool of geostatistics. It quantifies how properties vary spatially. The semivariance that summarizes the spatial variation for all possible pairing of data is calculated by (3.1)

$$\gamma(\mathbf{h}) = \frac{1}{2N(\mathbf{h})} \sum_{i=1}^{N(h)} \{z(\mathbf{x}_i) - z(\mathbf{x}_i + \mathbf{h})\}^2 \tag{3.1}$$

where $\gamma(\mathbf{h})$ is the semivariance at each lag (separating distance), **h**, N(**h**) is the number of point pairs separated by the giving lag, and z($\mathbf{x}_i$) and z($\mathbf{x}_i$+ **h**) are the results of measurements at location $\mathbf{x}_i$ and $\mathbf{x}_i$+ **h** respectively. A plot of the estimated γ(h) values against h is called a *semivariogram* or *variogram*.

By definition, the variogram value at zero lag should be zero, but in practice it usually intercepts the ordinate at a positive value known as the *nugget variance* (C_0). The nugget represents measurement error and unexplained or random spatial variability at distances smaller than the shortest sampling interval. The variogram value, at which the plotted points level off is known as the *sill*, and the lag distance (a), at which the variogram levels off is known as the *range* (or *the zone of influence*), beyond which there is no longer spatial correlation and, hence, no longer spatial dependence. The difference between C_0 and sill is called *the structural variance*, C, representing the variance accounted for by the spatial dependence.

Positive definite models are fitted to empirical variograms to capture the major spatial features of the property. The most commonly used models are: linear, power, linear with sill, spherical, exponential, and Gaussian (McBratney and Webster, 1986). More complicated nested model assumes that the value of a soil property at a point $\mathbf{x}_i$ is the sum of a number of independent, spatially random functions. *Nested model* accounts for situations, where differences in soil have been caused by independently acting soil-forming processes having different weights that operated at different scales (Taylor and Burrough, 1986).

Semivariance estimations may depend on parameters, such as lag intervals, number of lags, anisotropy, etc. In this study, we chose the lag of h=1 m, the maximum lag of h did not exceed linear dimensions of the plots, the minimal number of pair was not less than 70. Geostatistical analyses were performed using Variowin, version 2.2.; models were fitted by eye and by minimizing the "Indicative Goodness of Fit" (Pannatier, 1996).

Results and discussion

The statistical parameters describing litter thickness variability are shown in Table 3.1. High variation of litter thickness values indicates its formation processes had diverse manifestations within the same forest type depending on ecological conditions. The greatest variability was demonstrated by fresh bilberry spruce stands (Kivach 1, Kivach 2, Valkea-Kotinen), where the coefficient of variation of the litter thickness reached 107%, 99% and 81%, respectively. As the soils grew moister, litter thickness stabilized, its coefficient of variation decreased to 33% and 58% (Gabselga, Bolshoi Klimetskiy). The coefficient of litter thickness variation in a secondary forest type (Gomselga) equalled 51%. Some zero values of litter thickness have been recorded from all sites except for site 4 (Gabselga). Litter was missing where the measurement point coincided with a trunk, uprooting, fallen tree, bedrock outcrop, etc. The greatest litter thickness was recorded from the moist bilberry spruce stand (site Bolshoi Klimetskiy) and equalled 37 cm. The increase in litter thickness in the site was due to higher moisture of the soils.

Table 3.1: Summary statistics of forest litter cores

	secondary forest type	moist bilberry spruce forest	fresh bilberry spruce stand			
	Gomselga	Bolshoi Klimetskiy	Gabselga	Valkea-Kotinen	Kivach 1	Kivach 2
Stand age	50	100	100-120	155-190	70-220	80-250
n	2500	6500	72	400	2916	2916
min	0.00	0.0	4.0	0.0	0.0	0.0
max	29.0	37.0	24.0	19.0	19.0	14.0
$\bar{x}$	4.2	10.7	12.1	3.2	3.8	2.4
med	1.0	10.2	12.0	3.0	3.5	2.0
S^2	4.5	38.5	16.4	6.7	14.0	6.6
S	2.1	6.2	4.1	2.6	3.7	2.6
CV, %	51	58	33	81	99	107

As demonstrated by Fig. 3.2, total percent cover of the forest litter also varied. Compared to other sample plots, the two sites situated in the Kivach reserve had the lowest percent cover of the forest litter, equaling 63% and 66%, respectively. The reason for that was a great number of tree uprootings.

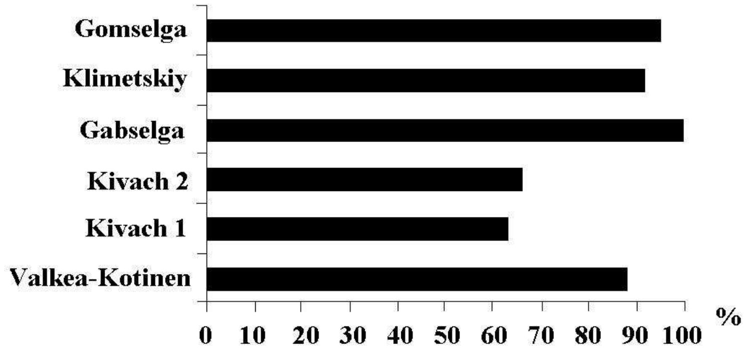

Figure 3.2: Total percent cover of the forest litter

Calculations of γ(h) were performed and variograms were plotted for all six sites. The results revealed a wide range of values, which could not be described by the simplified model of regular change in litter thickness from the trunk to the crown of the edificator plant.

The litter thickness variogram for site 1 (fresh bilberry spruce stand, Valkea-Kotinen) reflected a nearly 100% nugget effect (Fig. 3.3, Tab. 3.2). The variogram was described by a linear model, but the slope being insignificant:

$$\gamma(h) = 6.42 + 0.0149h \tag{3.2}$$

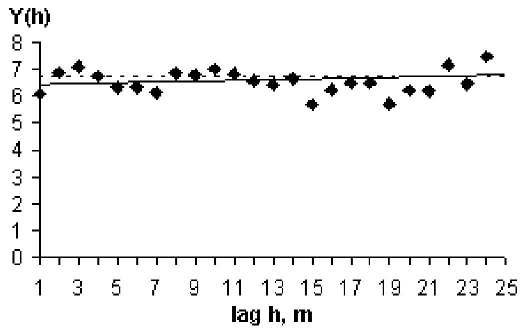

Figure 3.3: Variogram models for forest litter thickness for site 1 (fresh bilberry spruce stand, Valkea-Kotinen). Hereinafter, points indicate sample semivariances, solid lines is fitted models, dotted line is variance

Nugget variance nearly coincided with the variance (Tab. 3.1, 3.2). One can conclude that litter thickness variations could not be distinguished from variations of the uncorrelated random variable, i.e. with the selected lag (1 m), large-scale

Table 3.2: Parameters for semi-variogram models for forest litter thickness

Site	Forest type and age	Model	Nugget (Co)	Sill (C)	Range (a), m
Gomselga	secondary forest type, 50 years	Exponential and periodic	2.69	4.53	30
Bolshoy Klimetskiy	moist bilberry spruce stand, 100 years	Exponential	29.03	39.16	>50
Valkea-Kotinen	fresh bilberry spruce stand, 155-190 years	Linear	6.42	6.79	>25
Kivach 1	fresh bilberry spruce stand, 70-220 years	Exponential	13.50	16.05	30
Kivach 2	fresh bilberry spruce stand, 80-250 years	Exponential	5.67	7.69	35

variation was indistinguishable from "noise". Data variation occurred around a mean value of 3.18 (Tab. 3.1).

The variograms for the sites 2 and 3 (fresh bilberry spruce stand, Kivach 1 and Kivach 2) (Fig. 3.4) were best described by the exponential model. The equations for the function γ(h) for the sites 2 and 3 had the following form, respectively:

$$\gamma(h) = 13.5 + 2.55 * (1 - \exp(-h/97.6)) \quad (3.3)$$

$$\gamma(h) = 5.67 + 2.02 * (1 - \exp(-h/97.6)) \quad (3.4)$$

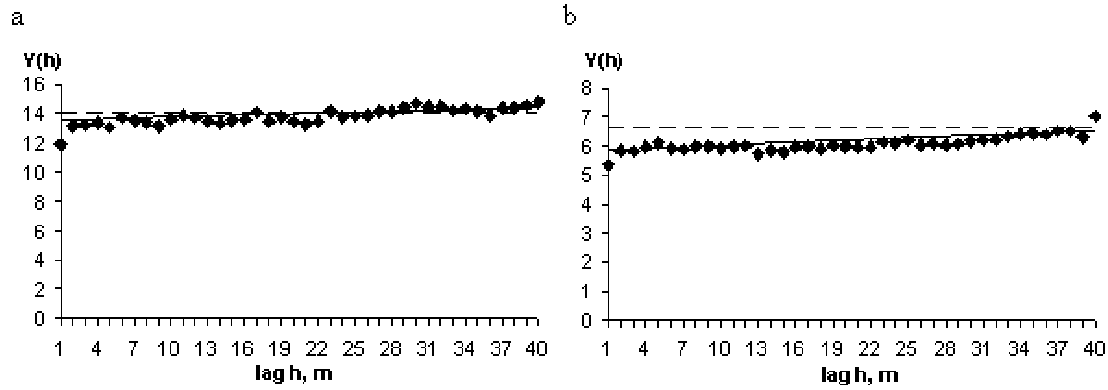

Figure 3.4: Variogram models for forest litter thickness for: a. site 2 (fresh bilberry spruce stand, Kivach 1); b. site 3 (fresh bilberry spruce stand, Kivach 2)

The insignificant slope of the curve in the variograms of the sites 2 and 3 indicated that the study area could be considered to be homogeneous. High nugget variance for the sites 2 and 3 was ascribed to the variability of soil properties at distances smaller than the lag (1 m), and to measurement errors.

The variogram plotted to determine the variation of litter thickness in site 4 (fresh bilberry spruce stand, Gabselga) looked quite unusual (Fig. 3.5). Neither of the models fitted to the variogram sufficiently well. Visually, the periodic model corresponded to the experimental variogram, but approximation yielded no satisfactory results. Apparently, the periodicity of litter thickness change related to the patchy structure of the community complicated the situation in our case: in places the semivariance was higher than variance (which value appears in the figure as a straight dotted line parallel to the X axis), although theoretically the former should be tending toward the latter. One should note that the number of point pairs, for which the calculations were done, significantly decreased for the lag h > 5, making data for greater distances less reliable (though the number of pairs was more than 70 for every lag distance, making possible geostatistical analyses).

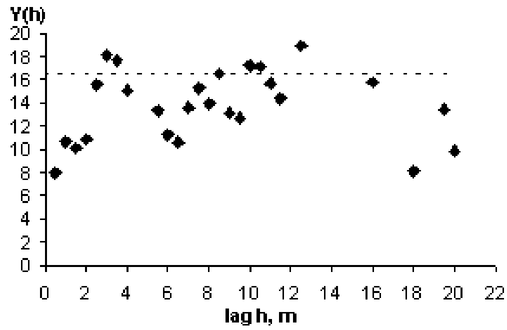

Figure 3.5: Variogram models for forest litter thickness for site 4 (fresh bilberry spruce stand, Gabselga)

The variogram for the site 5 (moist bilberry spruce stand, B.Klimetskiy) (Fig. 3.6) was best described by the exponential model. The equation for the function γ(h) had the following form:

$$\gamma(h) = 29.03 + 16.03 * (1 - \exp(-h/84.8)) \tag{3.5}$$

Thus, the variogram had a limited form. Its sill was slightly higher than the variance value (Tab. 3.2). Nugget variance equaled 29.03. High semivariance and nugget variance were ascribed to a very motley soil cover. The variance increased with growing lag distance, and had a high range value. This fact might testify the presence of a linear trend in the data distribution. The trend appeared as an increase/decrease in the value along a certain gradient. Since the topography of the site was characterized by the presence of a moderate slope from NE to SW, we suggested that the trend was due to the difference in soil moisture content along the slope, which affected the thickness of forest litter.

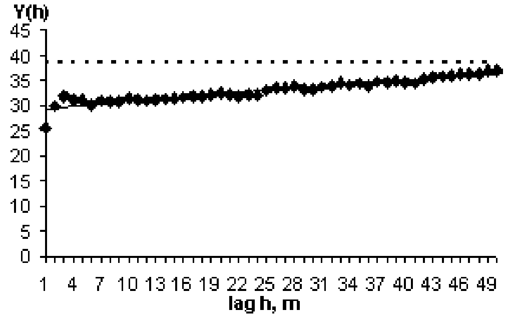

Figure 3.6: Variogram models for forest litter thickness for site 5 (moist bilberry spruce stand, B. Klimetskiy)

The variogram plotted for the site 6 (secondary forest type, Gomselga) had a periodic form (Fig. 3.7), and was described by a complex function, representing the sum of exponential and periodic models (nested model).

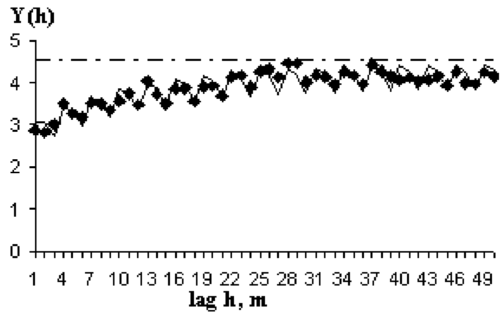

Figure 3.7: Variogram models for forest litter thickness for site 6 (secondary forest type, Gomselga)

The equation for the function γ(h) had the following form:

$$\gamma(h) = 2.69 + 1.49 * (1 - \exp(-h/10.98)) - 0.35 * \sin(2.09h + 1.81) \tag{3.6}$$

The sinusoidal function period equaled 3, approximately corresponding to the radius of tree crowns. The variogram had a limited form. The sill value was 3.83 (variance equals 4.54, Tab. 3.2). The nugget variance value was 2.69. The variogram's complex form might be due to high heterogeneity of the litter thickness, since the territory have been exposed to human impact (fellings) and actually is covered by a secondary forest.

Conclusions

The study has demonstrated that forest litter depths are described by several models. For secondary forest types, the litter thickness variogram is described by exponential and periodic models (Gomselga), or tend to have periodicity (Gabselga). Thus, large-scale spatial coherence of litter thickness in old-growth relatively undisturbed forests is low. We attribute this fact to superimposition of many litter formation stages during the forest community development, each of the stages "recording" its own parcellar structure. This superimposition averaged regular spatial variability of the forest litter out. On the other hand, total litter thickness variability increased due to accumulation of random disturbances (uprooting, local-scope paludification, etc.). In regenerating disturbed forests, litter thickness is determined by the only cycle of organic residue deposition, which is controlled by the unit structure of the new biogeocoenosis. As the result, such forests demonstrate a more or less expressed periodicity of the litter thickness distribution. Recent study in montane cloud forests (Negrete Yankelevich et al., 2006) showed that during the first stages of succession (first 100 years) the patchiness, or spatial structure of litter distribution increased; we suppose that for spruce forests it should be also true. However, later cycles of development of forest ecosystems and random processes (such as windfall) should mix and homogenize the spatial structure of the litter. For the litter of the forests older than 100 years, no significant changes occur with time. A linear model describes the variogram showing the variation of litter thickness in the Valkea-Kotinen fresh bilberry spruce forest. Exponential models with very high nugget values were chosen for the Kivach 1 and Klimetskiy bilberry spruce stands. For these sites also the sill was the highest. We ascribed high variability of forest litter depth to high surface stoniness (Kivach 1) and abundant rock outcrops (Klimetskiy) effects on forest litter distribution. Thus, our data show, that for old-growth forests the geological situations affects the spatial distribution of forest litter, rather than the age of the stand.

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Chapter 4

Spatial distribution of the soil properties controlling soil resistance to erosion at a coffee growing farm in Sierra Sur de Oaxaca

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Abstract

The chapter deals with the spatial distribution of soil aggregates stability, which determines soil resistance to hydric erosion, in the territory of a coffee growing farm El Sinaí, situated in a subtropical altitudinal belt of Sierra Sur de Oaxaca. We found aggregate stability to depend positively on organic C and sand fraction contents in the soil. The latter finding (the presence of more stable aggregates in light-textured soils) does not agree with data from the literature. We proposed a hypothesis explaining this unusual dependence. The soils having high clay content are rather old, and contain mainly kaolinite in their clay fraction. This mineral does not form complexes with soil organic matter. Slightly lighter-textured soils contain, together with kaolinite, some 2:1 minerals, which form complexes with humic substances through bivalent base "bridges". The presence of clay-organic complexes, first, stabilizes soil organic matter, wherefore soils with a more sandy texture generally contain more organic C in the study area. Second, clay organic complexes are known to form more resistant soil aggregates than free organic matter. Thus, the most stable aggregates are found in relatively light-textured soils with high organic C content. The spatial distribution of aggregates stability seemed strange in the quadrates studied in detail. No similarity was found either between the studied properties (organic C and sand contents, aggregate stability), or between the quadrates. We concluded that distances less than 100 m are not suitable for determining the spatial structure in the studied landscape. Study of the spatial distribution of organic C content and aggregate stability at the scale of the whole farm (distances up to 2000 m) revealed a distinct periodic structure for both features, and some periods were the same for the two properties. We concluded that

the heterogeneity of the studied soil properties' distribution is related mainly to slope processes, determining the age of the surface, which, in turn, regulates organic matter accumulation and aggregate stability.

Introduction

Intensive slope processes characterize mountainous territories. These processes are of major importance in wet tropical areas, where rainfall events are often very intensive (Drees et al., 2003). Also, clayey kaolinitic tropical soils are easily affected both by landslides (Dykes, 2002) and by intensive sheet erosion (Veihe, 2002). The development of slope processes leads to the development of a mosaic structure of the soil mantle, where deeply weathered profiles are neighboring immature soils formed on the surfaces exposed by erosion and landslides (Krasilnikov et al., 2005).

Thus, the spatial organization of the soil mantle in mountainous tropical and subtropical areas depends to a great extend on slope processes. It is clear also that these processes are regulated by internal soil properties, related to soil stability as an integral characteristic of soil resistance to various external disturbances. One of the most important characteristics related to soil resistance to erosional processes is aggregate stability (Gavande, 1992; Martí et al., 2001). The spatial distribution of aggregate stability is difficult to predict, because it depends, in turn, on various soil parameters, and this dependence is complex. Most researchers pointed out that aggregate stability depended on soil texture. It was generally believed that an increase in clay content resulted in an increase in aggregate stability (Gavande, 1992); in clayey soils the stability of aggregates was regulated by clay mineralogy and composition of exchangeable cations (Akaigbo et al., 1999; Warrick, 2002). Some recent papers (e.g., Veihe, 2002) showed that for practical purposes it was better to estimate correlation between aggregate stability and sand fraction content instead of clay fraction content, which was more difficult to determine; since sand and clay content were interdependent, there was a negative correlation between sand content and aggregate stability. The joint effect of the content of clay and organic matter was discussed for tropical soils of Brazil and Venezuela (Roth, 1992). Many researchers reported a positive effect of organic matter on aggregate stability (van der Watt and Valentin, 1992; Gavande, 1992; Warrick, 2002). However, the aggregating effect of organic matter was reported to be more pronounced in sandy textured soils (van der Watt and Valentin, 1992). A number of authors (van der Watt and Valentin, 1992, see also bibliography) stressed a significant role of the mineralogical composition of the clay fraction in aggregate formation. According to these authors, the most stable aggregates were found in kaolinite-dominated soils, whereas soils containing mainly smectite and illite minerals were found to be less stable. Similar results were reported by Warrick (2002), who found that soils with high kaolinite and iron oxides content were less compact (i.e. better structured), than soils where 2:1 minerals dominated in the clay fraction. However, some recent studies (Denef et al., 2002) showed that aggregate stability depended not only on soil mineralogy and soil organic matter content separately, but on their interaction, as well. The above researchers found that the highest aggregate stability was in soils with a high proportion of 2:1 minerals in the clay fraction and high organic matter content. The results were considered to corroborate the importance of organic-mineral interactions for aggregate stability. Clay minerals with the 1:1 structure and Fe and Al (hydr)oxides poorly interact with soil organic matter (due to the lack of permanent charge), while most 2:1 soil clay minerals are negatively charged (illites, vermiculites, smectites and mixed-layered minerals). The latter group of minerals tends to form complexes with soil organic substances (also mostly negatively charged) through "bridges" of bivalent exchangeable bases (Nayan et al., 2002). Thus, aggregate stability can be expressed as a complex function of soil texture, clay mineralogy, organic mater content and composition, and exchangeable bases content. Obviously, all the parameters mentioned above have their own rules of spatial distribution; however, certain interdependence should also be expected. Thus, the spatial distribution of aggregate stability should be rather complex, especially in mountainous areas. One should realize also that for every given area these rules would be of local significance, and would depend on regional environmental conditions.

The objectives of the present study were: (1) to estimate aggregate stability in the territory of the coffee-growing farm El Sinaí, situated in the subtropical altitudinal belt of Sierra Sur de Oaxaca, (2) find out the factors determining aggregate stability in the study area, (3) establish the rules of spatial variation of aggregate stability and the factors controlling it, and to interpret the results.

Objects and methods

The research was conducted at the coffee-growing farm El Sinaí, Oaxaca State, Mexico (Fig. 4.1). This region is a typical landscape of the south-western escarpment of the Sierra Sur de Oaxaca mountains, the system formed by a tectonic uplift in the Miocene (Morán et al., 1996; Centeno-García, 2004); minor uplifts also occurred in the Pliocene and even the Quaternary time. The rocks are mainly gneiss and amphibolites formed during the Paleozoic epoch, and Cenozoic granites (Hernández et al., 1996). Recent sediments of the area are much less studied. It is believed that mainly there are weathering products of igneous and metamorphic rocks, sometimes deep weathered regoliths, redistributed on the slopes by gravitation and temporal water flows (Centeno-García, 2004). All of the Pacific coast of Mexico is a seismically active zone (Rojas et al., 1987). The first seismic event reported from the region happened in 1460. Later, numerous earthquakes of varying intensities were observed in the 18^{th} and 19^{th} centuries. The two most intensive ones occurred in 1784 and 1787. Several major earthquakes were reported from this area in the 20th century; the last one was in 1999.

The climate of the region is classified as warm humid isothermal, with annual rainfall of about 1800 to 2000 mm and mean annual temperature of 21 to 21.9 $^{\circ}$C

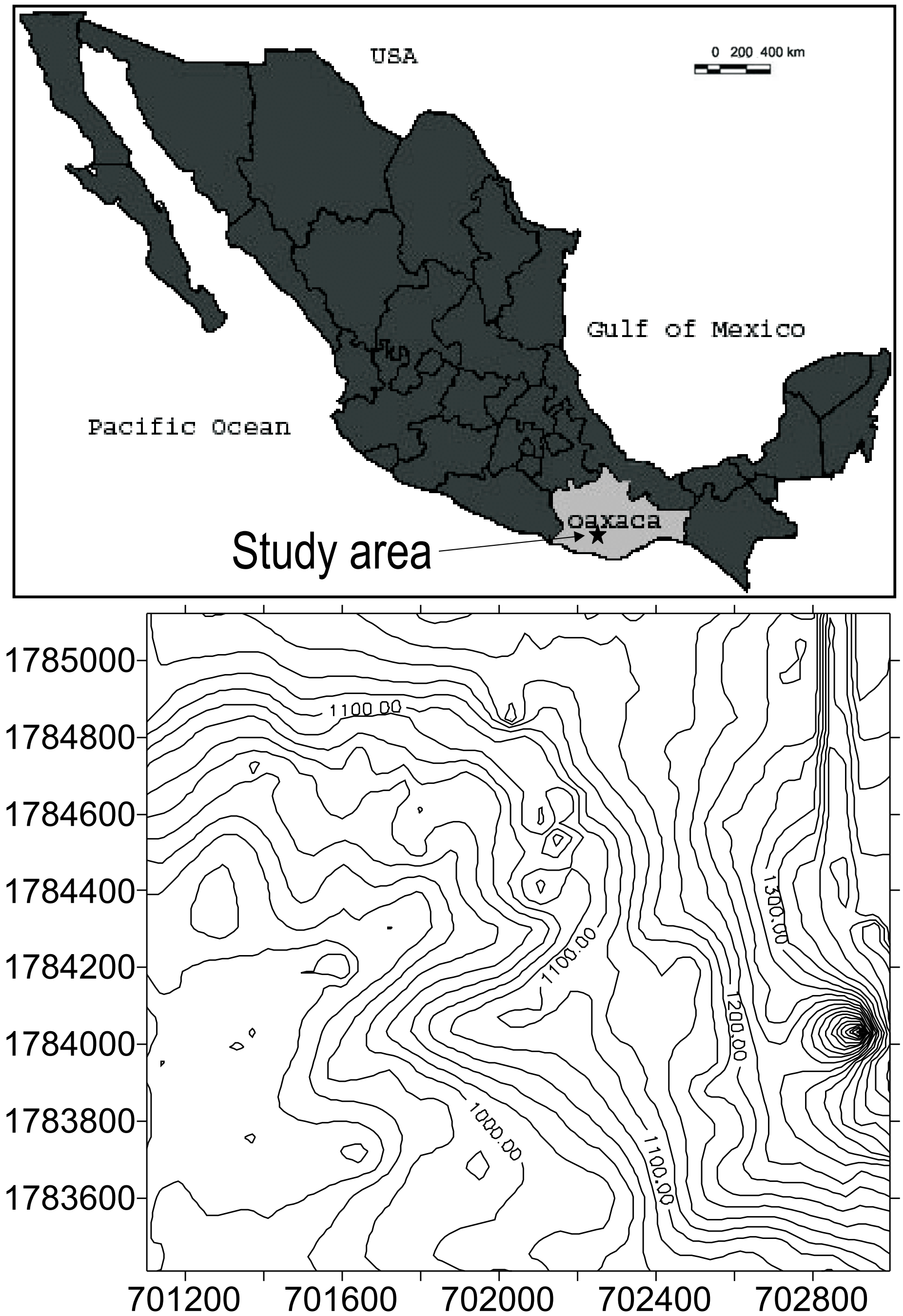

Figure 4.1: The location of the study area and a schematic hypsographic map of the coffee-growing farm El Sinaí

(García, 1973). The region has two main seasons – dry from December through May and wet from June through November. In autumn, rapid air movement often provokes hurricanes, which cause treefalls, enhancing water erosion (García Calderón et al., 2000). The climate and vegetation on the Pacific escarpment of the mountainous system are arranged in distinct altitudinal belts: under 500 m asl there are xerophytic tropical forests, *Bosque tropical caducifolio*; between the altitudes of 500 up to approximately 1500 m asl – tropical semideciduous forest, *Bosque tropical subcaducifolio*; and over 1500 m asl – pine forests with fragments of montane cloud forests (Rzedowski, 1978). The study was conducted in the tropical semideciduous forest. Vegetation in the area consists of coffee plantations (*Coffea arabica* var. typica L.) under the canopy of residual natural vegetation. The most abundant tree species include *Brosimum alicastrum*, *Enterolobium cyclocarpus*, *Pterocarpus acapulcensis*, *Bursera simaruba*, *Caesalpinia coriacea*, *Ceiba pentandra*, *Cordia aliodora*, and *Ficus* spp. (Lorence and García, 1989; Flores and Manzanero, 1999). Closed-canopy coffee growing is the main agricultural practice in the region; it has been successfully used there for more than 150 years. The practice involves partial cutting of the original forest vegetation and cultivating coffee under the shadow of remaining trees. No fertilisers are used except for decomposed coffee pulp. The productivity of these coffee plantations is relatively low, but the quality of the coffee is high (Staver, 1998).

Little is known about soils of the region. A recent review (Alfaro Sánches, 2004), based mainly on the analysis of soil maps of the scale 1:250,000, has demonstrated a lack of data rather than a clear understanding of the distribution of soils in the region. Some results of the study of soils in the area were published recently (García Calderón et al. 2000; Krasilnikov et al., 2005). According to the data reported, soils of the coffee-growing farms of the Sierra Sur of Oaxaca are Alisols, Acrisols, Luvisols, Umbrisols, Leptosols and Cambisols (IUSS Working Group WRB, 2006). Soils of the Finca Sinaí farm were also partially described (Ibáñez et al., 1995; García Calderón et al., 2006).

The farm Finca Sinaí is situated at 16° 07'41.5" N and 97° 06'12.9" W, at altitudes ranging from 700 to 1200 – 1300 m above sea level. Total area of the farm is 365 ha. Mountain slopes are complex, with the aspect varying from north-eastern to south-western direction and slopes reaching 40°. The slope surfaces are dissected with erosional processes, forming deep gullies.

To study the spatial distribution of the factors controlling soil resistance to erosion in a detailed scale, we established two squares 100x100 m. From each square, we collected 100 samples from the surface layer (0-20 cm) following a regular grid with a 1 m lag. To show the overall spatial distribution of soil properties, we collected also 152 samples from the soil surface (0-20 cm) throughout the farm territory following a regular grid with a lag distance of 100 m.

Organic carbon content was determined using wet combustion method (van

Reeuwijk, 2002), the percentage of the sand fraction (particles 0.02–2 mm) – by sieving, and aggregate stability – by calculating resistant aggregates after 10 aggregates had been immersed in water for 3 minutes (Martí et al., 2001). Aggregate stability was classified into 4 classes: very stable, stable, slightly stable, and unstable.

To interpret the results we employed also data on the clay mineralogy of surface horizons of 6 selected profiles of contrasting morphology and properties. The clay fraction was separated and pre-treated using methods described in Kunze and Dixon (1986), and Dixon and White (1999). X-ray difractograms were obtained on the difractometer DRON-3 (SIE "Burevestnik", St. Petersburg, Russia, 1987), Cu-Kα radiation – with a graphite monochromer, 2θ 2-45°, U = 40 kV, I = 25 mA.

To find out the dependence of aggregate stability on the organic c content and soil texture we used linear regression analysis (Dmitriev, 1995). Since the aggregate stability was determined semiquantitatively (i.e. the level of aggregate stability was established for every range of the numbers of aggregates decomposed in water), the values might be regarded as non-parametric values, and the coefficients of regression were expected to be low (Dmitriev, 1995). For the regression graphics we used standard software package Excel (Microsoft). To find out the spatial structure of the variables, we used variography, with a special emphasis on the search of periodical distribution. Variorams were calculated and approximated with VARIOWIN 2.2 (Pannatier, 1996) and GenStat (2002) (evaluation version) software. The maps of spatial distribution of soil properties were constructed using SURFER Version 6.02 software (Copyright © 1993-1996, Golden Software, Inc.). For the construction of the cartograms ordinary kriging was used throughout.

Kriging is a generic name adopted by the geostitisticians for a family of generalized least-squares regressions algorithms. There are many different kriging algorithms. A standard version of kriging is called *ordinary kriging*. The predictions are made as in the equation:

$$\hat{z}_0 = \lambda_1 z(\mathbf{x}_1) + \lambda_2 z(\mathbf{x}_2) + \ldots + \lambda_n z(\mathbf{x}_n) \tag{4.1}$$

where the $\lambda_I$are coefficients or weights associated with the data points. In kriging, the weights are chosen in that a way, that the error, associated with the estimate, is less than for any other linear sum. The weights take into account the known spatial dependences expressed in the semivariogram, and the geometric relationships among the observed points. In general, closer points carry more weight than distant point (Burgess and Webster, 1980).

Results

As a rule, mapping of soil properties in a cartogram is the last stage in the study of spatial distribution of soil characteristics. In our case, however, the aim was not depiction of soil properties, but scientific interpretation of the factors controlling spatial distribution of aggregate stability.

The distribution of organic carbon content in the surface soil horizon in the farm territory at large is shown in Fig. 4.1. The range of values was great: from almost zero to more than 140 $g \cdot kg^{-1}$ of organic carbon. The relation between organic carbon content and relief was found to be weak (data not shown): the only general tendency was that carbon content, as it had been expected, at the bottoms of the gullies and on relatively flat surfaces was higher than on steep slopes, especially on convex ones. Unfortunately, more precise estimation of the relation of organic carbon content with relief forms and elements was impossible, since no detailed topographic maps were available for the study area. Our topographic map (which was based on 400 points where we determined the coordinates using GPS system, and altitudes using an altimeter) did not reflect all minor elements of the relief, which might have major importance for organic carbon distribution.

Two squares in the farm territory were established tentatively in the areas with low and high organic carbon contents (Fig. 4.2). The internal distribution of organic carbon inside both squares was complex. In the first square, carbon content varied in a wide range (10 to 120 $g \cdot kg^{-1}$) (Fig. 4.3). The soils with higher carbon content were found mainly in the south-western part of the square (situated lower along the slope). The distribution of the sand fraction was somewhat different (sand content was the highest along a small gully); however, more sandy soils tended to contain more organic carbon. Aggregate stability had another distribution pattern, which corresponded with the distribution of neither carbon nor sand. The most stable aggregates were found both in sandy soils rich in organic carbon, and in heavier soils, poor in organic matter.

In the second square, the variability of organic carbon content was not so high. The soils rich in organic matter were found in a flat area and at the bottom of shallow gullies. The sand fraction content varied significantly, and had little in common with the distribution of carbon. The aggregate stability followed mainly the distribution of the organic carbon content.

Linear regression showed a positive correlation between aggregate stability and both organic C content and sand content in soil (Fig. 4.4). Leaving apart a detailed discussion of these results (see our previous paper García Calderón et al., 2004), we should note that the regression equations are not very reliable, since the aggregate stability was not expressed quantitatively. Nevertheless, the results were obtained on 200 samples from two squares, and could not be regarded to be an error or an accident. Positive dependence of aggregate stability on soil organic matter content was confirmed by many authors (van der Watt and Valentin, 1992; Gavande, 1992; Warrick, 2002).

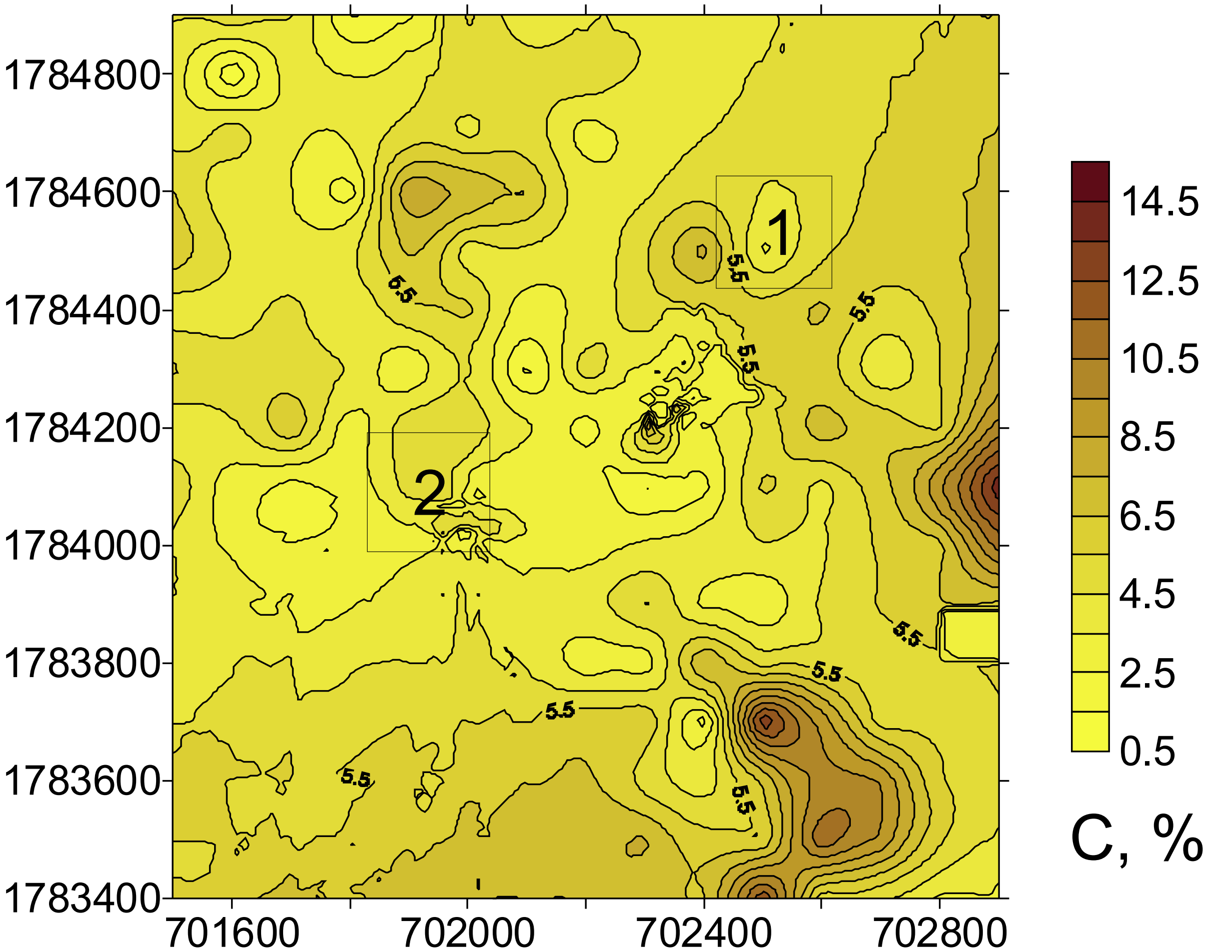

Figure 4.2: Spatial distribution of organic carbon content in the surface horizons of soils of the coffee-growing farm El Sinaí; the small squares are 100x100 m grids: 1 – first square, 2 – second square

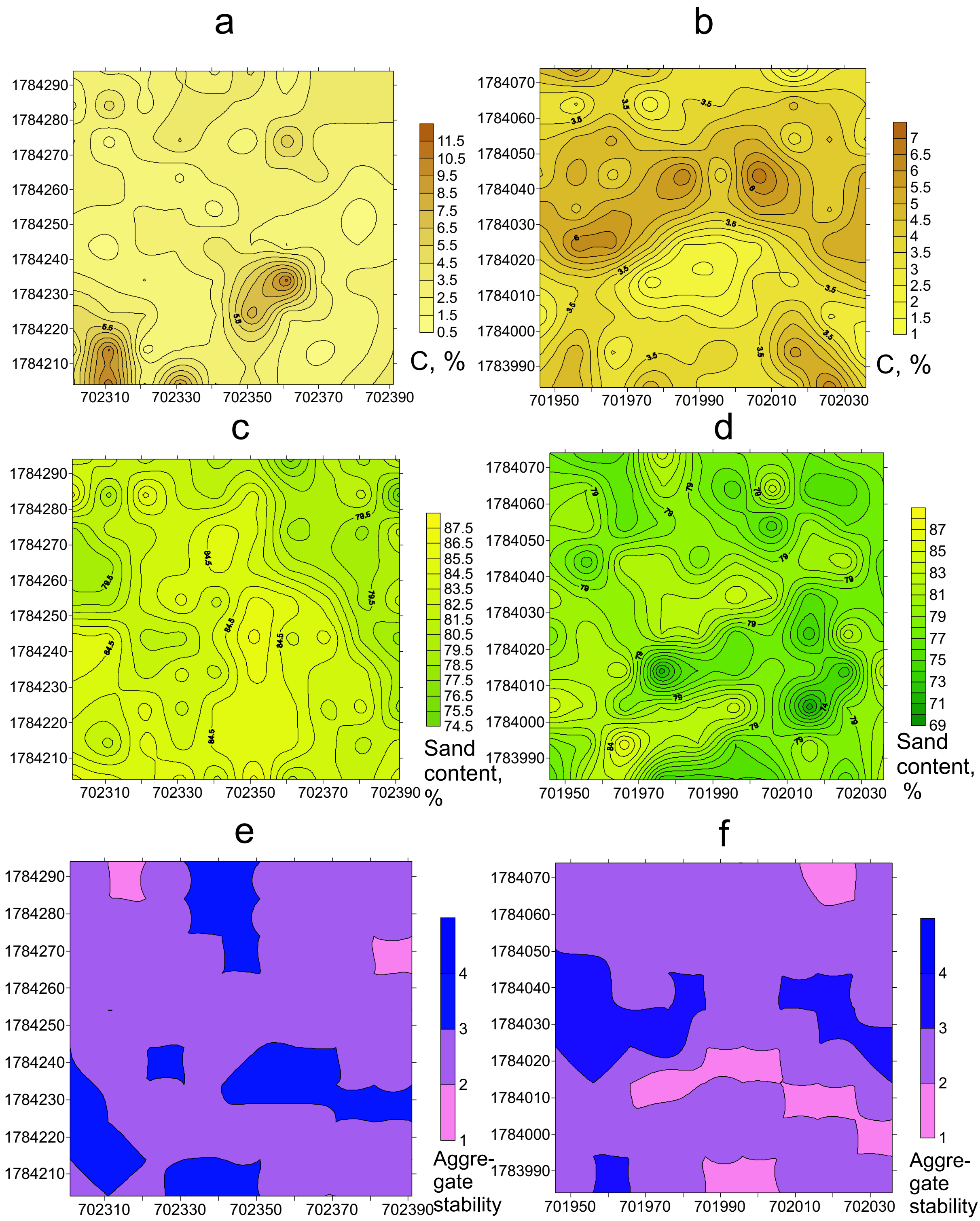

Figure 4.3: Spatial distribution of organic carbon content (a – square 1, b – square 2), sand fraction content (c – square 1, d – square 2), and aggregate stability (e – square 1, f – square 2) in the surface soil horizon

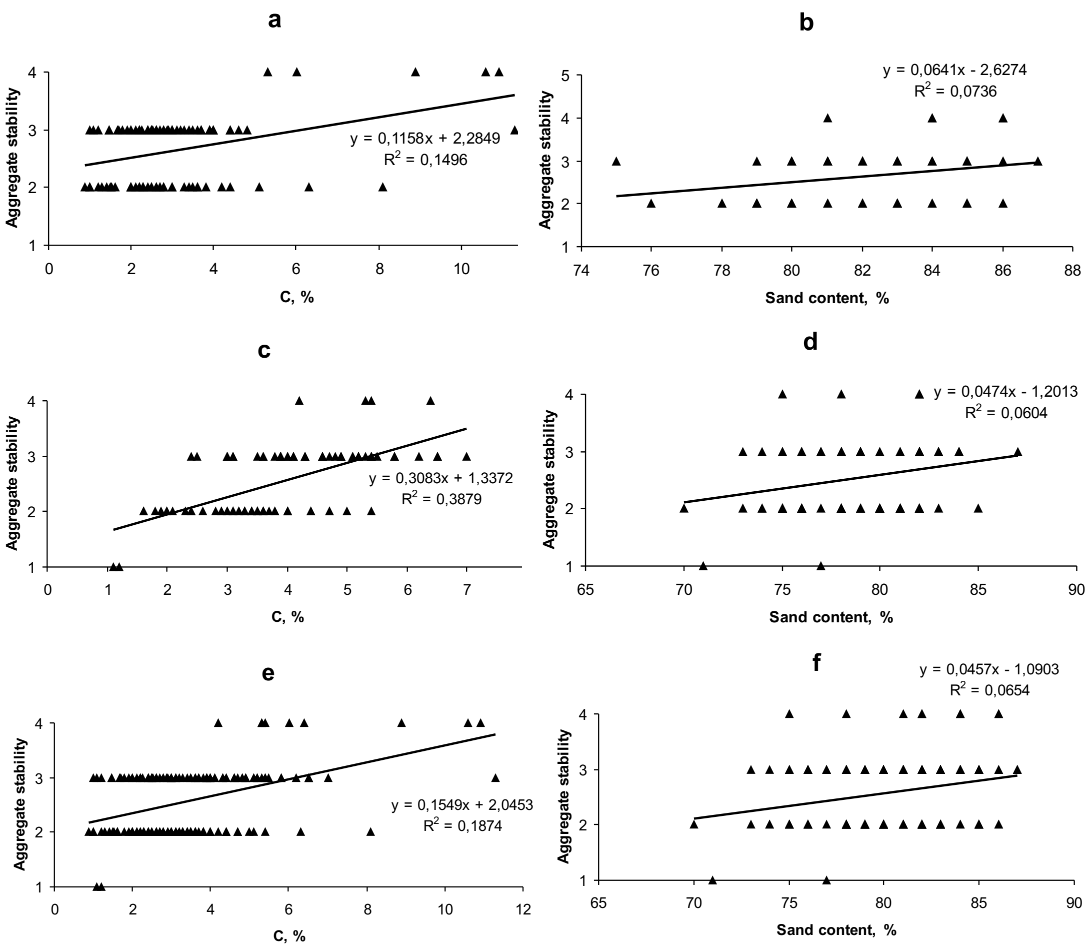

Figure 4.4: Linear regression for the dependence of aggregate stability on organic carbon content (a – square 1, c – square 2, e – for the two squares together), and sand fraction content (b – square 1, d – square 2, f– for the two squares together)

However, the increase in aggregate stability with increasing sand content contradicted both general considerations (Gavande, 1992) and experimental results obtained by other researchers (Akaigbo et al., 1999; Veihe, 2002).

We hypothesized that the stability of aggregates depended on soil mineralogy and, thus, indirectly to soil texture. The hypothesis was based on the data on soil mineralogy obtained both for the region of the study – Sierra Sur de Oaxaca (García Calderón et al., 2000; Krasilnikov et al., 2005), and for the particular study area (García Calderón et al., 2005). Thus, we analysed the mineralogical composition of the clay fraction in 6 points, where soil profiles had been established previously. The results are shown in Table 4.1; the points in the table are presented in accordance with increasing sand content in soil samples. The data show that the dominant minerals in heavier soils with a lower sand content were kaolinite and gibbsite. In soils with a higher sand content there were significant amounts of 2:1 minerals in the clay fraction.

Table 4.1: Mineralogical composition of clays and percentage of the sand fraction in some surface horizons of soils of the coffee-growing farm El Sinaí

Site	Sand content, %	Clay fraction mineralogical composition			
		Illite	Illite-vermiculite	Kaolinite	Gibbsite
Los Zanjones	54.0			XX*	
La Presa	68.0		X	XX	XX
La Primavera	68.8		X	XX	X
El Mirador	64.0		XX	XX	X
El Portillo	74.8	X	X	XX	X
El Espinaso	77.6	X	X	XX	

*XX – dominant mineral; X – detectable mineral

The spatial distribution of the studied soil properties was processed using geostatistical methods. The variograms obtained for organic carbon and sand contents and aggregate stability are shown at Fig. 4.5. The shapes of the experimental variograms differed between the soil properties studied in the same square, and between the squares for the same soil parameter. The distribution of organic carbon in the first square was close to pure nugget.

The distribution of the sand fraction was close to a linear function, which indicated the presence of a trend. The distribution of aggregate stability had a tendency to quasiperiodicity. In the second square, all the properties had a distribution similar to vague periodicity. The variogram for organic carbon distribution had maxima of semivariance at lags of about 40 and 120 m, for the sand fraction – of about 20 and 60 m, and for aggregate stability – of about 60 and 120 m. Some similarity in the spatial pattern of organic carbon content and aggregate stability distributions could be noted for the second square only. The periodic structure of the distribution of organic C and sand content was ascribed to the effect of the system of gullies, which has a characteristic distance between minor gullies of about 20 m.

We also processed the data for carbon content and aggregate stability for the whole farm, taking also the data for small grids into account. The variograms for both parameters had distinct periodicity (Fig. 4.6). Selection of standard model variograms was possible, although it was clear that neither an exponential model (used for organic carbon distribution) nor a Gaussian one (used for aggregate stability distribution) fit our experimental data adequately. Periodic models were also difficult to apply, since the maxima of semivariance had no regular periodic distribution. The variogram for organic carbon content had maxima at lags of about 120, 250, 350, 600, 850, and 1300 m, and semivariance values were different at these maxima. An extremely strong increase in semivariance was found for the lag 1300 m. Such extreme values are usually related to insufficient data set, but in our case (a more than 400-point data set) the explanation was not suitable. Moreover, a maximum at the same lag distance was found also in the variogram for aggregate stability distribution. The latter also showed maxima at lags of 250 and 750 m. In general, one can see that at least some lag distances with maximum semivariance are the same for organic carbon content and aggregate stability. It may indicate similar patterns of spatial distribution for these two soil parameters.

Discussion

The spatial distribution of aggregate stability in the study area has a regular character, which allows predicting soil resistance to erosion. In the study area, we confirmed that aggregate stability increased with increasing organic carbon content in topsoil; the data correspond well with those presented in the literature. We found also that aggregate stability grew with increasing sand content, too. This result contradicts most data reported in the literature, and we have to explain the phenomenon. We proposed the following hypothesis. Soils with high clay content (consequently, poor in sand) are usually old, and the dominant mineral in the clay fraction is kaolinite, which does not form complexes with organic substances in the soil. Soils with a higher sand content are generally less mature and, together with kaolinite, contain minerals of the 2:1 structure in the clay fraction. These 2:1 minerals form complexes with soil humus through "bridges" of bivalent exchangeable bases (Nayan et al., 2002). The presence of clay-organic complexes, on the one hand, stabilizes soil humus, and hence, the mineralization rate is lower in these soils. As the result, the residual organic matter concentration is higher. On the other hand, clay-organic complexes are known to stabilize the soil structure better than free organic matter. Thus, the most stable aggregates would be found in relatively light-textured soils with elevated content of organic carbon.

Earlier, we proposed a general scheme for the formation of the soil pattern in this study area (García Calderón et al., 2005). According to our scheme, the

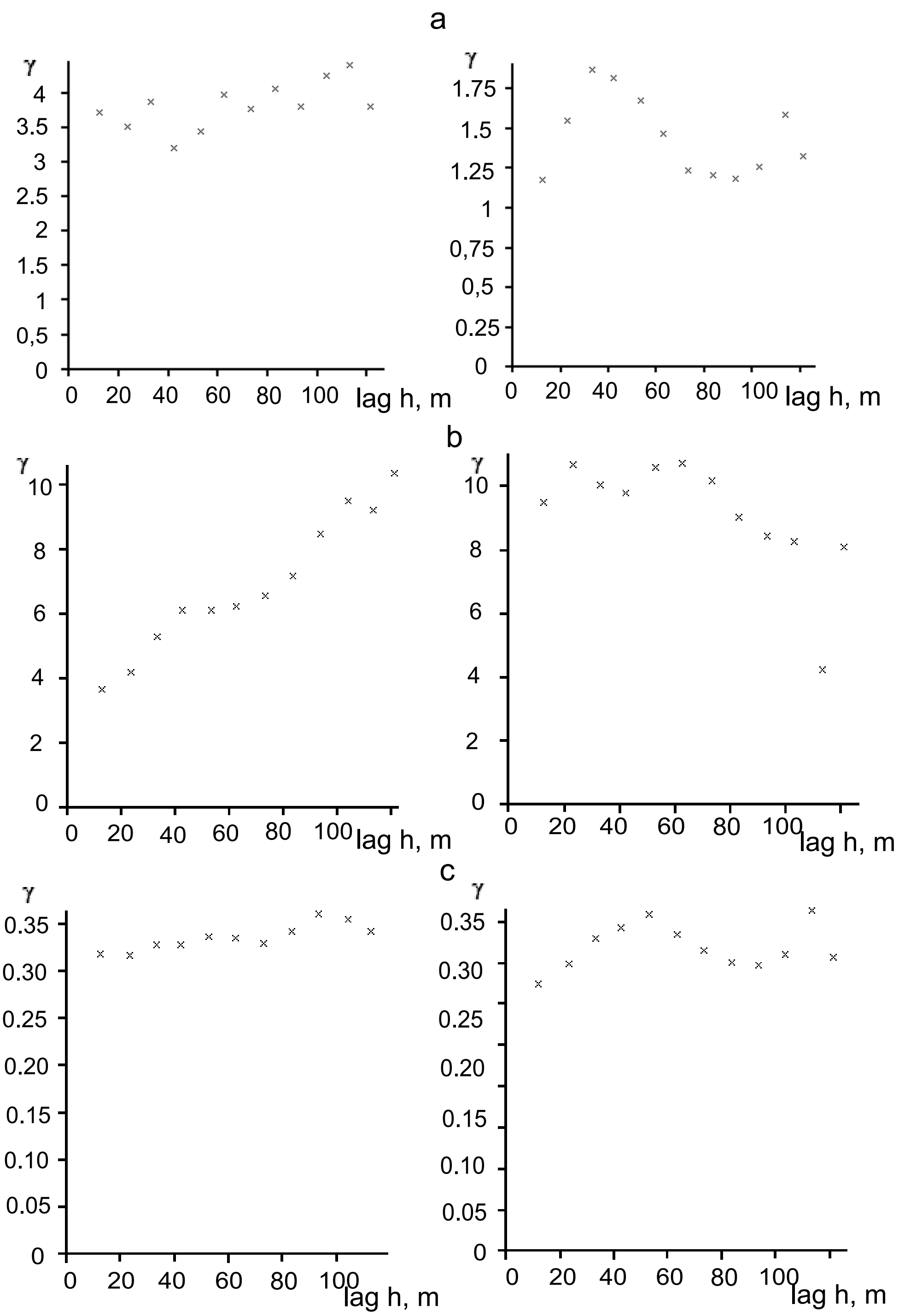

Figure 4.5: Experimental variograms for organic carbon distribution (a), sand fraction content (b), and aggregate stability (c) in surface horizons of soils in small squares; left-hand column – data for square 1, right-hand – for square 2.

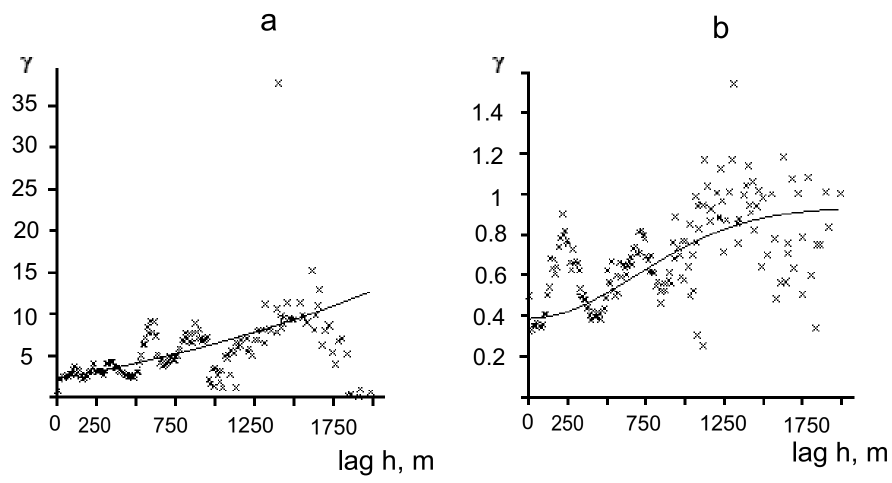

Figure 4.6: The variograms for the distribution of (a) – organic carbon content (points – experimental variogram, line – exponential model), and (b) – aggregate stability (points – experimental variogram, line – Gaussian model) for the whole territory of the coffee-growing farm El Sinaí.

zero-moment for soil formation should be the exposure of "fresh" surface by slope processes. At this stage, one can observe immature light-textures soils with low humus content, rich in exchangeable bases (Regosols). Later on, percolating water and living organisms lead to the formation of the surface humus horizon and alteration of the subsurface material, thus forming Cambisols. Leaching of bases results in Umbrisols formation. Mineral weathering and clay illuviation finally lead to the formation of soils with a clay-enriched illuvial horizon: Luvisols and Alisols. At the final stage, the soils can be truncated by landslides, which occur in the clay-enriched horizon when it grows saturated with water (Dykes, 2002). In this manner, one can interpret this mountainous territory as a mosaic of surfaces of different ages, exposed by slope processes; these surfaces are occupied with soils at different development stages.

This study allowed explaining an additional mechanism behind the formation of this polychronic soil mosaic. At early stages of development, the surface exposed by slope processes has a sandy soil. Rapidly – due to intensive biochemical processes in wet tropical environment – organic matter accumulates in this soil, forming clay-organic complexes with 2:1 clay minerals still present in this soil, thus stabilizing soil aggregates. At a millennium time scale, however, the situation turns different. First, lixiviation results in the loss of bases, which served as "bridges" for clay-organic complexes. Then, weathering destroys 2:1 layer silicates, leaving inert kaolinite and gibbsite. Untied organic matter rapidly gets mineralized, soil aggregates lose stability, and erosion destroys the soil. A new cycle of soil formation starts on the exposed surface.

Since the above scheme is based on slope processes, the spatial distribution of aggregate stability, as well as the soil properties controlling it, is related to the geomorphology of the area. Landslides and erosional landforms have certain characteristic size; for example, a landslide cannot occur if the mass of ground does not reach a critical value. Thus, the pattern of soil properties appears at certain scales only. Our data shows that in small grids there are hardly any regularities in the spatial distribution of the studied soil properties, or, more precisely, these regularities have a local scope (depending on the aspect, gradient, form and cleaving of the slope) and do not reflect regional specificity of the soil distribution pattern.

Organic matter content and aggregate stability at the scale of the whole farm show a periodic structure, which indicates a distinct regularity in data distribution. Lag distances found in periodic variograms both for carbon content and aggregate stability (250 and 1300 m) are more likely to reflect variations in the dissection of the relief. The data corresponds to our field observations: small gullies are separated by distances of 150-300 m, and deep canyons – by distances of about 1200-1500 m.

Special attention should be given to irregular periodicity of maximum semivariance values in periodic variograms of the carbon content and aggregate stability distribution. We believe these variograms to reflect superimposition of several periodic spatial structures. Unfortunately, we still have no mathematical methods to enable the study of such spatial patterns. Better understanding of the physical meaning of the spatial pattern of soil variables is needed to apply mathematical models, which may provide further information on the organization of soil cover.

Acknowledgements

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Chapter 5

Geostatistical analysis of the spatial structure of acidity and organic carbon in zonal soils of the Russian plain

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Abstract [1]

The chapter considers geostatistical parameters of variation in pH values (in the aqueous and saline extracts) and organic carbon content in the zonal series of the Russian plain soils: gray soils (Greyic Phaeozems), illuvial clay chernozerms (Luvic Chernozems), chernozerms (Glossic Chernozems) and chestnut soils (Kastanozems). Zonal patterns are shown to exist in the variation of the above soil properties: the correlation radius of acidity fluctuations increases north to south whilst spatial coherence grows weaker; the period of organic carbon content fluctuations grows longer. At the same time, many parameters demonstrate regional or local characteristics. More studies are needed to successfully extrapolate geostatistical models onto unsurveyed areas.

Introduction

For a global scale, the distribution of soils, is regulated by bioclimatic zonality (Arnold, 1994). These zones have a different extent and configuration throughout the world, and a regular sequence of zones from north to south might be found only in few places, including the Russian plain. Unlike at the early stages of the development of soil geography, we believe that a soil zone is characterized by a certain combination of soils, rather than by a single dominant soil group. The soil cover of a soil zone should be described in the terms of soil cover structure (Fridland, 1974), or soilscapes (Finke and Montanarella, 1999). These soilscapes are specific in the different soil zones (Fridland, 1976). However, we still do not know, how the

[1]This chapter is an extended and improved translation of the text published in Russian in "Geostatistics and Soil Geography", Moscow, Nauka Publ., P. 67-80.

internal spatial structure of soil polygons varies between soil-bioclimatic zones. It is an important characteristic to take into account and we believe that geostatistics can be a useful tool for providing adequate methods to study it.

The objective of the present study was to find out whether specific patterns of some soil properties (acidity and organic carbon content) can be identified in relatively uniform soil cover such as within extensive soil zones at the Russian plain.

Background

To be able to create expert systems capable of extrapolating geostatistical data onto a more or less wide class of objects we need to identify geographically interpretable parameters of model variograms on which the geostatistical method is in fact based (Demianov et al., 1999). The first parameter to be named is spatial correlation proper. Its presence – although geostatistics is declared to view all parameters as a field of values, generated by a random function (Webster, this volume) – indicates there exists a spatial structure. Where values are distributed absolutely randomly, chaotically, no correlation is found, and the variation is described by the "pure nugget" model (Jongman et al., 1995). To estimate spatial correlation, Cambardella et al. (1994) suggested using the empirical criterion: if the ratio of nugget to threshold (max semivariance the variogram attains reaching the sill) is lower than 25%, spatial correlation is classed as high; if it is 25 to 75% – as medium, over 75% – as low. This criterion is certainly not applicable to linear, power and periodic models. In the geographic sense, the presence of spatial correlation points to fuzzy data periodicity at characteristic distances greater than the sampling interval (lag distance), but smaller than the range (interval at which the variogram reaches the sill attaining maximum semivariance). According to Jongman et al. (1995), smooth variation is reflected by the Gaussian model, whereas abrupt data changes at irregular distances – by the spherical and exponential models, the spherical model being characteristic of not totally regular changes in space, and the exponential one – of changes at all distances, i.e. of the most random distribution. However, even the presence of the "pure nugget" does not always imply total absence of spatial correlation: quite often, it means that variation mainly takes place at distances smaller than the sampling interval. Where the periodic model is present, data can be said to have relatively strict mosaic organization. The presence of a trend (reflected by a linear or a power, or, in the case of a quadratic trend, by a pseudoperiodic variogram) indicates a regular increase/decrease of the values within a study site.

Material and methods

Surveys were done in the Tula (site 1), Belgorod (site 2), Rostov (site 3) and Volgograd (site 4) regions (Fig. 5.1).

Site 1, which area is 126 ha, was established in an arable field near the town of Shchyokino (53 ° 49′ N 37 ° 19' E). The study area belongs to the gray forest soil subzone of the Oka-Don province of podzolized, leached and typical medium

Figure 5.1: The location of the study sites

humic, and of rich (very humic) deep chernozems (Haplic Chernozems in WRB (IUSS Working Group WRB, 2006)) and gray forest soils (Dobrovolskiy and Urusevskaya, 1984). Mantle calcareous loams are the parent rock there. Topographically, the site features a gentle slope of the southern aspect; gray forest soils (gray soils – in the new Russian classification (Shishov et al., 2004), or Greyic Phaeozems in WRB (IUSS Working Group WRB, 2006)) predominate in the soil cover structure; gray gleyic soils (Greyic Gleyic Phaeozems) lie on the lower slope. Site 2, covering 182 ha, was established in an arable field near the town of Alekseevka (51° 38′ N 36° 13’ E). The study area belongs to the forest-steppe chernozem subzone of the Oka-Don province of podzolized, leached and typical medium humic, and of rich (very humic) deep chernozems and gray forest soils (Dobrovolskiy and Urusevskaya, 1984). The parent rocks are mantle heavy loams, locally calcareous. The relief includes a relatively low, sublatitudinally trending ridge; the soil cover is made up of leached chernozems (illuvial clay chernozems (Shishov et al., 2004), or Luvic Chernozems (IUSS Working Group WRB, 2006)). Site 3, covering 270 ha, was established in an arable field near the town of Millerovo (49° 02’ N 40° 30’ E). The study area belongs to the South-Russian province of ordinary medium humic and southern slightly humic chernozems (Dobrovolskiy and Urusevskaya, 1984). The parent rocks are loess heavy loams. Topographically, the site is a gentle slope of the SW aspect; southern chernozems (textural calcic chernozems (Shishov et al., 2004), or Glossic Chernozems (IUSS Working Group WRB, 2006)) dominate in the soil cover structure; meadow-chernozemic soils (hydrometamorphozed chernozems (Shishov et al., 2004), or Gleyic Chernozems (IUSS Working Group WRB, 2006)) are the subordinate soil groups found in depressions. Site 4, covering 290 ha, was also established in an arable field near the town of Kotelnikovo (47 ° 50' N 43 ° 06' E). The study area belongs to the Don province of dark-chestnut and chestnut soils (Dobrovolskiy and Urusevskaya, 1984). The parent rocks are loess loams. Topographically, the site is a gentle slope of the southern aspect. Chestnut soils (termed chestnut in the new Russian classification, too (Shishov et al., 2004), or Kastanozems (IUSS Working Group WRB, 2006)) predominate in the soil cover structure. Samples were taken from a depth of 0-20 cm following a random-regular pattern with an interval of 150 m. The geopositioning system was used to determine sampling point coordinates and absolute elevation. All in all, 59 samples were taken from site 1, 85 – from site 2, 100 – from site 3 and 74 – from site 4.

The soil samples were analysed for pH of the aqueous extract and KCl, as well as for organic carbon content by wet combustion (van Reewijk, 2002).

We studied the variability of soil properties using geostatictical methods, calculating directional variograms for all plots and properties. The variation of soil is not always the same in all directions; in other words, it is not always isotropic. For example, the variation of soil texture parallel to a river would be different from that sampled normal to the river; soil properties may have a gradient along a slope; drainage and irrigation channels also affect the distribution of soil characteristics in a certain direction etc. In these situations the variation of soil properties in each direction may be described by its own semi-variogram, differing from those for other directions, which is called *anisotropic*, or *directional variogram. The direction* is set by the value of the angle φ, (the angle between the vector and an axis X). To both sides from this vector *the angular tolerance* α is added. It determines the spatial sector within the limits of which the points for calculation of the variogram are considered.

The anisotropy of variograms can testify the presence of a trend in the data spatial distribution. *The trend* appears as an increase/decrease in the value along a certain gradient. The trend can be determined using the regression on coordinates (trend surfaces interpolation) (Dmitriev, 1995; Lark and Webster, 2006; Hengl, 2007). The regression on coordinates is based on the following model:

$$Z(\mathbf{s}) = f(\mathbf{x}, \mathbf{y}) + \varepsilon \tag{5.1}$$

and the predictions are made by:

$$z(\mathbf{s}_0) = \sum_{r,s \in N} a_{rs} \mathbf{x}^{\mathbf{r}} y^s \tag{5.2}$$

where r+s≤p, p is the order of the surface. The model coefficients (a) are determined by maximizing the local fit:

$$\sum_{i=1}^{n}(z_i-\hat{z}_i)^2 \rightarrow \min \qquad (5.3)$$

For the statistical analysis we used standard software package Excel (Microsoft). Regression analysis was conducted using STATGRAPHICS Plus. Variograms were plotted using VARIOWIN 2.2 (Pannatier, 1996) and GenStat (2002) (evaluation version) software packages. Both omnidirectional variograms, and variograms for the directions along and across the slopes or other landforms were plotted. Lag of h was 150 m, the minimal number of pair was not less than 70, and the angular tolerance was 20 ˚ . Where a trend was found, variograms were built both for source data and for detrended data (residuals of regression).

Results

Table 5.1 shows the data obtained through statistical treatment of the results gathered. Mean values reflected well-known patterns in the zonal distribution of soil properties (Dobrovolskiy and Urusevskaya, 1984): pH values (both in the aqueous and in the saline extracts) grow north to south in a regular way from acidic to neutral and weakly alkaline values. The content of organic carbon increases from Greyic Phaeozems through Luvic Chernozems to Haplic Chernozems, then decreasing in Kastanozems of the dry steppe subzone.

Table 5.1: Statistical indices of the properties of: 1 – Greyic Phaeozems, 2 – Luvic Chernozems, 3 – Glossic Chernozems, 4 – Kastanozems

statistical	pH(KCl)				$pH(H_2O)$				C, %			
index	1	2	3	4	1	2	3	4	1	2	3	4
n	59	85	100	74	59	85	100	74	59	85	100	74
mean	4.79	5.00	6.72	7.12	5.95	6.07	7.17	7.89	0.73	2.65	3.64	2.50
variance	0.50	0.17	0.17	0.26	0.39	0.14	0.21	0.26	0.06	0.05	1.68	0.29
range	3.70	2.00	1.75	1.80	3.20	2.10	1.88	1.70	1.46	1.41	8.83	2.52
CV, %	14.81	8.18	6.19	7.13	10.40	6.11	6.45	6.40	33.19	8.38	35.69	21.40
min	3.10	4.60	5.70	6.00	4.50	5.60	6.02	6.90	0.30	1.97	0.14	1.23
lower quartile	4.23	4.70	6.44	6.71	5.50	5.80	6.79	7.51	0.59	2.53	2.76	2.10
median	4.90	4.90	6.75	7.30	6.00	6.00	7.20	8.10	0.73	2.63	3.56	2.38
upper quartile	5.20	5.30	7.07	7.50	6.28	6.30	7.56	8.20	0.85	2.75	4.58	2.86
max	6.80	6.60	7.45	7.80	7.70	7.70	7.90	8.60	1.76	3.38	8.97	3.75
skewness	0.095	1.58	-0.30	-0.64	0.23	2.13	-0.37	-0.66	1.21	0.24	0.47	0.21
kurtosis	0.26	3.53	-0.93	-0.92	0.56	6.75	-0.85	-0.86	3.64	1.68	1.81	-0.19

The highest variability of all variation indices (variance, range, coefficient of variation) of the saline extract pH is observed in Greyic Phaeozems. These indices are significantly lower in all Chernozems (especially in Luvic Chernozems), and are slightly higher in the Kastanozems than in Chernozems. Variability of the aqueous extract pH is also maximal (all indices) in Greyic Phaeozems. Variability of the aqueous pH in Glossic Chernozems and Kastanozems is equally low. The situation with organic carbon variability is more complicated. As regards variance and range, the lowest variation is demonstrated by Greyic Phaeozems and Luvic Chernozems, and the highest – by Glossic Chernozems. The coefficient of variation decreases in the following sequence: Glossic Chernozems – Greyic Phaeozems – Kastanozems – Luvic Chernozems.

For all the soils, pH values had medium to low coefficients of variation, less than 25%. Thus, at the studied scale, the heterogeneity of these properties was not very high. Coefficients of variation obtained for organic carbon content were considerably higher for Greyic Phaeozems and Glossic Chernozems, than for the other soils. Thus, the heterogeneity of organic carbon content for the soils mentioned above was high.

The coefficients of skewness and kurtosis indicated that organic carbon content had normal distribution or close to that. However, the organic carbon content for Greyic Phaeozems seemed to depart slightly from the normal distribution, because it had a positive skewness and a bigger tail than it should have.

The pH values (both in the aqueous and in the saline extracts) for Greyic Phaeozems had the near-normal distribution. Southwards, the soil acidity decreased, as it have been expected according to the classical zonal theory. However, it is interesting to note that the decrease in medium acidity values was mainly related to the increase of the minimum values. In Greyic Phaeozems, the lowest 25% of the pH (KCl) values were in the range from 3.10 to 4.23 (for aqueous pH – from 4.50 to 5.50). In Luvic Chernozems the same range was much narrower, from 4.6 to 4.7 for pH (KCl), and from 5.6 to 5.8 for aqueous pH. However, the other statistical parameters, such as median, upper quartile, and maximum, did not change. As a result, we observed a positive asymmethry in data distribution, which was also confirmed by high coefficients of skewness and kurtosis for the pHs of Luvic Chernozem.

For Glossic Chernozems and Kastanozems, the distribution of the pH values was almost normal. However, a certain negative asymmetry was observed there, because a number of higher pH values were detected: more than a half of the values were higher than the mean. Thus, the data distribution of pH values in the studied soils were near normal. However, it is important to note that a slight asymmetry existed: a positive one in acid soils, and a negative – in slightly alcaline.

The simplest way to model large-scale spatial variation in the studied characteristics is to plot the regression surface (trend surface) on the basis of the data obtained at separate sampling points. The following regression equations (linear trend) were obtained for the Greyic Phaeozems:

$$z_1 = 5.62 - 0.0013x_1; (\alpha < 0.01; R^2 = 36.23) \tag{5.4}$$

$$z_2 = 6.68 - 0.0011x_1; (\alpha < 0.01; R^2 = 36.01) \tag{5.5}$$

For Luvic Chernozems the quadratic trend was obtained:

$$z_1 = 5.60 + 0.00019x_1 - 0.0014x_2 + 3.61 * 10^{-7}x_2^2; (\alpha < 0.01; R^2 = 51.89) \quad (5.6)$$

$$z_2 = 6.11 + 0.00067x_1 - 0.00033x_2 - 6.33 * 10^{-7}x_1x_2; (\alpha < 0.01; R^2 = 47.20) \quad (5.7)$$

$$z_3 = 3.16 - 0.00078x_1 - 0.00063x_2 + 9.46 * 10^{-7}x_1x_2; (\alpha < 0.01; R^2 = 19.28) \quad (5.8)$$

where x_1 and x_2 are the coordinates of the sampling points, $z_1$is the estimate of the pH of the KCl extract value, z_2 is the estimate of aqueous extract pH value, z_3 is the estimate of the organic carbon content, α is the significance level, and R^2 is the multiple determination coefficient.

For the rest of the studied soils the regression models explained not more than 10% of the observed variability in the studied soil properties, or were not statistically significant (Sidorova and Krasilnikov, 2007). So, they did not allow reaching unambiguous conclusions about the relationship between these properties and the coordinates of the sampling points.

Variographic data are shown in Table 5.2. Acidity values of the Greyic Phaeozems KCl extract were distributed according to a power model (of 0.99 power, i.e. the variogram was nearly linear). Linear shape of the variogram testifies the presence of a trend, and we made corrections (detrending) of the data. The detrended variogram took the shape of a spherical model. Variograms were plotted also direction-wise. Since the along-slope variogram was also modeled by the power function, the trend was related to the slope. Aqueous extract pH values had the same distribution parameters and were approximated by the same models. The distribution of organic carbon was also periodic in nature, both for all directions, and for the directions along and across the slope. It is interesting that the period for all the data falls into the along-slope and across-slope vectors (periods of 1012, 509 and 863 m form a nearly perfect right-angled triangle with an angle of ca. 30 °). Thus, the direction of periodicity does not coincide with the slope.

Acidity values of the Luvic Chernozem KCl extract were distributed according to a power model (of 1.04 power, i.e. the variogram was also linear). After detrending, the variogram took the shape of a spherical model. Variograms were plotted also direction-wise. Periodicity of distribution with a period of ca. 800 m was detected along the ridge. A power function modeled the distribution of values across the ridge. Aqueous extract pH values had nearly the same distribution parameters, but after the data had been detrended, the variogram became periodic in nature. Organic carbon distribution was periodic both for source data and for detrended data, with

Table 5.2: Model parameters of variograms for the properties of 1 – Greyic Phaeozems, 2 – Luvic Chernozems, 3 – Glossic Chernozems, 4 – Kastanozems

property	soil	direction	model	nugget	sill	range, m	period, m
pH(KCl)	1	source data	power (0.99)	0.22	0.00054	-	-
		detrended data	spherical	0.20	0.32	198	-
		along the slope	power (1.34)	0.21	0.00009	-	-
		across-slope	spherical	0	0.492	485	-
	2	source data	power (1.04)	0.032	0.00018	-	-
		detrended data	spherical	0.019	0.084	288	-
		along the ridge	pseudoperiodic	0.11	0.060	-	798
		across the-ridge	power (1.54)	0.084	0.0000079	-	-
	3	source data	power (1.27)	0.15	0.000004	-	-
		along the plot	nugget	0.18	-	-	-
		across the plot	pseudoperiodic	-	-	-	-
	4	source data	Gaussian	0.217	0.26	483	-
		along the slope	spherical	0.069	0.28	546	-
		across-slope	Gaussian	0.16	0.29	406	-
pH(H_2O)	1	source data	power (0.99)	0.14	0.00047	-	-
		detrended data	spherical	0.18	0.24	208	-
		along the slope	power (1.46)	0.16	0.000028	-	-
		across-slope	spherical	0	0.4	565	-
	2	source data	power (1.01)	0.03	0.00017	-	-
		detrended data	pseudoperiodic	0.073	0.013	-	1525
		along the ridge	pseudoperiodic	0.074	0.029	-	1400
		across the-ridge	power (1.38)	0.08	0.00003	-	-
	3	source data	spherical	0.15	0.21	340	-
		along the plot	nugget	0.22	-	-	-
		across the plot	pseudoperiodic	0.16	0.038	-	908
	4	source data	exponential	0.14	0.28	358	-
		along the slope	nugget	0.27	-	-	-
		across-slope	Gaussian	0.11	0.29	350	-
C	1	source data	periodic	0.041	0.0052	-	1012
		along the slope	periodic	0.044	0.012	-	509
		across-slope	periodic	0.031	0.013	-	863
	2	source data	pseudoperiodic	0.059	0.019	-	2059
		detrended data	pseudoperiodic	0.049	0.014	-	2060
		along the ridge	power (1,32)	0.03	0.0000036	-	-
		across the-ridge	periodic	0.042	0.010	-	635.6
	3	source data	pseudoperiodic	1.68	0.17	-	1934
		along the plot	pseudoperiodic	1.57	0.34	-	3239
		across the plot	pseudoperiodic	1.67	0.33	-	988
	4	source data	spherical	0.099	0.28	357	-
		along the slope	pseudoperiodic	0.28	0.039		1685
		across-slope	Gaussian	0.16	0.33	553	-

a similar period of ca. 2060 m. The along-ridge distribution was described by a power function, and the across-ridge distribution was periodic, but the period was much smaller than for the whole data pool (636 m).

Discussion

We have investigated the spatial variability of the sites established within the distribution range of the zonal series soils. The study has revealed certain distinctions in geostatistical parameters of the sites. Greyic Phaeozems feature high variability of acidity measured as pH of the KCl and aqueous extracts. Acidity varies regularly in space at characteristic distances of up to 200 m, the spatial correlation of the data assessed as high. At the same time, these parameters show quite high variation also at characteristic distances smaller than the sampling interval (less than 150 m). Yet, high sill/nugget ratio indicates that most variation takes place at characteristic distances of 150-200 m. Regular change of pH values usually proceeds along the slope – most probably due to more intensive leaching of carbonates from the upper slope or the vicinity of carbonaceous groundwater discharge at the foot of the hill. Across-slope distribution of pH values is described by a spherical model, indicating that the parameter values change abruptly at irregular distances; the correlation radius in this direction is larger, reaching 480–565 m (for pH values of the saline and aqueous extracts, respectively). Zero nugget means that in this direction hardly any changes take place in the values at characteristic distances smaller than 150 m, i.e. pH values change at 150-500 m distances. Organic carbon content shows relatively little variation, its spatial distribution being periodic, with a period of ca. 1000 m; variation at distances below 150 m is negligible. Periodicity of the organic carbon distribution has no correlation to the slope; the period in our case being at an angle of ca. 30° to the slope. Detailed *in situ* studies are needed to determine the reason for such periodicity; this is exactly the case when geostatistical data, revealing hidden patterns in data distribution, provide the ground for soil-geography studies.

Acidity in Luvic Chernozems shows little variation in the saline extract pH, but the variation of pH values in the aqueous extract is much higher. The pH of KCl extract is known to be a more stable acidity parameter, since it does not depend on the initial ionic force of the solution. Apparently, it should be taken into account that it is in Luvic Chernozems that the values of the aqueous extract pH are the least stable. The same factor seems to be responsible for differences in the spatial distribution of these acidity parameters. The distribution of the KCl extract pH values is described by a spherical model; spatial correlation is of medium strength, most variation takes place at characteristic distances of 150–300 m. Acidity distribution is determined by the topography: the distribution along the ridge slope is described by a power function, i.e. a trend is present in the data distribution. Periodicity of the distribution is observed along the ridge, the reasons for it still undetermined. Little variation is seen in organic carbon content; its distribution is periodic, with a period of ca. 2000 m, which may be connected to the mesotopography.

Acidity variation in Glossic Chernozems is minor (variation of all indices is lower than in other soils). Spatial coherence of the aqueous extract pH values is described as medium, but close to weak; the distribution is characterized by a spherical model. Judging by the high nugget, variation most probably occurs at distances less than 150 m. The presence of "across-the-site" periodicity (or, more accurately, pseudo periodicity) is most probably due to the forest strips growing along the site edges and producing a slight acidifying effect on the soil. The pH(KCl) distribution is described by a low-slope power function, i.e. approaches pure nugget. Glossic Chernozems are noted for maximal variation of the organic carbon content, which is described by a periodic model in all directions. The data, however, are somewhat doubtful: direction-wise periods queerly coincide with the linear dimensions of the site, and the period in all directions is their arithmetic mean. If our guess is correct, this is a case of pseudo periodicity caused by the "edge effect" of the field. Anyhow, even if periodicity of some kind does exist, the amplitude of change appears negligible against the high nugget background. Most changes in organic carbon content take place at distances smaller than 150 m – a fact we attribute to the microtopography and short-range transport of organic material along the slope (Sidorova and Krasilnikov, 2004, 2007).

The variation of acidity in Kastanozems is relatively low, although somewhat higher than in Glossic Chernozems. A Gaussian model with a low degree of spatial correlation was used for the distribution of the saline extract pH values. Changes mostly occur at distances less than 150 m; changes at distances of 150–480 m are smaller and smoother. On the other hand, changes along the slope are described by a spherical model, which implies more abrupt shifts in values, this fact possibly being an outcome of slope-related processes. The structure of the distribution of the aqueous extract pH values is somewhat different. The model for all values is exponential, and spatial correlation is classified as medium. The distribution along the slope is described as pure nugget, across the slope – as a Gaussian model. Organic carbon content shows medium variation (lower than in Glossic Chernozems, but higher than in Luvic Chernozems). The spatial distribution of organic carbon content is described by a spherical model; spatial correlation is of medium strength, the correlation radius is ca. 360 m, i.e. the variation is made up of two nearly equal components: variation at distances less than 150 and 150–360 m. Variation across the slope is described by a Gaussian model, whereas variation along the slope demonstrates periodicity with a period of ca. 1500 m, which may be due to sheet erosion.

The research results for zonal soils are summarized in Table 5.3 (data distribution by directions and trends not taken into account). The distribution of the saline extract pH values is characterized by a spherical model in Greyic Phaeozems and Luvic Chernozems, by a power model – in Haolic Chernozems, and by a Gaussian model – in Kastanozems. The nugget is the lowest in Luvic Chernozems, and nearly equal to each other in the rest of the soils. The sill is also the lowest in Luvic Chernozems, somewhat higher in Greyic Phaeozems and the highest in Kastanozems; this parameter is not applicable to the power model. The range increases in the north-to-south zonal series: its value for Greyic Phaeozems is ca. 200 m, for Luvic Chernozems – ca. 300 m, for Kastanozems – nearly 500 m. Spatial correlation is defined as high for Greyic Phaeozems, as medium – for Glossic Chernozems and as low – for Kastanozems. The patterns in the distribution of the aqueous extract pH values are somewhat different: the distribution is described by a spherical model in Greyic Phaeozems and Glossic Chernozems, by a periodic model – Luvic Chernozems, and by an exponential model – in Kastanozems.

Table 5.3: Model parameters of variograms (omnidirectional; detrended data) for the properties of 1 – Greyic Phaeozems, 2 – Luvic Chernozems, 3 – Glossic Chernozems, 4 – Kastanozems

properties	soil	model	nugget	sill	range, m	period, m	nugget/sill, %
pH(KCl)	1	spherical	0.20	0.32	198	-	62
	2	spherical	0.019	0.065	288	-	29
	3	power (1.27)	0.15	0.000004	-	-	-
	4	Gaussian	0.21	0.26	483	-	78
pH(H_2O)	1	spherical	0.18	0.24	208	-	75
	2	periodical	0.073	0.013	-	1525	-
	3	spherical	0.15	0.21	340	-	73
	4	exponential	0.14	0.28	358	-	50
C	1	periodical	0.041	0.0052	-	1012	-
	2	periodical	0.049	0.014	-	2060	-
	3	periodical	1.68	0.17	-	1934	-
	4	spherical	0.099	0.28	357	-	36

The distribution of organic carbon follows periodic models in Greyic Phaeozems, Luvic Chernozems and Glossic Chernozems, and a spherical model – in Kastanozems. The period is ca. 1000 m in Greyic Phaeozems and ca. 2000 m in Luvic and Glossic Chernozems. The correlation radius (range) in chestnut soils is ca. 350 m, and spatial correlation is defined as medium.

Conclusions

The study shows that it is quite feasible to interpret geostatistical parameters of the zonal soil series. This finding raises one hope about the possibilities of typifying such parameters, at least at the regional level, and of allowing for further extrapolation. However, one of the main outputs showed also how difficult it is to distinguish any spatial variability patterns in very specific locations, and it is therefore important to consider the results as preliminary. This is maybe due to the low number of study sites (four only). Thus, further research is needed to distinguish general patterns of spatial variation of soil properties for such regional scale.

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Chapter 6

Effect of beavers on variability of soil properties in southern Karelia

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Abstract [1]

We studied the alteration of spatial variability of soil properties in southern Karelia induced by inundation caused by beavers' activity. The study was conducted at an unaltered reference site and at a site affected by flooding. After flooding the territory was paludified; causing an increase in organic carbon content and a slight decrease in pH values. The spatial distribution of organic carbon in the surface soil horizon changed after flooding. The reference site had a pseudostochastic spatial distribution of organic carbon, whereas in the once flooded site there was a square trend oriented outward from the lake.

Introduction

Animal activity is one of the main soil formation factors (Jenny, 1941). Dmitriev and Gauricheva (1983) introduced the notion of the zoophytochore – a specific structure at the biogeocoenosis level in which one of the key factors for the development of vegetation and soils is animal activities. Naiman (1988) notes that mammals produce a considerable effect on ecosystems due to their significant size, life span, demand for food and shelter.

Many researchers have focused in their studies on the role of digging mammals in soil formation processes (Abaturov and Karpachevsky, 1965; Abaturov and Zubkova, 1969; Tadzhiev and Odinoshoev, 1987; Dmitriev, 1988). Abaturov (1984) distinguished the following impacts of digging animals on soils: their burrows loosen the soil, enhance aeration, facilitate deeper moistening; material from deeper horizons is moved to the surface; specific landforms are generated; the thickness of the humus

[1] This chapter is an extended and improved translation of the text published in Russian in "Geostatistics and Soil Geography", Moscow, Nauka Publ., P. 92-108.

horizon increases as it is mixed with the parent rock; the loosened soil material becomes more prone to weathering.

There exists however indirect impacts of animals, in addition to those listed above. One of the agents is the beaver, which influences soil not only directly, through digging and foraging activities, but also indirectly – through changing the hydrology of water-bodies and soils.

Settling at a water-body, beavers transform the whole waterside rapidly and profoundly: a vegetation shift takes place, changes occur in the chemical composition of the soil and water, in the hydrological conditions in water-bodies, in waterside features and fauna, etc. The presence of beavers in a water-body affects, sometimes enormously, the whole waterside complex. Beavers considerably enhance the self-purifying capacity of water-bodies. Other important factors are the effects of beaver ponds such as equalizing streamflow, improving the habitat conditions for forest animals and fish (Dezhkin et al., 1986; Balodis, 1990; Burns and McDonnell, 1998; Zavyalov and Bobrov, 1999).

Beaver activities are also a powerful soil formation factor, e.g., burrowing contributes to micro- and nanotopography formation, modifies the temperature and water regime in soils, influences the direction and rate of soil-formation processes (Zavyalov and Zueva, 1998). Drainage is another function of burrows. Owing to water seepage from the pond, the aquifer gets recharged to a distance of 100-150 m, and the groundwater level around the pond rises by 1 m. The rise in the groundwater level leads to intensified gleying and peat deposition. A tendency for the development of Histic and Mollic Gleysols, immature peaty soils is observed in beaver-modified flood plains. Histic Gleysols with high content of clay particles in organic layer form in microtopographic lows due to intensive clay deposition. Beaver activities induce degradation and water-logging of soils; conditions are created for the formation of wetland plant communities (Sinitsyn and Rusanov, 1989). Drawing upon their studies in the northern USA and Canada, Naiman et al. (1988) also note that wetlands or occasionally inundated meadows form in place of abandoned beaver colonies. Gilliam et al. (1999) observe that the properties of a "young" wetland formed 8 years after the erection of beaver dams and resulting flooding are not any different from those of "old", naturally formed wetlands.

Tree root systems also get impaired by the rise in the groundwater level. Large old trees fall and block the channel. Spruce trees of different size, sometimes reaching 3-4 m in diameter, get uprooted. Windthrow processes suppress the ground cover underneath the fallen trunks and lead to degradation of the soil in the uprooting points (Sinitsyn and Rusanov, 1989).

Physiochemical properties of soils also change under the effect of inundation. Zavyalov and Zueva (1998) studied soils on the banks of two beaver ponds and in a reference site of the river floodplain unaffected by beavers (in the Darwin nature reserve). The authors distinguish three affected zones: 1) from water edge to 7 m away from the shore – pH values close to neutral (5.97), high oxalate-soluble Fe content in the gleyed B horizon and exchange Al in the A horizon; 2) 7 to 25 m – pH falling sharply to acidic values (4.1), reduction in the content of oxalate-soluble Fe and exchange Al; 3) 25 m and further away from the water edge – pH values gradually changing to medium acidity (4.73), oxalate-soluble Fe and exchange Al content leveling out. No such dramatic differentiation was observed in the reference site. Organic material content was also observed to decrease in the inundated site outward from the river (from 26.0 to 0.18 %) (Zavyalov and Zueva, 1998).

Donkor and Fryxell (2000) arrived at similar conclusions studying the effect of the Canadian beaver on lowland boreal forests surrounding beaver ponds in Algonquin Park, Ontario. Deposits in their study sites varied from dry, thin, gravelly till overlying crystalline bedrock to very wet heavy lacustrine loams. They investigated changes in organic matter content, pH values (in the aqueous extract), moisture and concentrations of P (after Olsen), K and Mg (exchange) depending on the distance from the pond. Regression analysis revealed a square correlation between all the investigated parameters and the distance to the pond. As the distance increased, moisture, potassium concentrations and pH values decreased, whereas organic material content, phosphorus and magnesium concentrations grew, and then vice versa. Changes in the distance are responsible for 75% of variation in moisture, 43% – in organic material content, 25, 23 and 16% – in potassium, magnesium and phosphorus concentrations, respectively, and for only 6% of pH variation.

Naiman et al. (1988) researched into changes in soil properties and vegetation at inhabited and abandoned beaver ponds of Minnesota in relation to the moisture status. A nearly two-fold drop in pH values was observed along the hydrological gradient: 6.0 or more in bottom sediments and near the bank, 4.7 – in moist soils and 3.9 – in well-drained forest soils. The studies have demonstrated also that paludification involves a sharp (4.3-fold) rise in nitrogen available to plants (nitrogen determined in the KCl extract and nitrogen in the soil solution) – 29.8 and 6.8 kg/ha in the flooded area and in the forest, respectively. Thus, beavers increase the amount of available nitrogen in the landscape through their activities.

The environment-shaping function of beavers has been studied quite profoundly (Dezhkin et al., 1986). Yet, quantitative details on the effect of beavers on soil formation processes are insufficient. The aim of the present study has been to assess changes in the spatial distribution of basic soil properties under the action of beavers in taiga forests of Karelia.

Objects and methods

Surveys were done in an abandoned beaver colony on Lake Pertilambi (vil. Kaskesnavolok, Pryazha District, Republic of Karelia). The predominant type of forest along the shore prior to the arrival of beavers had been the herb-rich birch stand *Betuletum mixto-herbosum* with a minor proportion of aspen (reconstrued context). After the beavers had arrived and erected two dams at the lake outlet, ca. 15 ha of adjoining forest was flooded. After the beavers' departure (14 years ago), collapse of the dams and fall in the water level a wetland community of a mixed category including birch-overgrown Sphagnum, sedge-Sphagnum (*Caretum sphagnosum*), Sphagnum-cottongrass (*Sphagnetum eriophorosum*) and various dwarf shrub-Sphagnum communities (*Fruticuletum sphagnosum*) with different dwarf shrub species prevailing formed in the place of the former beaver pond. Two sample plots 20x95 m each were established. One in the formerly flooded area, where the soils are gley peaty podzols (Histic Gleyic Podzols), the other one – in an undisturbed reference area, where the soils are gleyic podzols (Endogleyic Podzols). The plots were oriented outward from the lake.

Samples were collected from a depth of 0-10 cm immediately beneath the litterfall horizon (O) following a regular grid, the sampling points preferably spaced 5 m. A hundred samples were taken from each plot. The samples were not differentiated by types of horizons underlying the litter (A, Ah, H). We determined the parameters, which are known to alter readily after soil disturbance or a change in environmental conditions: pH(H_2O), pH(KCl), and organic carbon content. Total nitrogen content was determined only in 20 samples from plot 1 and in 28 samples from plot 2. The sample volume was calculated by statistical analysis of a single sample entity (Dmitriev, 1995). The numbers of the samples to be included in the analysis were determined by the random numbers method.

Spatial variability of soil properties was determined using the geostatistical method for estimating the relationship between the variance of the properties and the sampling interval (Burgess and Webster, 1980; Jongman et al., 1995; Demianov et al., 1999; Kuzyakova et al., 2001). The resultant data were employed to plot variograms – curves showing the relationship between semivariance γ(h) and shift values h. Kriging was used to compile cartograms of soil properties. If trends were present, then regression kriging was used. Like regression, *regression kriging* recognizes that the variation has two components, namely *the trend* and *the residuals from the trend*. It differs from regression in that it takes into account the dependence in the residuals, which it treats as spatially correlated stationary random variables. So the residuals have a variogram, and the kriging systems draw their entries from this variograms.

The regression kriging predictions are computed as follow. The first step is to model trend, as in trend-surface analysis, and remove it from the data. The residuals from the trend (or detrended data) are treated as spatially correlated stationary random variables. Their variogram is computed and modeled and then used to krig. Finally, the trend is added back to the kriged estimates (Lark and Webster, 2006; Hengl, 2007).

Calculations and variogram plotting were made with Variowin, version 2.2. (Pannatier, 1996) and Excel (Microsoft) software packages, spatial distribution maps based on forecasted values – with SURFER Version 6.02 software (Copyright © 1993-1996, Golden Software, Inc.). GenStat (2002) (evaluation version) software was used for kriging.

Results

The range of values of the parameters studied is quite wide. Therefore, all sample extremes were subjected to statistical check for bias in rejection of results. As the result, 5 samples from plot 2 were rejected. No grounds were found for rejecting the rest of the values.

Comparative analysis of the two sample entities (Blagoveshchenskii et al., 1987) revealed reliable distinctions between the two plots in organic carbon, total nitrogen and acidity. Thus, the saline extract pH in the soil of the formerly flooded plot was reliably ($P_{0.93}$) 0.4 lower than in the reference site, the aqueous extract pH was reliably 0.22 lower ($P_{0.99}$), organic carbon content was on average reliably 32.7% higher ($P_{0.999}$), total nitrogen content was reliably 1.6% higher ($P_{0.999}$). The range of values of the properties and the coefficient of variation were also observed to grow in the once flooded site (Tab. 6.1, Fig. 6.1).

Table 6.1: Statistical indices of the properties of upper (0–10 cm) soil horizons: 1 – formerly flooded site, 2 – reference site

statistical index	pH (KCl)		pH (H_2O)		C, %		N, %	
	1	2	1	2	1	2	1	2
no of observations	100	95	100	95	100	95	20	28
range of values	1.74	1.50	2.13	1.66	50.76	5.88	1.17	0.25
min	2.96	3.06	3.51	3.64	1.44	1.20	1.12	0.12
lower quartile	3.20	3.60	4.06	4.38	34.80	2.82	1.53	0.23
median	3.38	3.84	4.42	4.64	39.30	3.51	1.89	0.26
upper quartile	3.56	4.01	4.65	4.82	43.20	4.14	2.14	0.29
max	4.70	4.56	5.64	5.30	52.20	7.08	2.30	0.37
mean	3.46	3.82	4.38	4.60	36.28	3.61	1.84	0.26
variance	0.13	0.09	0.18	0.10	148.52	1.20	0.12	0.0031
standard deviation	0.37	0.30	0.43	0.32	12.19	1.10	0.35	0.056
CV, %	10.57	7.98	9.75	7.01	33.59	30.35	18.75	21.61
kurtosis	1.72	-0.15	0.13	0.11	2.54	0.23	-0.83	0.52
skewness	1.36	-0.14	0.35	-0.38	-1.74	0.39	-0.38	-0.32

The simplest way to model large-scale spatial changes is to draw the regression line or surface using empirical data from individual points (trend surface interpolation) (see Chapter 5).

We applied the least squares method to data from both plots to select the quadratic surface (2^{nd} order trend) in the form (Dmitriev, 1995; Jongman et al., 1995):

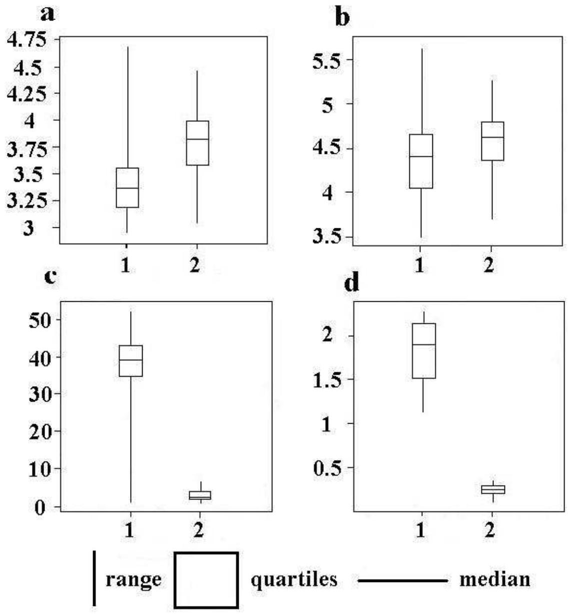

Figure 6.1: Statistical parameters for pH(KCl) (a), pH(H_2O) (b), organic carbon content, % (c) and total nitrogen content, % (d). 1 – formerly flooded site, 2 – reference site

$$z = b_0 + b_1x + b_2y + b_3x^2 + b_4y^2 + b_5xy \tag{6.1}$$

The reference site yielded no trend surface. The following surfaces were found for the formerly flooded site:

$$pH(KCl) = 3.98 - 0.023y - 0.0011x^2 + 0.00016y^2 + 0.00051xy \tag{6.2}$$

$$pH(H_2O) = 4.96 - 0.025y - 0.00075x^2 + 0.00014y^2 + 0.00060xy \tag{6.3}$$

$$C = 3.56 + 1.26x + 1.07y - 0.0069y^2 - 0.019xy \tag{6.4}$$

$$N = 1.34 + 0.01y + 0.002x^2 - 0.000067y^2 - 0.00026xy \tag{6.5}$$

The surfaces account with quite high probability (95-99%) for the changes in carbon content (58.8%), total nitrogen content (56.2%), aqueous (31.9%) and saline (25.5 %) pH values. Thus, the pattern observed in the formerly flooded site in the direction outward from the lake is a decrease in pH values and a rise in the humus and nitrogen content first, and, vice versa, a rise in pH and a decrease in the humus content further away (Fig. 6.2).

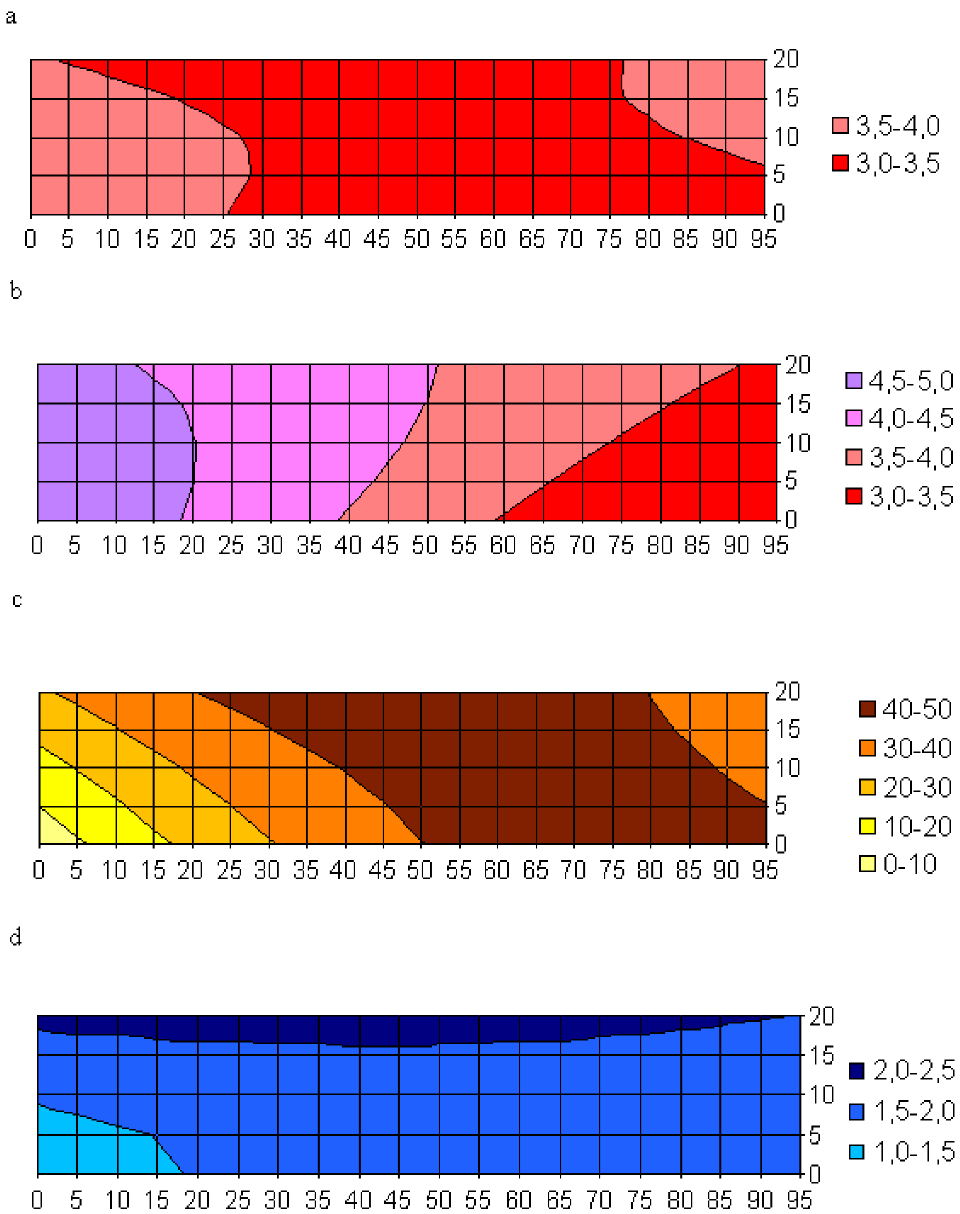

Figure 6.2: 2^{nd} order trend estimated field for pH(KCl) (a), pH(H_2O) (b), organic carbon content, % (c) and total nitrogen content, % (d). Hereinafter, the grid scale is expressed in metres from the coordinate (0,0).

Like any regression equation, the trend surface equation can be used to calculate or interpolate trait values to sites not covered by empirical surveys. Yet, trend surfaces do not ensure precise interpolation. Since they are models of large-scale variations, the influence of the extremes of remote data points may be too high, leading to erroneous estimates.

Then, we applied geostatistical methods. The semivariances were computed for original data and for quadratic residuals, so that we could choose a function to interpolate the surfaces by kriging.

The variograms for pH(H_2O) and pH(KCl) of both sites were represented quite well by the spherical model in the form (McBratney and Webster, 1986):

$$\gamma(h) = \begin{cases} 0, h = 0 \\ c_0 + c\left(\frac{3}{2}\frac{h}{a} - \frac{1}{2}\left(\frac{h}{a}\right)^3\right), 0 < h < a \\ c_0 + c, h \geq a \end{cases} \quad (6.6)$$

The nugget variance values for pH(KCl) nearly coincided (Tab. 6.2, Fig. 6.3a). One should note however that the nugget effect for the formerly flooded site accounted for a smaller part of the variance compared to the reference site (43% vs. 60%). Since there is little probability of an increase in the analytical error when the same analysis procedure is employed, the above fact indicates that variation in acidity values in the reference site takes place mostly at distances below 5 m (sampling interval). Sill and range values in site 1 grow 1.5 times.

Table 6.2: Variance and model parameters of variograms for the properties of 1a – formerly flooded site, source data; 1b – formerly flooded site, detrended data; 2 – reference site

property	site	model	nugget, C_0	sill, (C_0+C)	range (a), m	C_0/(C_0+C), %
pH(KCl)	1a	spherical	0.052	0.120	22.9	43.3
	1b	spherical	0.037	0.087	10.2	42.5
	2	spherical	0.058	0.096	16.4	60.4
pH(H_2O)	1a	spherical	0.054	0.180	26.1	30.0
	1b	spherical	0.058	0.118	10.7	49.1
	2	spherical	0.084	0.104	20.16	80.8
C	1a	linear	52.50	-	-	-
	1b	power (p=0.01)	57.95	58.09	-	98.9
	2	spherical	0.828	1.236	12.6	67.0

Variograms for the carbon content in the two sites differed significantly. A sharp rise in the variogram in the flooded site testifies to the presence of a trend. The nugget effect in the reference site again accounts for a substantial part of the variance (Tab. 6.2, Fig. 6.3c).

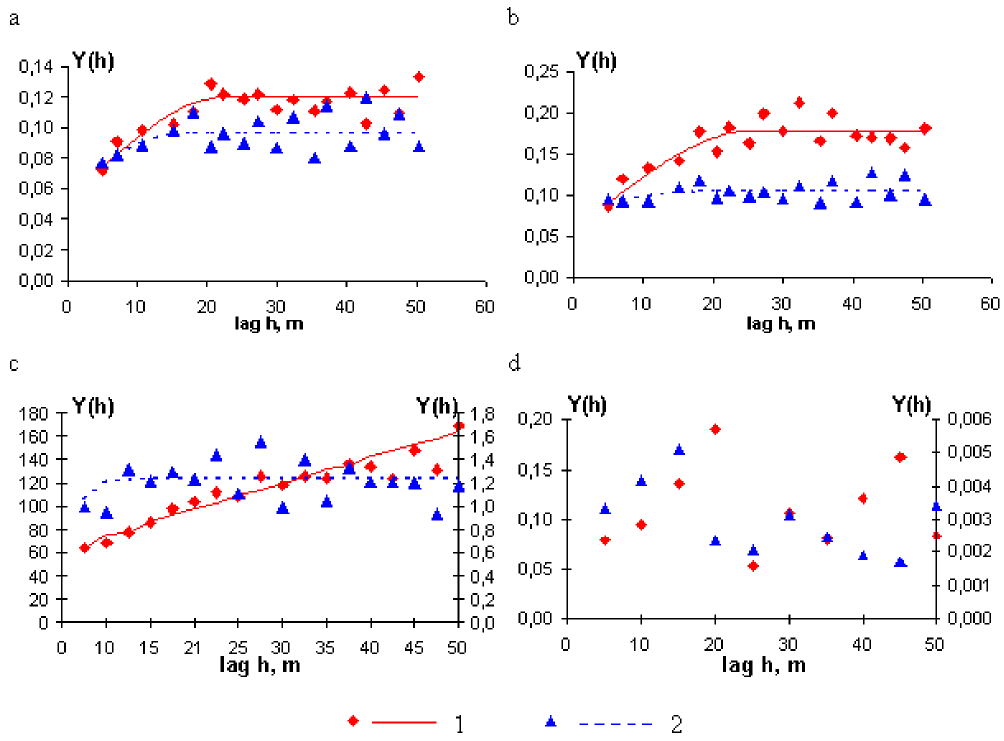

Figure 6.3: Variogram models for pH(KCl) (a), pH(H_2O) (b), organic carbon content, $\%^2$ (c) and total nitrogen content, $\%^2$ (d). 1 - formerly flooded site, 2 - reference site. Hereinafter, the dots indicate the semivariance, the lines are the corresponding models.

Analysis of the total nitrogen content yielded disordered data (Fig. 6.3d). We failed to find the model describing the variation of the property. The possible reason for that is that the number of observation points is insufficient for the analysis of the variograms, or the sampling resolution was too coarse.

Since all properties of site 1 demonstrated regular alteration depending on point coordinates, variograms were additionally plotted for regression residuals (detrended data). The sill and range values in the resultant variograms decrease significantly, virtually degenerating into the nugget effect (Tab. 6.2, Fig. 6.4). This fact indicates that the dimension of the next level of heterogeneity is less than 5 m.

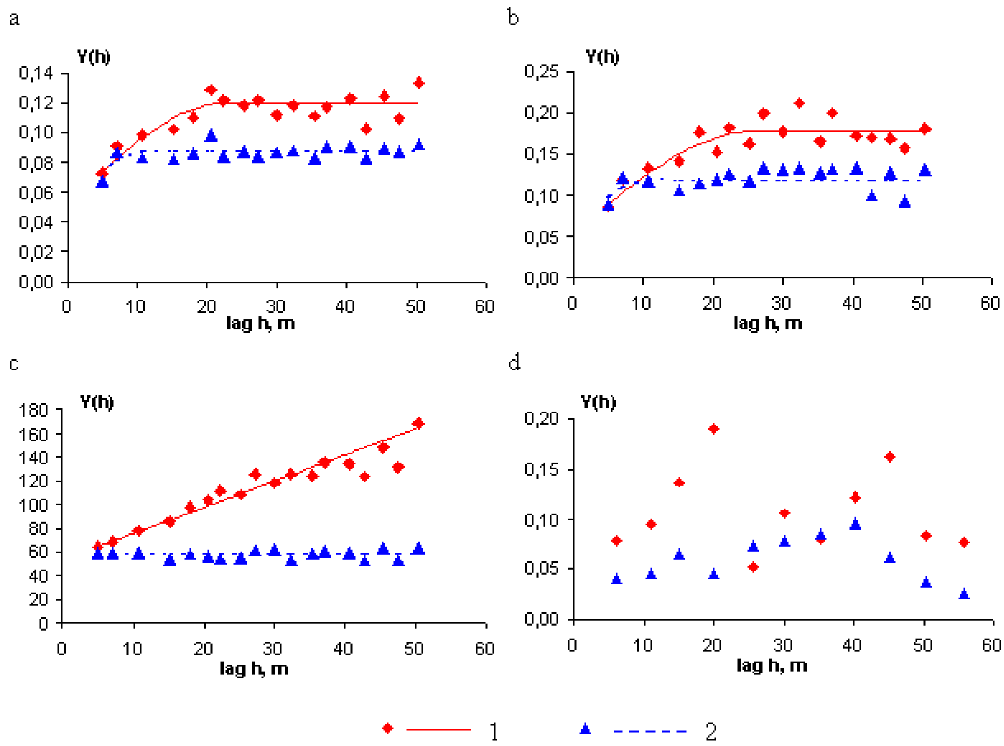

Figure 6.4: Variogram models for pH(KCl) (a), pH(H_2O) (b), organic carbon content, $\%^2$ (c) and total nitrogen content, $\%^2$ (d) for formerly flooded site. 1 - source data; 2 - detrended data

Drawing upon the variograms, soil property cartograms can be produced using the ordinary or regression kriging methods (Burgess and Webster, 1980; Lark and Webster, 2006). Spatial patterns in the variability of the properties are readily distinguishable from the cartograms (Fig. 6.5- 6.7).

Discussion

Soils in the reference site feature a medium level of acidity and organic carbon variability. Values of pH(KCl) in the investigated site varied from 3.06 to 4.56, the

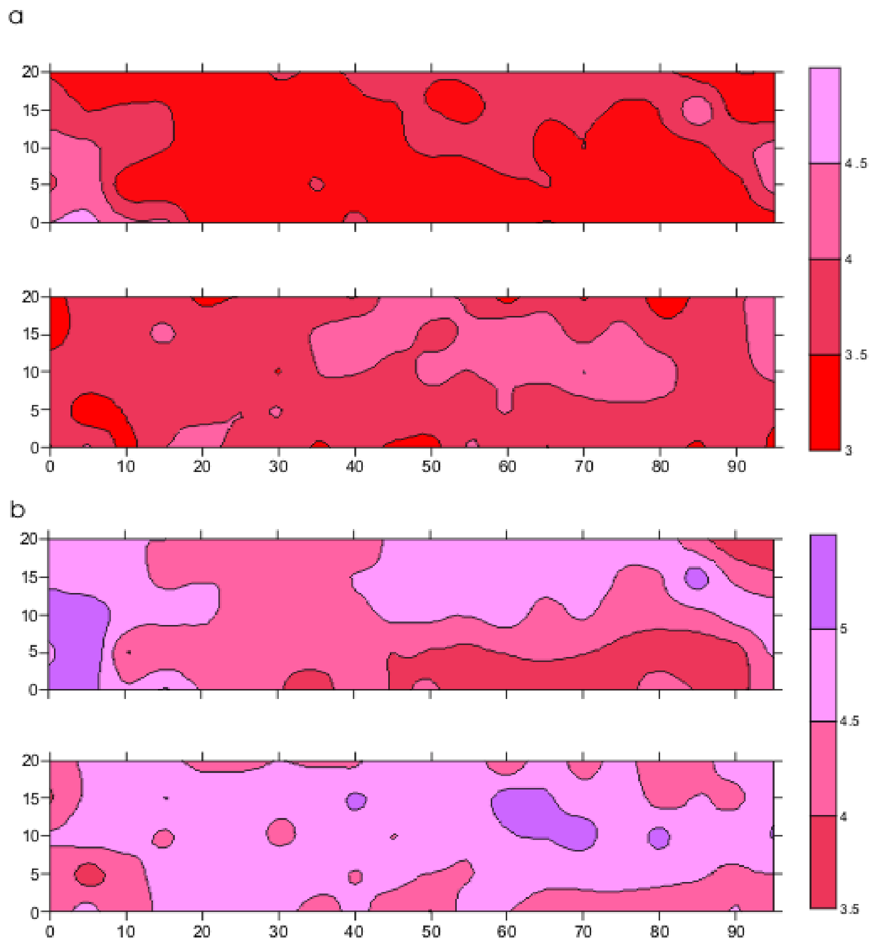

Figure 6.5: Kriging maps of pH(KCl) (a), pH(H_2O) (b) in the formerly flooded site (upper) and in the reference site (lower)

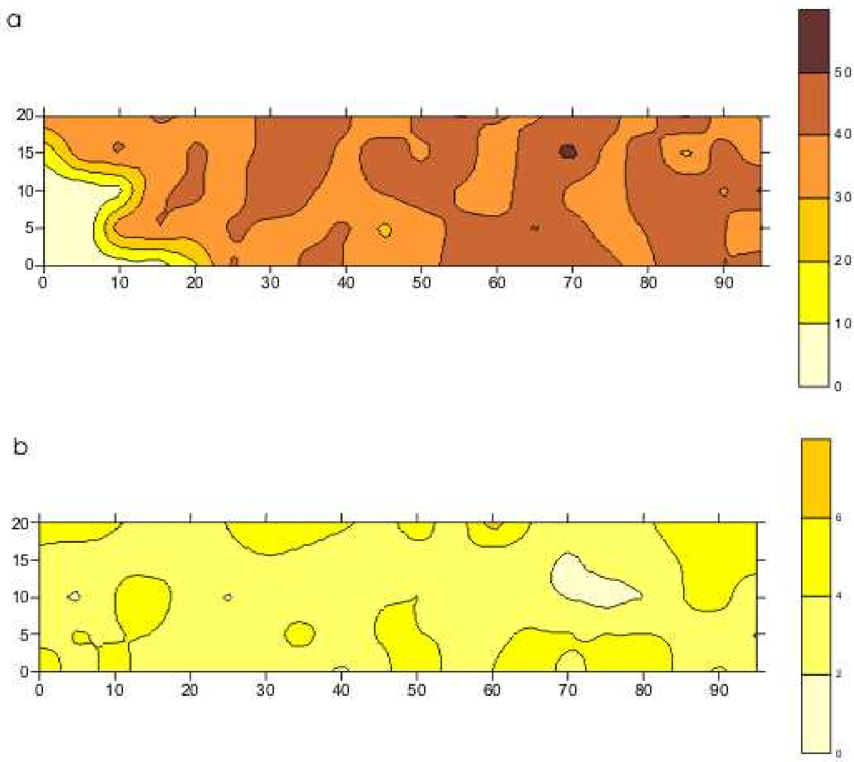

Figure 6.6: Kriging maps of organic carbon content in the formerly flooded site (a) and in the reference site (b)

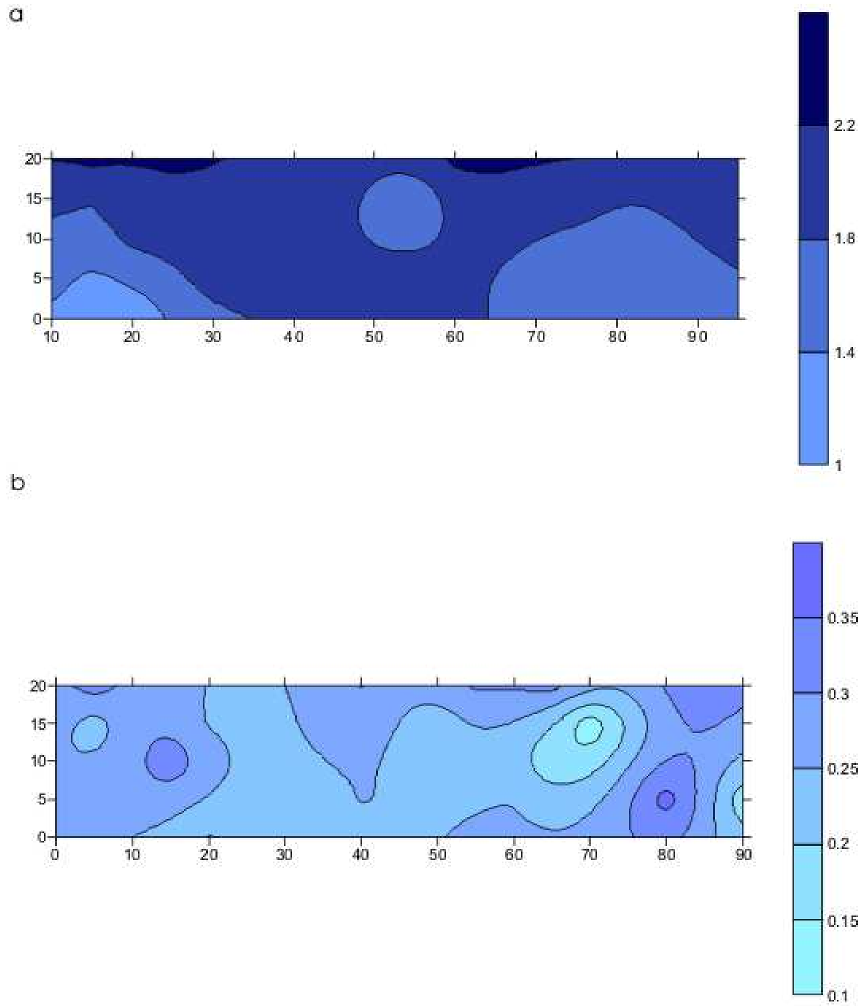

Figure 6.7: Kriging maps of total nitrogen content in the formerly flooded site (a) and in the reference site (b)

mean being 3.82. Carbon content varied from 1.20 to 7.08% (mean – 3.61%), total nitrogen – from 0.12 to 0.37% (mean – 0.26%). The coefficient of variation of the properties was 8 to 30%. Thus, at a first approximation, the plot can be said to have homogenized values of pH(KCl), organic carbon and total nitrogen. The distance at which samples remained spatially correlated (range) ranged from 12 to 16 m. Spatial coherence is evaluated as medium to weak (residual variance is 60-67%).

The results are in conformity with data from other studies of undisturbed forests (Bruckner et al., 1999; Goovaerts, 1998; Liski, 1995; Qian and Klinka, 1995). Chemical properties of forest soils usually exhibit spatial correlation at a distance of several meters (5 to 20 m). The correlation is of medium strength (30-70%). The authors believe this range of spatial correlation to reflect the effect of woody vegetation (location, distance between trees, crown diameter) on soil properties.

Inundation alters both soil properties and their spatial distribution. The least affected parameter is pH. The range of acidity values increases, and an average significant decrease in values by 0.5 takes place. Organic carbon and total nitrogen concentrations grow sharply (7-10-fold), and their distribution changes.

In the once flooded site, a correlation is observed between the studied properties and the location of the sampling points. The distribution of organic carbon, total nitrogen and acidity in the flooded site depends primarily on the distance from the lake and is described by a quadratic function. Samples collected closer to the shore have higher pH values. The explanation suggested by Shcherbakova and Zavyalov (1995) as applied to forest-steppe areas is that the groundwater level is higher closer to the shore, and alkalinization by water from the impoundment takes place. This explanation is not applicable to our sites, since water mineralization in natural water-bodies of Karelia is negligible and no alkalinization can happen. Some authors (Sinitsyn and Rusanov, 1991; Stavrovskiy and Stavrovskaya, 1983) attribute spatially-related alterations in soil properties to shifts in vegetation, since the vegetation factor is the most labile. Vegetation is quick to respond to changes in the environment, rapidly replaced and, hence, alters chemical parameters of soils. Donkor and Fryxell (2000) found that the richness and diversity of plant species around a beaver pond was also a square function of the distance to the lake. The species diversity was the highest 25 m away from the water edge. Our data about a decrease in organic carbon content and a rise in pH values with distance from the water edge can also be interpreted as a result of changes in biogeochemical cycles in the soil related to a shift in vegetation and the conditions for decomposition of organic material. The total input of organic remains to the soil is lower in moister sites, whereas decomposition of organic material under anaerobic conditions is slower. As the result, the soil accumulates some organic material and its acidity grows somewhat lower since lower amounts of acidic products of primary plant remains are generated.

Naiman et al. (1988) note that the effect of beavers on soils is the strongest at a distance of 40 m away from the shore. Donkor and Fryxell (2000) also confirm that the distance hardly ever exceeds 60 m. Geostatistical analysis of our data has demonstrated that the correlation radius in the formerly flooded site is 23 m for acidity and over 95 m – for organic carbon content, i.e. different points remain spatially interconnected in terms of the above properties within these distances.

The variograms plotted for regression residuals indicate that the dimensions of the next level of heterogeneity are equal to or smaller than 10 m for pH and 5 m – for organic carbon content. These correlation radii are smaller than the corresponding values for the reference site. A possible explanation is the shift in vegetation, since a dwarf shrub community replaced a birch stand, eliminating the effect of trees and their crowns on the soil. At the same time, a primary factor in hydromorphic soils in the microtopography, which is responsible for moisture fluxes. Since the microtopography in the studied landscape has smaller characteristic distances than the patchy structure of the original birch forest, the average size of the lowest level of heterogeneity changes, too.

Conclusions

Beaver engineering in Karelia leads to inundation of riparian areas, and gley peaty podzols (Histic Gleyic Podzols) replace gleyic podzols (Endogleyic Podzols) there.

A distinct trend in the distribution of acidity, organic carbon and total nitrogen is observed in the flooded site: carbon and nitrogen concentrations grow, whereas acidity decreases somewhat towards the river bank.

The correlation radius reflecting the characteristic size of the soil properties' heterogeneity is 12-16 m for the reference site, and is determined by the forest community structure (tree locations and crown sizes). The characteristic dimension of heterogeneity after flooding and a shift in the plant community is 5-10 m. It is determined by the microtopography, which is responsible for redistribution of moisture in soils.

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Chapter 7

The use of geostatistical methods for mapping soil horizons

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Abstract [1]

We studied spatial variation of the thickness of soil horizons (litter, A, E, and B) at three sites in southern and central Karelia, each having an area of 15–20 km^2. The results were obtained from a detailed (1:10 000) soil survey of the sites. The variability of the horizons' thickness increased in the sequence B-O-E-A. For mapping purposes, indicator kriging was found to be more effective. It allows generating probability maps (maps of the probability of soil horizons' existence, in our case). We performed indicator kriging at the three sites for O, A, E, and B horizons. The shift in the zones of the horizons' presence/absence occurs mainly at distances of 700–900 m. In all the sites surveyed only the litter layer and the B horizon have continuous distribution, while the A and E horizons are represented by numerous polygons of various sizes. We found that a similar spatial arrangement of different soil horizons indicates low pedodiversity of the area. Ordinary kriging was used for estimating variability of soil horizons' thickness. In disturbed forests, the spatial coherence of forest litter thickness is low, increasing with recuperation of the community and reaching a maximum in old-growth spruce forest. A horizon thickness at the Gomselga site (the only one in which the horizon is present continuously) shows a "nested structure". At Gabselga site (which has large areas of the E horizon present), the thickness of the E and B horizons shows periodic distribution. The period for the B horizon thickness is twice as much as for the E horizon. We explain the phenomena by higher "sensitivity" of the podzolic horizon thickness to soil forming factors (mesorelief) compared to the B horizon, wherefore lower intermediate morainic ridges affected the thickness of the E, but not the B horizon.

[1] This chapter is an extended and improved translation of the text published in Russian in "Geostatistics and Soil Geography", Moscow, Nauka Publ., P. 19-42.

Introduction

The soil profile is a sequence of soil horizons. For classification purposes, at any level of taxonomy, soil surveyors usually first establish diagnostic horizons in the soil, and then make a conclusion about the taxonomic position of the soil. Laboratory analysis either confirms or disproves the field diagnosis, but soil division into horizons is the first step in soil survey anyway, being a basis for soil mapping. Thus, we can regard a soil map as a planar projection of the spatial distribution of complexes of soil horizons. Hence, soil mapping can be done as superimposition of the maps of the presence and absence of certain soil horizons. The presence of a complete set of horizons indicates the presence of a soil group X, the absence of one or several of them – some groups Y, Z etc. The process might seem more complex than a classical soil survey: the latter works with existing complexes of horizons, with soil profiles, which are extrapolated to a certain area. However, classical methods are not always effective for successful extrapolation of soil data. On the one hand, a soil profile is extrapolated to a soil polygon relying on the hypothesis of uniformity of soil formation factors; the boundaries where landforms, parent material, vegetation etc. change mainly delimit soil polygons (Hudson, 1992). Also, a methodology exists for establishing the limits of soil polygons using small soil pits, augering, and remote sensing data. On the other hand, many factors cannot be detected directly, e.g. ancient processes, such as paleocryogenesis, might form the soil mantle. Furthermore, many relations between soil forming factors and soil characteristics are still not well understood, and cannot be easily extrapolated. Consequently, some traditional soil maps are blamed for poor quality, mostly because soil limits do not correspond to reality. Thus, the use of geostatistical methods may help us to interpolate the presence and depth of soil horizons. Although geostatistics cannot replace soil surveys completely, it may be a useful tool for improving traditional soil mapping (Di et al., 1989; Warr et al., 2001).

An additional advantage of the use of geostatistics in soil survey is that it allows interpolation of quantitative characteristics – the horizons' depth. The depth of a particular soil horizon is often of major interest from a practical viewpoint. For example, the depth of the A horizon reflects the stores of nutrients in soil. In agriculture, the depth of the E horizon determines whether only A and E horizons would be included in the plough layer, or the material of the B horizon should also be included. Thus, in many countries, for example, in Russia, the depth of surface horizons is used as a diagnostic criterion in soil taxonomy at the lower level, and the polygons at detailed soil maps are separated according to the thickness of the A or E horizons (Rozanov, 1983; Krasilnikov, 2002). Correct soil diagnostics at lower levels of taxonomy is an important task in soil survey. The task is not so easy at it may seem. The depth of a particular soil horizon varies significantly in space, and often does not depend directly on easily observed external factors.

The objective of this study was to study the spatial variation of the presence and depth of soil horizons in three different forests in middle and northern taiga subzones.

A number of earlier studies illustrate high variability of soil horizons depth in various scales. Vazhenin et al. (1969) studied the variability of Albeluvisols, Greyic Phaeozems, and Chernozems in trenches. The study showed that the limits of the horizons had the most complex shape in the Albeluvisol profile, and the most smoothed outline – in the Chernozem profile. Fridland et al. (1969) studied the variation in the depths of the horizons of Chernozems in virgin steppe (Belgorod region). The most stable attribute was found to be the depth of the A horizon, less stable – the depth of (A+AC), and the least stable – the secondary carbonates depth. Also, Fridland (1976) studied the variability of soil properties in various elements of mesorelief in the Central Chernozemic Reserve, Kursk region. The depth of both the A and (A+AC) horizons increased from the drainage divide to the ravine slope. The depth of secondary carbonates leaching increased correspondingly. Zebarth et al. (2002) studied the relationship between landscape elements and soil characteristics in Canada. On the summit and shoulder of the hillslope Orthic Humic Podzols and Orthic Sombric Brunisols were found, while at the footslope there were Gleyic subgroups of the same great groups. The depth until the C horizon and until the underlying hard rock were found to have the strongest relation with landscape elements. The depth of the B horizon was the least at the backslope, and the highest at the footslope positions. The depth of the A horizon was the same at all the landscape elements, which was ascribed to the mixing of the upper horizons due to agricultural activities. Liski (1995) studied the variation of the organic F/H and mineral E horizon depths in Podzols in Southern Finland. The variation coefficients for F/H and E horizon depths were found to be 25 and 76%, respectively. The depth of horizons was 17% greater under the trees than in gaps. The greatest depth of both horizons was detected at a distance of 1-3 m from the trunk.

Traditional statistical methods are not always effective for managing spatially distributed data, thus, a number of researchers used geostatistical methods for the study of the spatial structure of soils, and for spatial interpolation of data. Blagoveshchenskii and Samsonova (2001) analysed the data on the depth of the A horizons, measured in three 20-m trenches made on sediment exposures of different age (40, 80, and 150 years). The medium depth of the A horizon significantly increased from 40 years-old sediments to 80 years-old ones, without any further significant increase. However, absolute variability increased throughout the soil development time range: the variation increased almost three times comparing the soils 40 and 150 years old. All the variograms were approximated by spherical models. The nugget constituted 1/5 to 1/3 of the whole variation. The nugget increased with soil age due to the increase of variability at the distances less horizontal than sampling resolution (1 m). The range was similar for all ages (15-20 cm). The authors showed that the fractal dimension of the boundary of the A horizon increases with soil age, and can be interpreted as an increase in the complexity of the boundary.

Qian and Klinka (1995) studied the depth of organic soil layers in three coastal forest ecosystems in British Columbia using kriging. The first plot was a Tsuga forest ca. 80 years old, after clear-cutting, with hemimor and lignomor as the dominant humus forms (Green et al., 1993). The second plot was a Tsuga forest with a well-developed grass floor, ca. 70 years old (after clear-cutting and consequent forest fire), with mor-moder as the dominant humus form. The third plot was an undisturbed juniper forest with a well-developed shrub and grass floor, ca. 450 years old, with leptomor and mull-moder as the main humus forms. The variograms for the depth of organic horizons were described well by spherical and exponential models. The residual variance (the percent ratio of nugget to sill) was as low as 0.2-14%. As the authors explained the phenomena, the surface horizons' depth was an easily measured property, thus the analytical error (which is a part of the nugget value) was not too great.

Liski (1995) used the method of variography to estimate spatial variation of the depths of the organic (F/H) and mineral (E) horizons. The residual variance was 29% for organic horizons, and 57% for the mineral one; the range was 1.7 and 2.6 m, respectively. The author concluded that the ranges reflected the effect of trees on the spatial distribution of the horizons (average distance between trees in the plot was 3 m). Additional analysis of cross-variograms confirmed also that the depth of the E horizon strongly depended on the organic C content in the layer 10-20 cm.

In many cases, analysis of anisotropic variograms can be a source of valuable information on spatial organization of soils. Di et al. (1989) used anisotropic variograms to analyse the distribution of the depth to gleyic mottling, the depth to gravel layer, and the depth of sandy loam or coarser surface sediments in Inceptisols and Entisols in New Zealand. The three studied characteristics were strongly anisotropic. The variogram for the depth of the surface sandy loam layer had the highest nugget value. The anisotropy of soil properties reflected gradual change in alluvial sediments and soil drainage in the direction perpendicular to the drainage channel. In the direction parallel to the drainage channel, the variation in soil properties was found to be insignificant.

There are a number of methods of interpolation, based on spatial correlation between observations for predicting values in unsampled points using data on one or several variables (Goovaerts, 1999; McBratney et al., 2000).

Bourennane et al., (1996, 2000) compared the use of universal kriging with other kriging methods: ordinary kriging, ordinary kriging with external drift, universal kriging with external drift, and linear regression. The study was made for the total depth of loose sediments, and for the depth of the silty clay layer in soil of a limestone plateau covered with Quaternary silt loam loesses and carbonate-free leached loams in Central France. The slope gradient, which correlated well with the depth of sediments, was used as the external variable. The results showed that the best prediction was made by the method of universal kriging with external drift. Also, expansion of the data set increased the precision of prediction by universal kriging, whereas the precision of prediction by linear regression remained the same.

Knotter et al. (1995) compared the use of kriging, co-kriging, and kriging combined with regression for spatial interpolation of the depth of loose sediments. Soil electric conductivity was used as the external variable. The depth of subsurface soil horizons is a property difficult to measure, and the authors recommended using additional information on correlated variables for spatial interpolation. The best prediction was made using kriging combined with regression. This method also had an advantage that it needed less parameters for modeling, and, thus, the calculation was facilitated.

The depth of a soil horizon is a continuous variable, in many cases having a positively skewed distribution. Positive skewness and abundant zero values make the use of ordinary kriging and logarithmic transformation of data impossible. However, precise estimation of soil properties requires information about whether a soil horizon is present or not. Warr et al. (2001) proposed using indicator kriging to find out the areas where the horizon was present, and then using ordinary kriging for horizon properties interpolation within the area. Precise estimation of the distribution of soil horizons using indicator kriging allows avoiding problems with data transformation, and enables delineation of the zones where the probability of the presence of horizons is higher than the probability of their absence.

Objects and methods

The study was made in the territory of the Karelian Republic, Northwest Russia (Atlas of Karelian Autonomous Soviet Socialist Republic, 1989). The study plots South Klimetski and Gomselga are situated in the subzone of middle taiga, and the plot Gabselga – in northern taiga (see Chapter 3 and Fig. 3.1).

All the study plots were established in hilly glacial and glaciofluvial landscapes with intensive tectonic discontinuities in pre-Cambrian crystalline rocks. The plots were characterized by the complexity of relief, the abundance of depressions occupied by lakes and peatlands, and the presence of bedrock outcrops.

The plot Klimetski was established under an old-growth (the age of the tree stand is more than 100 years) bilberry spruce forest with minor admixture of birch and aspen trees. The ground cover was represented by *Vaccinium myrtillus* (bilberry), *Oxalis* (wood sorrel), *Fragaria* (strawberry), *Convallaria* (lily-of-the-valley), *Rubus saxatilis* (stone bramble), *Vicia cracca* (tufted vetch), *Vaccinium vitis-ideae* (cowberry), *Equisetum sylvaticum* (wood horsetail). There were also some spots with no ground cover, and with abundant bedrock outcrops. The soil-forming material was mainly sandy and loamy sandy morainic till, in places – glaciolacustrine sands and loams. The soils were podzolized podburs (Entic Podzols), iron podzols (Rustic

Podzols), and humus-iron podzols (Haplic Podzols), with some spots of peaty gley soils (Histic Gleysols) and gravel soils (Leptosols).

The territory of the Gomselga plot used to be covered with spruce forests, which later were almost completely clearcut, and the territory grew occupied by secondary forests about 50 years old, where the dominant species were birch, aspen with admixture of pine and spruce. Undergrowth comprised pine, birch, aspen, rowan, willow, spruce and juniper. The ground cover was represented by *Vacccinium myrtillus* (bilberry), *Vaccinium vitis-ideae* (cowberry), *Rubus saxatilis* (stone bramble), *Convallaria* (lily-of-the-valley), *Dryopteris filix-mas* (fern), *Fragaria vesca* (strawberry), *Epilobium angustifolium* (rosebay willoherb), *Paris quadrifolia* (herb Paris), *Oxalis acetosella* (wood sorrel), *Trifolium pratense* (clover), *Sphagnum* sp. (peat moss), *Polytrichum commune* (hair cap moss). The soil-forming material was represented by silty sandy morainic till, and, to a lesser extent, by glaciolacustrine sands, loams and clays. The soils of the plot are diverse: iron-humus podzols (Haplic Podzols), podburs (Entic Podzols), raw-humus burozems (Dystric Cambisols), high-moor peat soils (Dystric Histosols), mud gley soils (Histic Gleysols), and sod-gley-podzolic soils (Dystric Planosols).

The plot Gabselga was situated in an uplifted ice-dividing hilly plain. About one-half of the total area of the plot carried a primary spruce forest 100-120 years old, with minor inclusions of birch. In undergrowth there were rowan, birch and juniper. On the surface, there were mainly *Vacccinium myrtillus*(bilberry) and green mosses, with less abundant *Vaccinium vitis-ideae* (cowberry), *Mayanthemum bifolium* and *Deshampsea coaespitosa*. However, secondary forests at various development stages occupied the other half of the area. The soil-forming material was loamy sandy morainic till; diorite underlay the till at a depth of 1.5-2.0 m. The soils were relatively uniform: iron-humus podzols (Haplic Podzols) and high-moor peat soils (Fibric-Dystric Histosols) occupied almost the entire area of the plot.

We studied spatial variability of various soil horizons, using the data of soil surveys of 15 to 20 km^2 from each plot. At each point we recorded the depth of O, A, E, and B horizons. No subdivision of B horizons (e.g. spodic, cambic, argic etc.) was done, and the presence of additional characteristics such as gleyic and stagnic properties, was not taken into account. At the Klimetsky plot, we recorded data from 159 profiles, at Gomselga – from 162, and at Gabselga – from 138 profiles. The scheme of data collection is presented in Fig. 7.1.

The distribution of sampling points was not uniform, and showed certain clustering. This clustering was due to two main reasons. First, there are abundant rock outcrops at all the sites (in these landscapes in places rock outcrops occupy more than 50% of the total area). No profiles were made, of course, at these outcrops. Second, the sampling density depended on the complexity of the soil cover. In places we found a more complex situation, and had to make additional profiles there.

We studied the spatial variation of soil horizons depth using geostatistical meth-

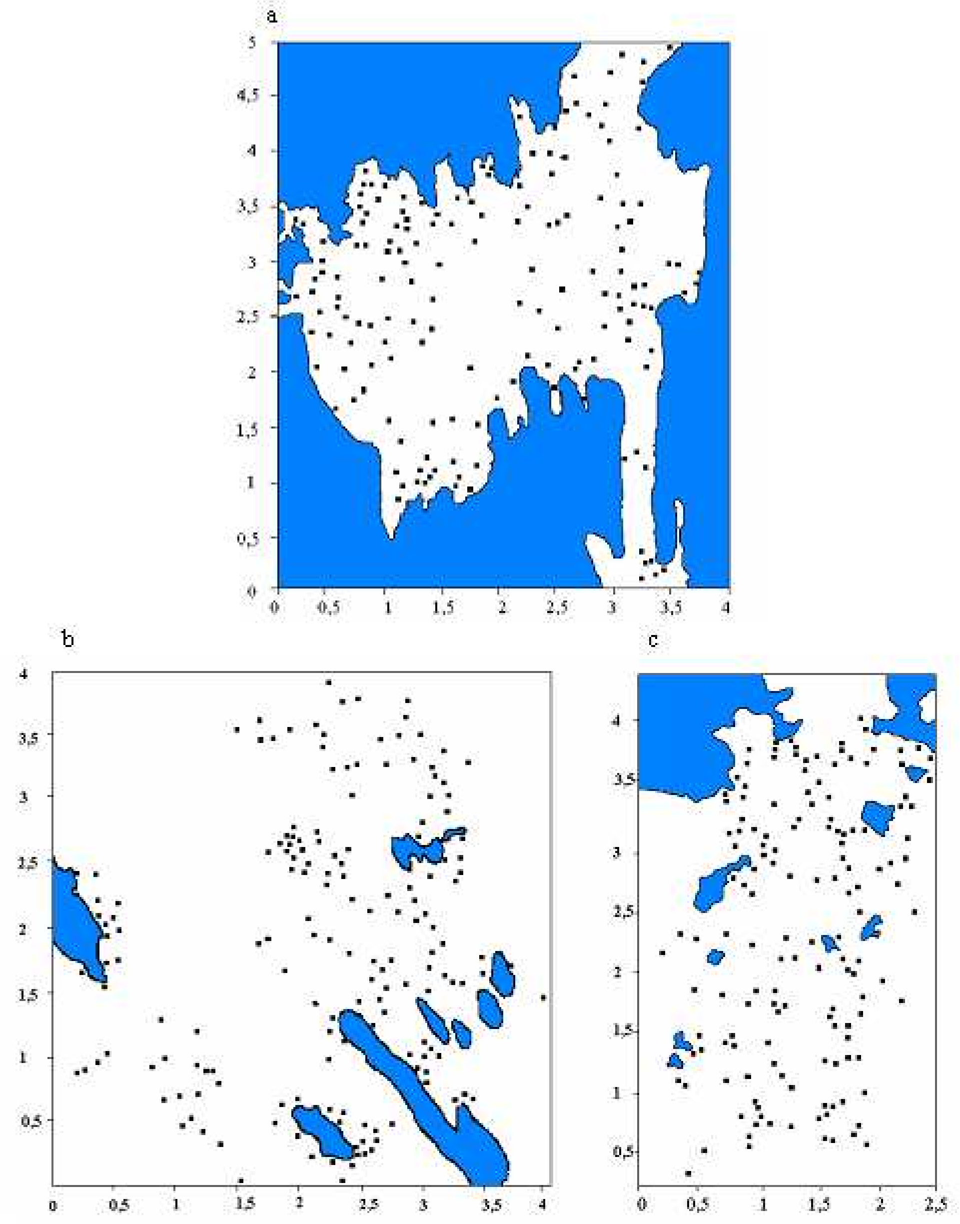

Figure 7.1: Sampling points in the study plots Klimetski (a), Gomselga (b), and Gabselga (c). Hereinafter, the grid scale is expressed in kilometers from the coordinate (0,0).

ods (Burgess and Webster, 1980; Jongman et al., 1995; Kuzyakova et al., 2001).

Ordinary and indicator kriging were used to map soil horizons. *Indicator kriging* (Demianov et al., 1999; Lark and Ferguson, 2004) is a non-parametric non-linear estimator, which allows modeling of spatial correlation for various levels of values even if the data variability is high. Indicator kriging is identical to ordinary kriging made for *indicator variable*s, derived from initial data in the following way:

$$I(\mathbf{x}, \mathbf{z_c}) = \begin{cases} 1, z(\mathbf{x}) \leq \mathbf{z_c} \\ 0, z(\mathbf{x}) > \mathbf{z_c} \end{cases} \tag{7.1}$$

Indicator estimations are the evaluations of the probability that $z\ (\boldsymbol{x}) \leq z_c$. The derived functions of distribution of the estimations allow making maps of probability and risks: evaluation of the probability of exceeding a certain value, or evaluation of the values exceeded with a given risk level, etc. Usually, indicator kriging is used for mapping the probability of exceeding critical concentration levels for radionucleids (Demianov et al., 1999) and heavy metals (Goovaerts et al., 1997), or, alternatively, the deficit of nutrients in soils (Lark and Ferguson, 2004).

The first step of indicator kriging is the change of ordinary variables into corresponding indicator variables according to equation (7.1).

The next step is finding the characteristics of spatial distribution of the indicator. To do that, indicator semivariance is used, which is identical to ordinary semivariance and is calculated in the following way:

$$\gamma(\mathbf{h}, \mathbf{z_c}) = \frac{1}{2N(h)} \sum_{j=1}^{N(h)} \{I(\mathbf{x_j}, \mathbf{z_c}) - I(\mathbf{x_j} + \mathbf{h}, \mathbf{z_c})\}^2 \tag{7.2}$$

where $I(\mathbf{x_j}, \mathbf{z_c})$ and $I(\mathbf{x_j} + \mathbf{h}, \mathbf{z_c})$ are indicators in points $\mathbf{x_j}$ and $\mathbf{x_j} + \mathbf{h}$, divided by the lag distance h, and $N(h)$ is the number of pairs divided by this lag. The value $\gamma(\mathbf{h},\mathbf{z}_c)$ is the measure of frequency of the event that two z values divided by the lag distance h are found on different sides of the limit value $\mathbf{z_c}$. In other words, it is the measure of frequency of changes between two classes divided by the limit level z as a function of distance. The higher the value $\gamma(\mathbf{h},\mathbf{z}_c)$, the less is the spatial dependence between low and high values (Goovaerts et al., 1997; Goovaerts, 1998).

For a set of indicator semivariances with different lags h it is possible to find one of the standard continuous models used for approximating variograms (McBratney and Webster, 1986). The indicator function can be estimated for a point $\mathbf{x}$ using ordinary kriging for neighboring data transformed by the indicator.

The advantage of indicator kriging is that it can be used not only for quantitative variables, but also qualitative data, which have a limited quantity of states.

At the first stage of our study, we used indicator kriging to delineate the areas of the presence of horizons. To do that we used an additional indicator variable:

$$I(\mathbf{x},\mathbf{0}) = \begin{cases} 1, h(\mathbf{x}) = 0 \\ 0, h(\mathbf{x}) > 0 \end{cases} \tag{7.3}$$

where $h(\mathbf{x})$ is the depth of a horizon in point $\mathbf{x}$. Additional "virtual" points with zero values, and corresponding indicator variables located in the coordinates of lakes, rock outcrops, and other non-soil bodies were added to the data obtained from sampling points.

The indicator variables were subjected to ordinary kriging. Then experimental semivariograms were calculated, and corresponding models were approximated using the least squares method.

For calculating and plotting the variograms we used the software Excel (Microsoft) and Variowin 2.2. (Pannatier, 1996), and for kriging procedure and drawing maps of the spatial distribution of predicted values – GenStat (2002) (evaluation version) software and Surfer 6.02 (Copyright © 1993-1996, Golden Software, Inc.).

Results and discussion

The statistical parameters related to spatial variability of the depth of soil horizons (Dmitriev, 1995) are presented in Table 7.1.

One of the main parameters of data variability is the coefficient of variation. For example, a 25% coefficient of variation is regarded as the limit dividing uniform and non-uniform areas (Rosanov, 1983). Thus, of all the horizons in our plots varied in depth, and the degree of variation increased in the following sequence of horizons: O – A – E – B. According to the traditional point of view, upper soil horizons have the highest variability, and the parent material – the lowest one. Rosanov (1983) concluded that spatial variability is a soil feature that increases gradually with time, and can be considered to be a result of pedogenesis. Our data generally agreed with these ideas, but the depth of organic horizons appeared to be less variable, than that of mineral surface horizons (A and E horizons). The data might seem strange, given that previously the spatial variability of the organic horizon depth in the study area was reported to be high (Solomatova et al., 1999). Yet, the latter results were obtained from small study sites (1 to 2.5 ha), and in the present study a different scale was used, and the situation was different. We believe there are two main reasons for the relatively low spatial variation of the depth of the O horizon in this study. First, the forest floor is a continuous layer in forest ecosystems, thus covering the whole territory except of non-soil bodies (water and rock outcrops) and Histosols, unlike the A and E horizons, which were discontinuous in the studied landscapes, and their variability increased due to the presence of zero values. Second, in the studies conducted in small plots the litter depth was measured precisely at every point, while the present study employed morphological descriptions of soil profiles. In soil surveys, the variability of forest litter within the soil profile is in most cases neglected, and researchers use averaged data.

Table 7.1: Summary statistics for the depth of soil horizons

Plots	Statistical values	O	A	E	B
Klimetski	Number of profiles	159	159	159	159
	Presence of horizons	131	92	70	132
	Max and min values	3÷20	1÷38	1÷36	19÷83
	Medium value	9.86	12.04	13.76	47.04
	Lower quartile	8.00	7.00	8.25	38.00
	Median	10.00	10.00	12.00	47.50
	Upper quartile	12.00	15.00	19.50	54.25
	Moda	10.00	10.00	8.00	50.00
	Variation	10.53	60.97	50.97	146.53
	Deviation	3.25	7.81	7.14	12.11
	Variation coefficient	32.91	64.83	51.90	25.73
	Skewness	0.26	1.75	0.81	0.37
	Kurtosis	-0.11	3.24	0.77	-0.004
Gomselga	Number of profiles	162	162	162	162
	Presence of horizons	150	128	63	145
	Max and min values	1÷17	1÷30	2÷24	15÷80
	Medium value	7.15	9.52	11.90	40.97
	Lower quartile	5.00	5.00	8.00	30.00
	Median	7.00	8.00	12.00	40.00
	Upper quartile	9.00	11.25	15.00	50.00
	Moda	7.00	10.00	20.00	40.00
	Variation	9.20	33.56	30.22	161.23
	Deviation	3.03	5.79	5.50	12.70
	Variation coefficient	42.44	60.88	46.17	31.00
	Skewness	0.78	1.32	0.11	0.61
	Kurtosis	0.79	1.81	-0.91	0.19
Gabselga	Number of profiles	138	138	138	138
	Presence of horizons	104	20	97	98
	Max and min values	2÷17	2÷20	1÷25	25÷80
	Medium value	8.95	7.95	12.18	46.56
	Lower quartile	6.00	5.00	10.00	36.25
	Median	8.00	6.50	11.00	45.00
	Upper quartile	10.00	10.00	15.00	55.00
	Moda	10.00	5.00	15.00	40.00
	Variation	11.33	19.94	24.75	151.84
	Deviation	3.37	4.47	4.98	12.32
	Variation coefficient	37.60	56.18	40.86	26.46
	Skewness	0.43	1.23	0.20	0.39
	Kurtosis	-0.39	1.41	-0.53	-0.45

The indicator variables were subjected to ordinary kriging. Then experimental semivariograms were calculated, and corresponding models were approximated using the least squares method (Figs. 7.2 and 7.3). The variogram parameters are presented in Table 7.2.

Table 7.2: The parameters of indicator variograms for the depth of soil horizons

Plot	Horizon	Model	Nugget	Sill	Range, m	Period, m	Nugget/sill, %
Klimetski	O	periodic	0.156	0.235	-	4290	-
	A	periodic	0.116	0.180	-	4335	-
	E	periodic	0.094	0.147	-	4617	-
	B	periodic	0.151	0.236	-	4541	-
Gomselga	O	exponential	0.045	0.246	750	-	18.3
	A	exponential	0.030	0.264	810	-	11.4
	E	exponential	0.020	0.196	750	-	10.2
	B	exponential	0.066	0.255	990	-	25.9
Gabselga	O	exponential	0.111	0.255	870	-	43.5
	A	spherical	0.009	0.097	270	-	9.3
	E	exponential	0.111	0.255	720	-	43.5
	B	exponential	0.108	0.255	720	-	42.4

For the Gomselga and Gabselga plots, the variograms of the depths of all the horizons (except of the A horizon in the Gabselga plot) were well described by exponential models with a range of 720 to 990 m.

For the Gabselga plot, indicator variograms for the horizons O, E and B had relatively high nugget values (42-43%). It means that the shifts of zones with the presence and absence of these horizons occurred at distances less than 100 m (the lag distance used for experimental variograms). The parameters of variograms were almost the same for different soil horizons; it might mean that the patterns in the spatial distribution of horizons were the same. The phenomenon was explained by low soil diversity of the plot, reported previously (Krasilnikov et al., 2000). Two soil groups, Podzols and Histosols, were the most abundant ones in the plot. It is natural that in Podzols O, E, and B horizons were always present together by definition. Our general conclusion was that a similar spatial structure for different soil horizons characterizes a monotonous soil cover (uniform, or a mosaic with few components). If patterns in the spatial distribution of soil horizons differ, one can expect more a complex soil combination.

For the Klimetski plot, the variograms had a pseudo-periodic character (increase in variance, followed by its decrease with increasing lag values). We ascribed this fact to the "island effect": the plot was situated on a peninsula, and was almost surrounded by water. The period of the variogram was equal to the width of the peninsula. It was just a mathematic effect of the zero values included for the water-covered area. This effect should be considered in the study of any plots surrounded

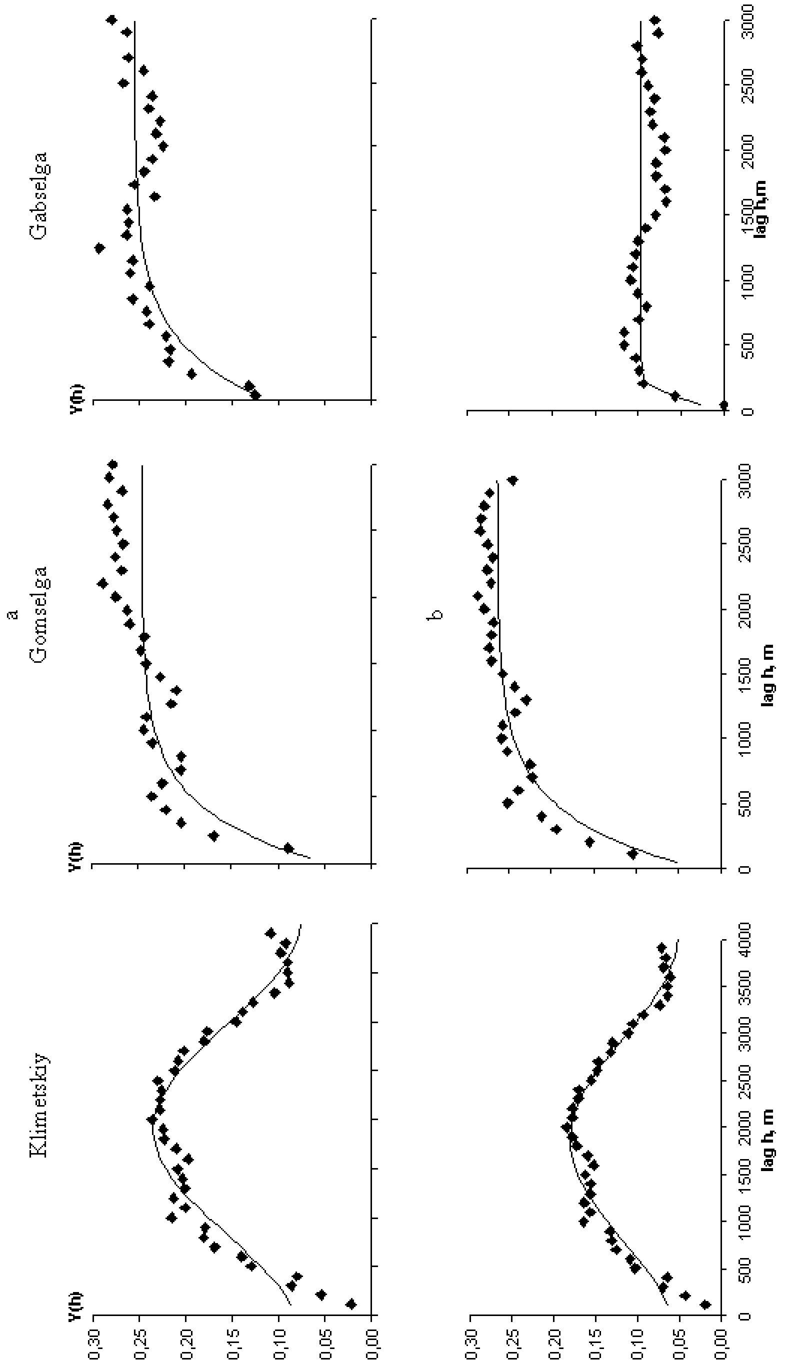

Figure 7.2: Indicator varigrams for the depth of organic horizons (a) and the A horizon (b). Hereinafter, the dots indicate the semivariance, the lines are the corresponding models.

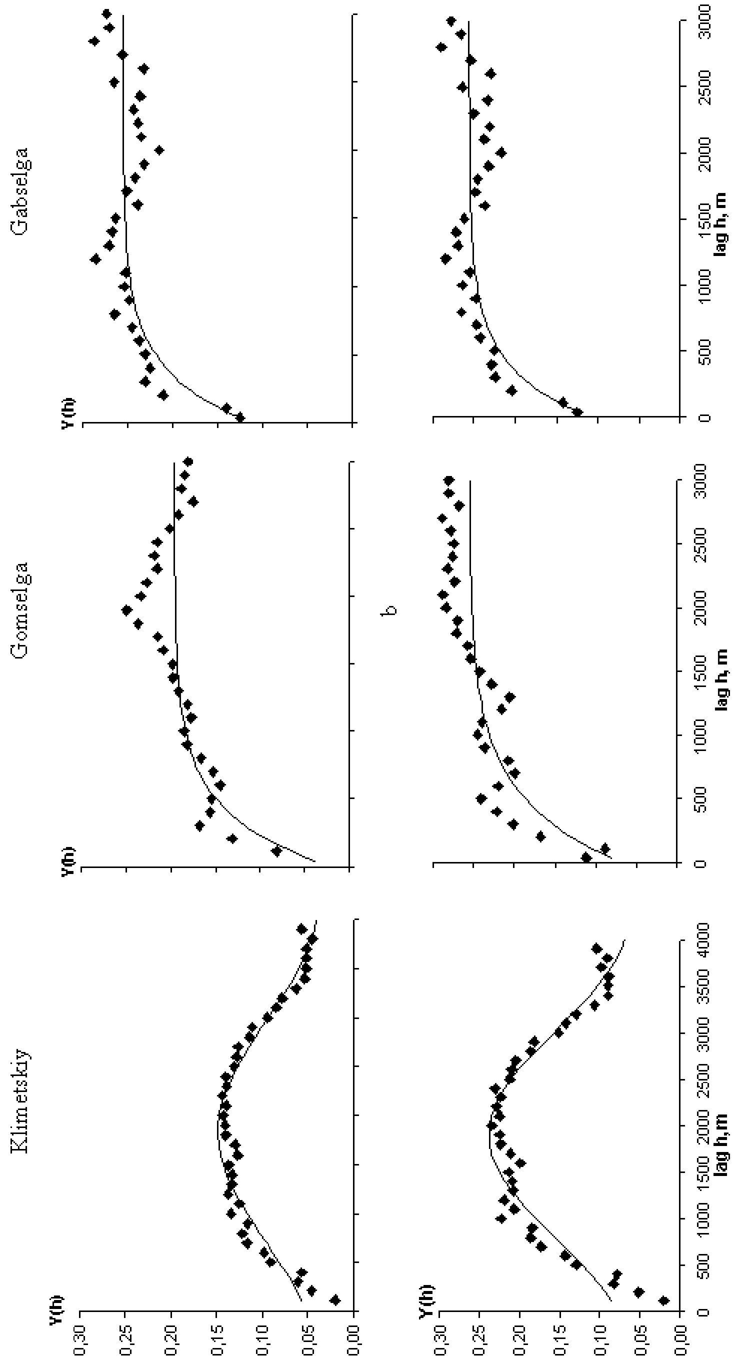

Figure 7.3: Indicator varigrams for the depth of the E (a) and B horizon (b). Points – experimental values, line – model

by non-soil bodies. May be, we can consider eliminating these values from the data set. Lower sill values for A and E horizon depths resulted from the discontinuity of these horizons: in most places their depth was equal to zero.

Using indicator variograms as the basis, we generated probability maps of the presence of soil horizons (Figs. 7.4–7.6).

The B horizon and forest litter were distributed relatively uniformly in all the plots. In contrast, the E horizon in the Gomselga plot, the A horizon in the Gabselga plot, and both of the above horizons in the Klimetski plot were present as rare spots. The comparison of probability maps and sampling schemes showed that most single polygons in the probability maps included 2 to 35 sampling points. This number was insufficient for kriging. Thus, for mapping the depths of soil horizons we recommend using medium values or, alternatively, the reverse distance method or any other deterministic or regression method (Laslett et al., 1987; Savelieva et al., 1999).

Further probability maps can be used in soil survey for making classical soil maps. Combining the probabilities of the presence of each soil horizon one can predict the presence of certain soil groups in every point, thus making the limits of soil polygons more precise. The maps can also be verified using disjunctive kriging (Webster and Oliver, 1989; VonSteiger et al., 1996).

This method allows including a range of limiting values, and, thus, dividing soils into polygons according to the classes based on the depth of horizons (deep, medium, shallow, etc.).

The spatial variability of the depth of soil horizons was estimated using variography. The parameters of model variograms are presented in Table 7.3.

Table 7.3: Parameters of model variograms for the depth of soil horizons

Plot	Horizon	Model	Nugget	Sill	Range, m	Period, m	Nugget/sill, %
Klimetski	O	spherical	3.41	10.23	390	-	33.3
	A	-	-	-	-	-	-
	E	-	-	-	-	-	-
	B	spherical	99	144	240	-	68.8
Gomselga	O	spherical	6.30	9.40	900	-	67.0
	A	double spherical	6.82	32.53	210 3000	-	20.6
	E	-	-	-	-	-	-
	B	spherical	128	169.60	3000	-	75.5
Gabselga	O	spherical	7.44	11.76	180	-	63.3
	A	-	-	-	-	-	-
	E	periodic	21.19	24.28	-	2036	-
	B	periodic	151	182.4	-	4162	-

The parameters of the models for different soil horizons and different plots showed a range of values (Fig. 7.7; Table 7.3).

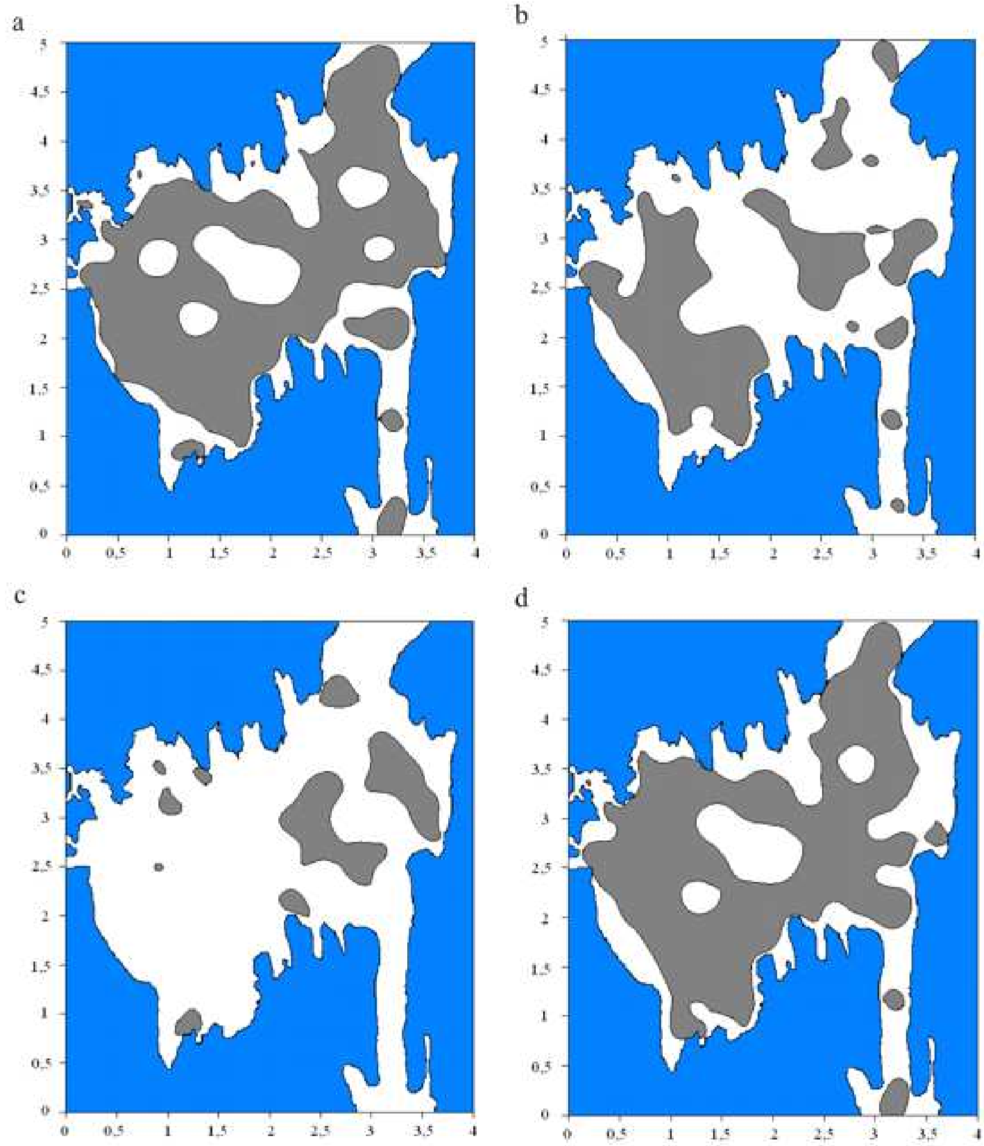

Figure 7.4: Probability maps of the presence of the horizons O (a), A (b), E (c) and B (d) in the Klimetski plot. Grey colour indicates the zones where the probability of the soil horizons' presence is more than 70%, blue - water bodies

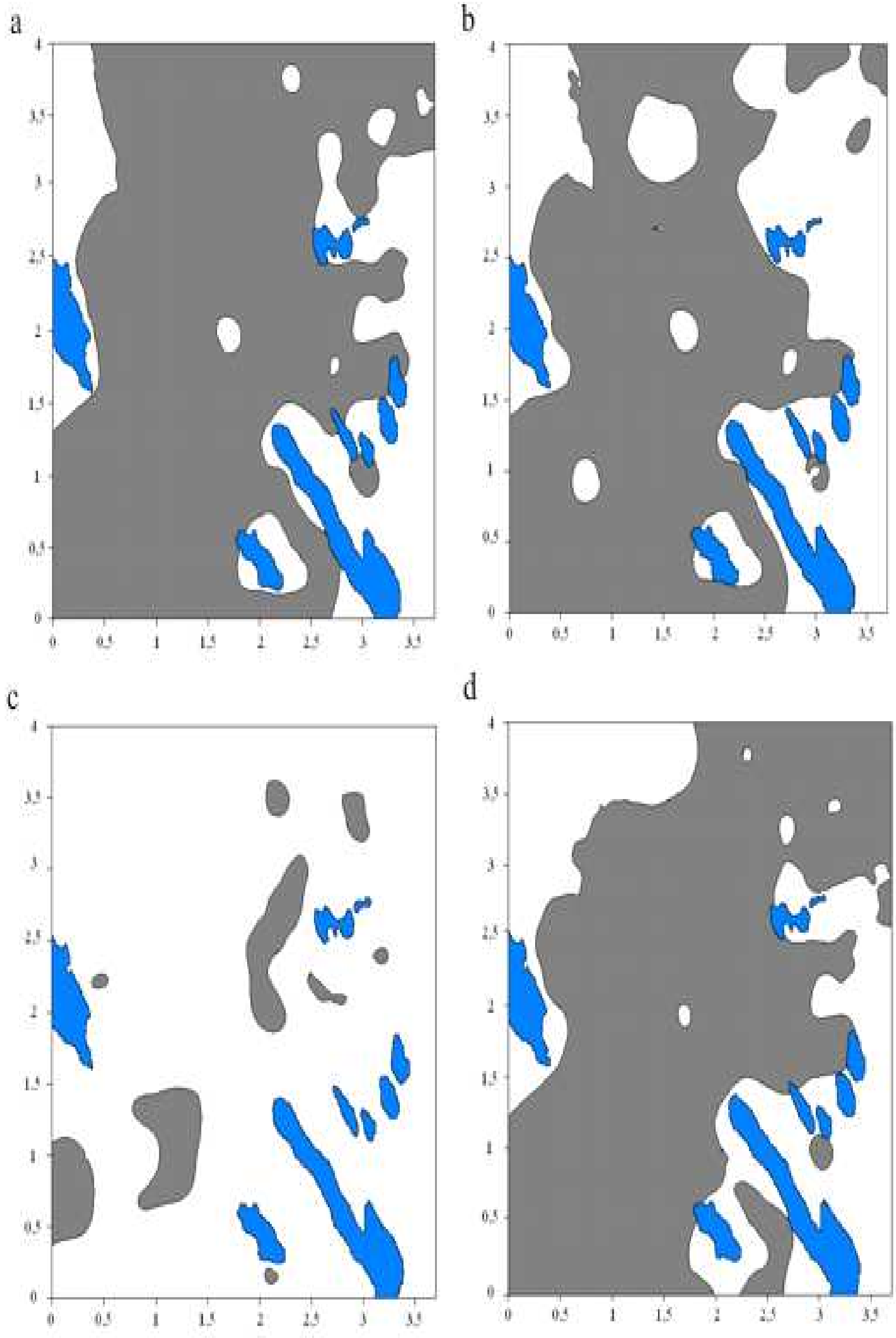

Figure 7.5: Probability maps of the presence of the horizons O (a), A (b), E (c) and B (d) in the Gomselga plot. Grey colour indicates the zones where the probability of the soil horizons' presence is more than 70%, blue - water bodies

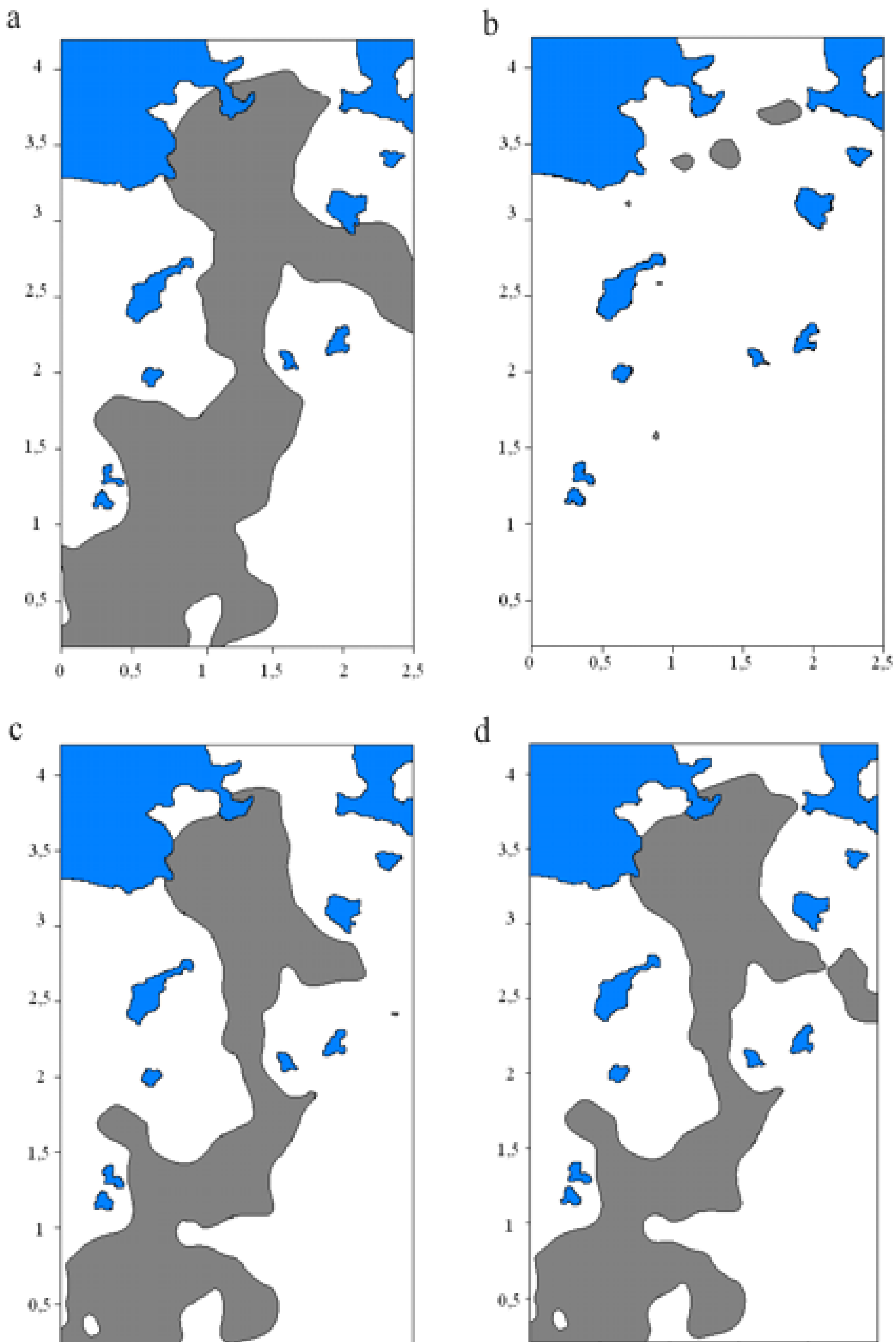

Figure 7.6: Probability maps of the presence of the horizons O (a), A (b), E (c) and B (d) in the Gabselga plot. Grey colour indicates the zones where the probability of the soil horizons' presence is more than 70%, blue - water bodies

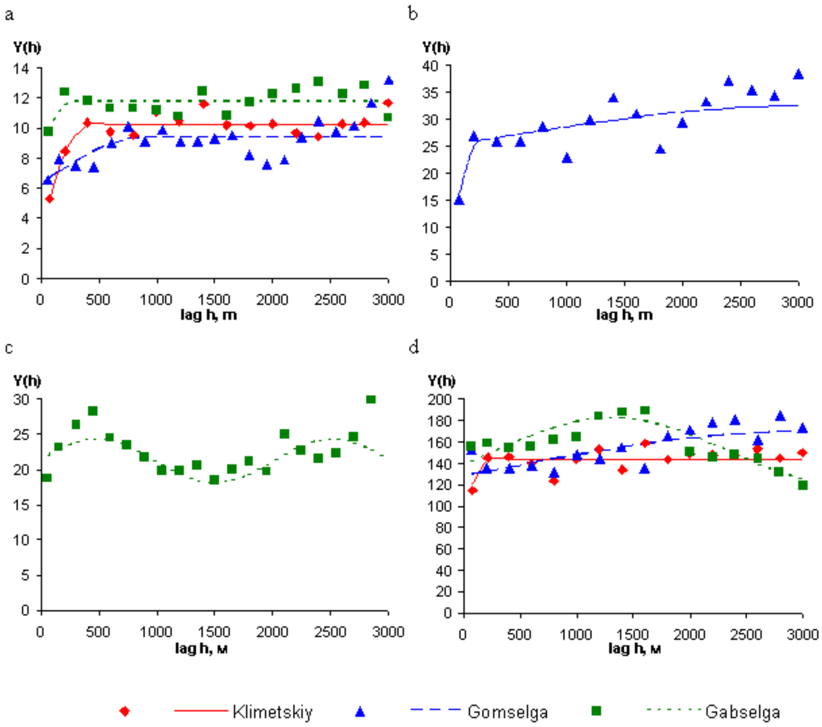

Figure 7.7: Variograms for the depth of the horizons O (a), A (b), E (c), and B (d)

The forest floor in the Gabselga plot was mainly randomly distributed; this fact was evidenced by a low range and high nugget values. The variation occurred mainly at distances less than 100 m, and deviations from medium values were rather strong: the sill of the variogram for forest floor thickness was the greatest in this plot. In the Gomselga plot, the variogram for the O horizon also had a high nugget value, but the range was also high. It means that, in addition to variation at short distances, spatial correlation existed until a distance of 900 m. In the Klimetski plot, the nugget and range values were significantly lower. Spatial correlation was observed at distances less than 390 m. The difference in the spatial structure of the forest floor depth was interpreted in the following way. The plots Gabselga and Gomselga were disturbed by clearcutting, and the forest floor has not completely restored in places. Also, clearcutting has locally led to secondary paludification, and, consequently, the thickness of the organic horizon is higher there. These randomly distributed factors lead to an increase in nugget values. The spatial correlation was higher in the Gomselga plot because the vegetation cover and forest floor have recovered in most of the site.

The A horizon was present in a significant area only in the Gomselga plot. The variogram was best approximated by a double spherical model. It means that at least three levels of spatial organization could be found there. The first level was the nugget-variation. It was rather low (the least nugget value detected for all the horizons in all the plots). The second level was variation at a distance less than 210 m. The highest variation in the thickness of the A horizon was found within this distance. The third level was variation at a distance less than 3000 m. Such a wide range means that spatial correlation between the points existed throughout the plot. Such a distribution indicates the presence of a “nested structure”. In real geographical space, it means that within some areas of a medium linear size of about 200 m there is significant variation in the depth of the A horizon. At a distance of about 3000 m the landscape changes, one can find other sites where variation is also high, but the absolute values of the variation range are different.

The E horizon was present in a significant area only in the Gabselga plot. Changes in the horizon depth there had a periodic nature, with a period of about 2000 m. The maximum values of variation were found at distances of 500 and 2500 m. This periodicity was ascribed to regular changes in the albic horizon thickness according to the relief: its depth on the summit of the hills is lower than at foot-slopes.

The variograms for the B horizon had high nugget values. We think it was mainly due to subjective error in the horizon depth determination. Most surface horizons had sharp lower boundaries, and their depth could be determined with a 1-3 cm precision. In contrast, the B horizon in most places had a gradual transition to parent material, and the precision of its determination was about 10 cm. In the Gabselga plot, the variogram for the B horizon had a periodic character, as for the E horizon, but the period was twice bigger (4160 m). Analysis of the relief and soil cover enabled us to propose a hypothesis explaining this periodicity. The territory had hills and ridges of different altitude. We purported that only the highest ridges affected the depth of the B horizons, while the E horizon, more sensitive to soil-forming factors, depended on all landforms.

Conclusions

The study of three forested areas in Southern and Middle Karelia showed that the depth of all soil horizons had high spatial variability. The variability increased in the sequence of horizons B-O-E-A.

When the variability of data is high, the best method for spatial interpolation is indicator kriging, which allows creating probability maps. Indicator kriging for the presence and thickness of the horizons O, A, E and B in the three plots showed that the change of the zones of absence/presence of the horizons occurred at distances of 700–900 m.

Similar spatial structure of different soil horizons, estimated using indicator kriging, testifies to low pedodiversity of the site.

Ordinary kriging of the forest floor depth revealed low spatial correlation of data in disturbed landscapes. After the original forest type restored, spatial coherence increased, and was the highest in the old-growth spruce forest.

Ordinary kriging of the thickness of the A horizon showed a “nested structure”: it means that within the plot there were blocks with different ranges of variation of the horizon depth, and internal variability within every block was high.

Ordinary kriging of the horizons E and B showed periodicity in the data distribution, and the period for the B horizon depth distribution was twice bigger than for the albic horizon. We hypothesized that intermediate low ridges did not affect the depth of the B horizon, but affected the thickness of the E horizon.

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Chapter 8

Spatial variability of soil hydro-physical properties: A case study in Herceghalom, Hungary

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Abstract [1]

Soils developed on loess material are the most homogeneous and best fertile agricultural areas in Hungary. However, even on these homogeneous areas the crop development and productivity is spatially variable. In a case study in Herceghalom – about 50 km NW from Budapest – spatial variability of different soil properties was studied in order to establish their potential effect in crop productivity. A regular grid sampling of the 1500 ha large-scale farm was used to establish the spatial validity of a point sample, and to generate the territorial pattern of the different soil properties and characteristics as water-retention values, particle-size fractions, organic matter and lime content, etc. The standard geostatistical methods were used to describe the spatial behaviour of the studied soil properties. Soil water content dynamics and soil water balance elements of two reference soil profiles were simulated for the vegetation periods of two meteorological years. Measured soil water content dynamics were used as references. Two different approaches – a regression technique and the scaling concept, (assuming geometrical similarity of soil structural elements) - were applied to perform spatial extension of the point simulation models. The scaling concept is commonly used in natural sciences to derive quantitative characteristics for a system, the properties of which can not be directly measured due to some (distance, size etc.) difficulties. The concept of scale is applicable if a system is represented proportionally by another system. Assuming the same spatial validity of the simulated evapotranspiration values, maps, indicating the spatial pattern of the cumulated evapotranspiration values as well as the transpiration ratio of the different crops were produced. Beside the area pattern of different soil properties of the Chernozem soil

[1] This chapter is an extended and improved translation of the text published in Russian in "Geostatistics and Soil Geography", Moscow, Nauka Publ., P. 43-66.

cover the simulation results showed that the spatial variability of the soil hydrophysical properties appears in the soil-crop water balance, and they affect the plant activity when the climatic conditions are dry and unfavourable.

Introduction

In Hungary Mollisols, developed on loess parent material are the best for agricultural utilisation. In agricultural practice they are handled and considered as homogeneous in most of the cases. Spatial variability of soil properties may appear in yield variation within a single field even in areas considered homogeneous from the soil survey point of view. Soil spatial distribution is represented by the soil patch pattern on soil maps. The identification of the pattern's border is based on reference soil profiles, assuming, that borders also mark the 'spatial pattern' of the soil. In many cases, like in precision agriculture practice, the within pattern spatial heterogeneity of soil properties has to be handled. The level of heterogeneity within the soil pattern depends on the examined soil property. Upchurch et al. (1988) studied the spatial variability of main soil properties using data, measured from soil samples, taken from different locations of a soil unit, identified on the soil map as homogeneous. The coefficient of variation (CV) of the studied soil properties ranged between 7 (bulk density) and 75 (saturated hydraulic conductivity). Wösten et al. (1985) found, that the CV of the potential amount of plant available water (PAW) is much lower, than that of the soil properties, used for calculation of the PAW. This indicates that the spatial variability of soil properties is different for basic and derived soil properties.

Effects of various sources of soil heterogeneity on the annual or long-term average soil water budget appear to be markedly different (Kim, 1995). Simulation models are tools for analysing the water regime with respect to physical properties of soils (e.g. Majerčák and Novák, 1994; Djurhuus et al, 1999). Simulation models, when used at field scale, have to be up-scaled from the point valid soil profiles using geostatistical methods (Van Meirvenne et al, 1995; Tóth and Kuti, 2002), or effective hydraulic parameters (Smith and Diekkrüger, 1996). Use of effective hydraulic parameters reduces the number of simulations significantly, but interprets the whole field as an equivalent soil profile. Disadvantage of this approach is that it does not reflect the spatial pattern of the soil water balance elements.

Our purpose was to analyse the differences of the soil water budget of a Mollisol due to spatial heterogeneity of soil hydraulic properties (soil water retention characteristics (SWRC) and soil hydraulic conductivity function). Since individual soil physical properties influence crop yield in different ways and in different extents, we decided to integrate their influence by simulating the soil water balance and to use transpiration as a crop yield indicator. We assumed that the field is composed by a set of one-dimensional non-interacting soil profiles each of them is represented by a set of soil hydraulic functions. The SOIL (Jansson, 1996) and SWAP (Soil-Water-Plant-Atmosphere) (Van Dam et al, 1997) soil water and heat dynamics simulation models were applied for soil water regime simulations, while regression and scaling techniques were used for spatial extension of the point models.

Materials and methods

Experimental site

The field studies were conducted on a Mollisol, formed on loam texture loess material at Herceghalom, Hungary (50 km W from Budapest). The investigation area belongs to the Herceghalom State Farm with an area of about 15 km^2 (1500 ha), with a moderately undulating relief (130-200 m above the see level).

The land use types in the study period were corn (498 ha), winter wheat (485 ha), alfalfa (150 ha) and grass (140 ha). The spatial variability of soil physical properties, caused probably by moderate wind and water erosion as well as by differences in land use, was mainly expressed in the cultivated soil layer. Two representative soil profiles, corresponding to the main land use types of corn and winter wheat were chosen. Description of the soil profiles was given in (Rajkai et al., 1997).

Soil sampling and analysis

Sampling of the reference soil profiles

Disturbed and undisturbed (100 cm^3) soil samples were taken from the genetic soil horizons of the representative soil profiles. The locations of the representative soil profiles were chosen based on the results of a reconnaissance sampling (Kertész and Tóth, 1994) and in-situ investigations of soil properties. Undisturbed soil cores of 5 cm length and 5.5 cm diameter were carefully trimmed, wrapped in plastic, and stored in refrigerator of 4^{o}C before analysis. The disturbed soil samples were used to determine the particle size distribution by the pipette method (Buzás, 1993). From the undisturbed cores, bulk density and soil water retention data were determined. Thus, soil water content was measured at pF values 0.0, 0.4, 1.0, 1.5, 2.0, 2.3 and 2.7 according to Várallyay (1973) and at pF values 3.4 and 4.2 on disturbed soil samples by the pressure membrane method (Várallyay, 1973). Soil water retention data were expressed in terms of volumetric water content using the bulk density of the sample cores for the conversion. From the undisturbed cores, bulk density and soil water retention data were determined.

Spatial soil sampling programme

A *preliminary* (reconnaissance) sampling, data and variogram analyses were performed in 1991 in order to work out the proper sampling strategy. The preliminary sampling consisted of two parts:

Taking soil samples from 64 points of an equidistant grid that covered the whole study area. The orientation of grid was nearly NS-EW, the distance between the grid points was 425 m.

Sampling the soil at 5 places along 2 transects in the NW-SE and NE-SW directions for a more precise calculation of variogram's parameters. Both transects had 4 sampling points, with the following distances from the main point: 25, 50, 100 and 200 m for the NW-SE transect and 35, 70, 140 and 280 m for the NE-SW transect. Two short additional transects were sampled in one of the cases. The distances between the main points and the sampling points were 5, 10, 15 and 20 m in order to find out the possible existence of spatial structure at finer scales.

The disturbed and undisturbed samples were taken from the topsoil (5-10 cm) layer. Soil bulk density, texture and soil water retention characteristics were determined, using the same methods as in case of samples, taken from the reference soil profiles.

The main purpose of the *representative* sampling, carried out in 1992 was to obtain data for the detailed farm-scale mapping of the selected soil physical properties of the study area. The 425 m long gridlines, used for soil sampling in 1991, were shortened into halves by 153 new sampling points such, that the distance between the soil sampling points became 212 m. Further division of the sampling distance into halves (with a sampling distance of 106 m) was performed on the 1/6 of the study area by taking additional 126 samples. Besides we took soil samples from 30 randomly selected locations to estimate the accuracy of the maps. The sampling points are shown in Fig. 8.10.

The soil sampling consisted of taking disturbed and 100 cm^3 undisturbed soil samples from the upper 5-10 cm soil layer at 448 locations. Considering the soil development in the study area, the subsoil was assumed to be homogenous. Soil properties, determined from the collected samples were similar to those, measured for the genetic soil horizons of the representative soil profiles. Besides the sampling, the elevation categories (hilltop, slope and valley) were recorded.

A spatial dataset consisting of geographical coordinates and soil physical properties of 448 measurement points was created to characterise the soil variability of the farm area.

Geostatistical analysis

Analysis of variance was applied to examine the effect of elevation and land use differences on the selected soil physical properties. We used the theory of regionalized variables to investigate the spatial variability of soil physical properties (Matheron, 1971). The semivariance function γ(h) is equal to half the expected squared difference between values at locations separated by a given lag and used to express spatial variation (Journel and Huijbregts, 1987). The GEO-EAS (1991) and GeoPack (Yates and Yates, 1990) geostatistical software were used to calculate the semivariogram function model fitting and to perform the spatial interpolation using punctual kriging. The Gaussian, spherical and exponential models were explored as models to fit the semivariogram functions for the selected soil physical properties. Cross-validation procedure was used to test the adequacy of the selected semivariogram models applying kriging. Punctual kriging was used to estimate values of soil physical properties at the unsampled locations.

Field measurements

Volumetric soil water contents were measured at the representative soil profiles up to 140 cm depth in 10 cm resolution. The measurements were performed 7 and 10 times in 1993 in soil profiles with wheat and corn, respectively and 12 times during the vegetation period of 1994. The soil water content measurements were performed by a BR-150 capacitive probe developed in the RISSAC (Andrén et al., 1991; Várallyay and Rajkai, 1987).

The near-saturated hydraulic conductivity of the soil surface (Rajkai et al., 1993; 1997; Jarvis et al., 2002) was determined next to the representative profiles by a tension disc infiltrometer (Ankeny et al., 1988) at -3, -6 and -12 cm tensions. The saturated hydraulic conductivity of the soil matrix was defined by the extrapolation of the exponential function, fitted to the measured conductivity values (Ankeny et al., 1988).

Evaluation of the soil water content dynamics

Application of the SOIL simulation model

The SOIL model represents, in one dimension, the water and heat dynamics in a layered soil profile covered with vegetation. As the solution to model equations is performed with a finite difference method, the soil profile is divided into a finite number of layers. Compartments for intercepted water and surface pounding are included to account for processes at the upper soil boundary. A detailed technical description of the model is presented in Jansson (1996).

Since deep groundwater table (> 5 m) is characteristic in the study area, only the unsaturated part of the soil was dealt with. Calculations were based on partial differential equations describing flows in the soil profile and are based on an extension of Richard's equation, assuming that soil water flow is laminar. Two soil physical functions must be known to solve the flow equation, namely the relation between soil water content and soil tension described by Brooks and Corey (1964) expression, and the function of unsaturated water conductivity. The unsaturated conductivity is calculated using the model given by Mualem (1976). To account for macropores the conductivity is increased when water content exceeds porosity minus 4%.

Vegetation can be seen as a link between water in soil and water vapour in the overlying air. Water flows from an area of high potential in soil to the atmosphere, which has a low water potential. The transition is governed by different resistances.

The potential vapour flow is calculated with the Penman-Monteith equation (Monteith, 1981). Reduction in water uptake caused by low soil temperature and/or dry soil conditions are simulated by using empirical reduction-factors. The Penman-Monteith equation is also used for calculating evaporation from soil and from interception storage. The various types of evaporation sources differ in term of available energy, surface resistances at the different boundaries and the aerodynamic resistances above their surfaces. The net radiation is distributed between the canopy and soil surface according to Beer's law.

The most important parameters describing the influence of vegetation are the leaf area index and surface resistance (Jansson, 1996; Van Dam, 2000). Root depth mainly affects the total storage of plant-available water. Water uptake by roots is described by defining the proportional distribution of roots among the different layers.

The model is driven by daily meteorological data such as air temperature, wind speed, air humidity, solar radiation and precipitation.

The simulation period started in mid April in case of wheat and mid May in case of maize. Input data, such as meteorological data and soil physical properties were determined by either, direct or indirect measurements. Model outputs, in terms of soil water dynamics were compared to field measured soil moisture contents and used for adjusting the unknown model parameters as e.g. soil surface resistance.

Model parameters are mainly related to either soil or stand properties. To the largest extent possible, independent measurements in the field or data reported in the literature have been used. Soil parameter values, as water retention characteristics and hydraulic conductivities were based on undisturbed soil samples, or direct in situ measurements.

Application of the SWAP simulation model

The SWAP numerical model (Van Dam et al. 1997) simulates the water flow in the unsaturated zone in relation to plant growth at field scale level for the entire growing season (Van Dam, 2000). The SWAP employs the Richards' equation for soil water movement in the soil matrix. The soil hydrophysical functions are introduced by the analytical expressions of Van Genuchten and Mualem (Van Genuchten, 1980). The model input data consisted of meteorological data, crop growth data, soil data plus initial and boundary conditions.

Daily *meteorological data* of Martonvásár (located 20 km from Herceghalom) meteorological station, consisting of air temperature, wind speed, solar radiation, air humidity for the vegetation periods of 1993-94 were used to estimate daily potential evapotranspiration according to Penman-Monteith (Monteith, 1981). The SWAP calculates the potential and actual soil evaporations according to expressions, suggested by Belmans et al. (1983) and Boesten and Stroosnijder (1986), respectively.

The simple *crop subroutine* of the SWAP model was chosen, that requires data on crop height, leaf area index, root depth, root distribution and soil cover fraction as functions of the development stage. The crop parameters were set according to Rajkai et al. (1997).

Initial conditions specified for the simulation consisted of initial soil water content profiles, measured on Julian Day (JD) 130 and 151 in 1993 and 1994, respectively. Assuming zero gradient of the soil water pressure head at the bottom of the soil profiles because of deep ground water level, free flux *bottom boundary conditions* were defined. *Upper boundary conditions* consisted of daily precipitation data, measured directly at the study area in 1993 and 1994.

The input *data on soil properties*, required by the model were the parameters of the soil water retention curve (Θ_r, Θ_s, α, n and m=1-1/n) and hydraulic conductivity function (K_s and λ), specified for each genetic horizon of the soil profiles according to Van-Genuchten – Mualem (Mualem 1976, Van Genuchten 1980). The RETC computer program (Van Genuchten 1980) was used to quantify the parameters of the Mualem-Van Genuchten model based on the experimental data of soil water retention characteristics and measured values of saturated hydraulic conductivity. The input data are given in Table 8.1.

Table 8.1: Mualem-Van Genuchten parameters, fitted to the measured soil hydrophysical data

Crop	Layer (cm)	Θ_r (m^3/m^3)	Θ_s (m^3/m^3)	α (1/cm)	n (-)	K_s (cm/day)	λ (-)
wheat	0-30	0.06	0.47	0.012	1.25	10.1	0.15
	30-70	0.06	0.51	0.052	1.22	8.6	0.14
	70-150	0.01	0.49	0.021	1.26	8.6	0.21
corn	0-20	0.09	0.49	0.012	1.26	15.2	0.17
	20-40	0.01	0.46	0.014	1.16	10.5	0.18
	40-70	0.01	0.50	0.040	1.14	10.5	0.18
	70-150	0.01	0.47	0.023	1.25	8.6	0.22

Θ_s and Θ_r are the saturated and residual water contents, respectively;
α and n are the Van Genuchten model parameters;
K_s is the saturated hydraulic conductivity and
λ is the parameter of the conductivity function.

The SWAP as the SOIL model was *calibrated* for the representative soil profiles against the measured soil water content data. The climate-, location- and crop-specific parameters were set this way, so the sensitivity of the soil water regime characteristics to changes in soil physical properties could be studied further. Model adaptation was achieved by tuning of model parameters. Because of the uncertainties in the estimation of the hydraulic conductivity function parameters, these data were tuned during the calibration. The adaptation was continued until the precision of prediction stopped responding to the changes in model parameters. The method, suggested by Addiscott (1993) was used to assess the accuracy of SWAP model fitting. Thus, the necessary level of accuracy (p) was defined and compared with the mean difference (M) between the simulated ($\Theta_{sim.}$) and measured ($\Theta_{meas.}$) soil water content values:

$$M = \frac{1}{N} \sum_{i=1}^{N} |\Theta_{meas} - \Theta_{sim}| \tag{8.1}$$

N refers for the number of cases. In case M < p, and the difference between the measured and simulated soil water contents does not exceed the accuracy level p

in 85-90% of the cases, the adaptation of the model is successful. Taking into consideration the soil water content sampling and measurement errors the level of accuracy, p, was set as ±5%.

The study consisted of four model calibrations (2 different years x 2 crops). In total 41 comparisons of measured and simulated soil water content profiles were performed: 7 (wheat) plus 10 (corn), and 12 (wheat) plus 12(corn) for 1993 and 1994, respectively. The accuracy of the model fitting was tested for 11 layers in case of each profile. Hence, the M measurements were applied for 41x11 layers.

Spatial extension of the profile-based simulation models

The spatial extension of the soil and SWAP simulation models was performed by regression and scaling methods, respectively.

Spatial extension of the SOIL simulation model

The regression technique, used for spatial extension of the simulation results consisted of statistical analyses followed by model sensitivity analyses. The spatial distribution of the soil water retention curves was represented by 5 curves (Table 8.2), each of the 6 characteristic points (soil water contents, corresponding to pF values of 0.0, 1.0, 2.3, 2.7, 3.4 and 4.2) of which was derived from the cumulative probability function (representing the average, min., max., 25%, and 75% values). These values were then used to perform sensitivity analyses with the previously calibrated SOIL model for testing the relationship between the soil physical input data and the model outputs (transpiration and other soil water balance elements).

Table 8.2: Characteristic values of the soil water retention curves, derived from the cumulative probability function

Value	Soil water content (v%), corresponding to					
	pF=0.0	pF=1.0	pF=2.3	pF=2.7	pF=3.4	pF=4.2
Minimum	39.6	38.5	29.7	24.9	17.9	13.4
25%	49.0	47.6	36.5	30.4	21.6	15.8
Average	50.6	49.1	37.6	31.3	22.2	16.3
75%	52.4	50.9	39.0	32.3	22.9	16.7
Maximum	59.4	57.6	44.0	36.4	25.6	18.6

Spatial extension of the SWAP simulation model

The scaling theory, introduced by Miller and Miller (1956) was applied for the spatial extension of the simulation model results. 445 soil water retention characteristic curves from 448 were scaled, using the SCALING software, developed by Clausnitzer et al. (1992). The program calculates a mean (reference) soil water retention curve for the study area and scaling factors for each SWRC curve, representing the deviation of the individual curve from the mean one. Providing the parameters of the reference curve and the scaling factors, SWAP generates the soil hydrophysical functions for each scaling factor value and simulates the corresponding water balance. Thus, the elements of the soil water balance, such as transpiration, evaporation, leaching and changes in soil water storage were estimated for the 445 measurement points for the vegetation period of two crops (wheat and maize).

The transpiration ratio (R) between the simulated transpiration and potential transpiration values was calculated for each sampling point. In this respect we assumed uniform (wheat or corn only) vegetation cover in the whole area. Punctual kriging was applied as interpolation technique to demonstrate the spatial pattern of the simulated transpiration ratio. The spherical model was fit to the experimental semivariogram.

Results and discussion

Statistical and geostatistical analyses

Statistical evaluation of the soil physical data

Results of the statistical evaluation of the saturated water content ($\Theta_{pF=0.0}$), field capacity ($\Theta_{pF=2.3}$) and wilting point ($\Theta_{pF=4.2}$) data are given in Table 8.3.

Table 8.3: Means (v%), standard deviations (SD) and coefficients of variation (CV %) of the characteristic points of the soil water retention curves

Landuse type	Num. of samples	$\Theta_{pF=0.0}$			$\Theta_{pF=2.3}$			$\Theta_{pF=4.2}$		
		Mean	SD	CV	Mean	SD	CV	Mean	SD	CV
Corn	168	50.3a	3.74	7.44	35.1a	3.02	8.60	15.9a	3.06	19.20
Wheat	164	50.7a	3.13	6.18	35.6a	2.85	8.00	15.0b	2.08	13.83
Alfalfa	51	49.0b	2.72	5.55	35.6a	1.55	4.35	16.6a	2.02	12.18
Grass	62	48.9b	2.94	6.02	36.9b	2.02	5.06	15.1b	1.54	10.20
Total	**445**	**0.50**	**0.03**	**6.7**	**0.36**	**0.03**	**7.7**	**0.16**	**0.02**	**15.8**

Mean values are significantly different at a probability level of 0.05 if the same letters do not follow them.

Statistically significant differences between the soil physical properties according to land use types were found. The relatively lower saturated soil water contents and bigger bulk density values (Table 8.4) in the alfalfa and grass fields indicate more compacted topsoil compared to that of the wheat and cornfields. These differences could be caused by the soil loosening effect of ploughing, applied in the annual crop fields. We suppose, that the bigger earthworms activity could increase the field capacity in the grassland due to its soil mixing and soil structure improving effect. According to the clay(highest in the alfalfa fields) and organic matter (highest in the grass) content data (Table 8.4), significant differences, found between the wilting point values could be caused by differences in the amount of organic and inorganic colloids (Rajkai et al., 1981).

The variability of clay and humus contents of the grass was much lower than that of the alfalfa fields. On the other hand, the coefficients of variation of the bulk density were similar for tilled (corn and wheat) and non-tilled or not regularly tilled (grass and alfalfa) soils.

Table 8.4: Mean, standard deviation (SD) and coefficient of variation (CV, %) of the clay content, bulk density (Bd) and organic matter content (OM)

Landuse type	Num. of samples	Clay content (%)			Bd (g cm^{-3})			OM (%)		
		Mean	SD	CV	Mean	SD	CV	Mean	SD	CV
Corn	168	27.23a	5.83	21.41	1.32a	0.10	7.58	3.31a	0.81	24.47
Wheat	164	25.06b	3.16	12.61	1.31a	0.10	7.63	2.56b	0.79	30.86
Alfalfa	51	28.32a	4.09	14.44	1.39b	0.07	5.04	3.53a	0.78	22.10
Grass	62	24.52b	2.22	9.05	1.38b	0.08	5.80	3.83a	0.62	16.19
Total	**445**	**26.2**	**4.57**	**17.4**	**1.33**	**0.10**	**7.50**	**3.40**	**0.80**	**23.40**

Mean values are significantly different at a probability level of 0.05 if the same letters do not follow them.

No significant differences according to elevation categories between bulk densities, clay content and total porosity values were found (not shown). The field capacity values for the hilltops were generally bigger than for slopes and valleys.

The results of the statistical evaluation indicated, that model simulation of the effects of soil hydrophysical properties on soil water balance has to be performed separately for the different land use types.

Geostatistical analyses

Semi-variogram models and model parameters, fitted to the measured soil physical properties are shown in Table 8.5. To define distinct classes of spatial dependence among soil properties with depth, ratios similar to those presented by Cambardella et al. (1994) were used. If the ratio is between 25% and 75%, the variable is considered moderately spatially dependent; if the ratio is bigger than 75% or less than 25%, the variable is considered weakly or strongly spatially dependent, respectively.

Table 8.5: Parameters for semi-variogram models for pF0, pF2.3 and pF4.3

Soil property	Model	Nugget $\%^2$	Sill $\%^2$	N/S %	Range m	Spatial class
$\Theta_{pF=0.0}$	Exponential	4.35	10.85	40.1	475	moderate
$\Theta_{pF=2.3}$	Spherical	2.65	7.50	35.3	475	moderate
$\Theta_{pF=4.2}$	Spherical	0.10	6.25	1.6	545	strong
Clay	Exponential	0.69	21.75	3.17	437	strong

Semi-variograms for pF0 and pF2.3 indicated the existence of moderate, while for pF4.2 of strong spatial dependence (Fig. 8.1). The 425 m distance between the measurements points was enough to construct variograms and perform kriging.

The level of the spatial dependence increase in the following order: pF0, pF2.3 and pF4.2. Because of the strong relationship between the wilting point moisture content and clay content, variogram for clay content had similar parameters to the one for pF4.2, and showed similar spatial structure as well. The weakening of the spatial structure towards pF0 can be explained by increasing independency of these

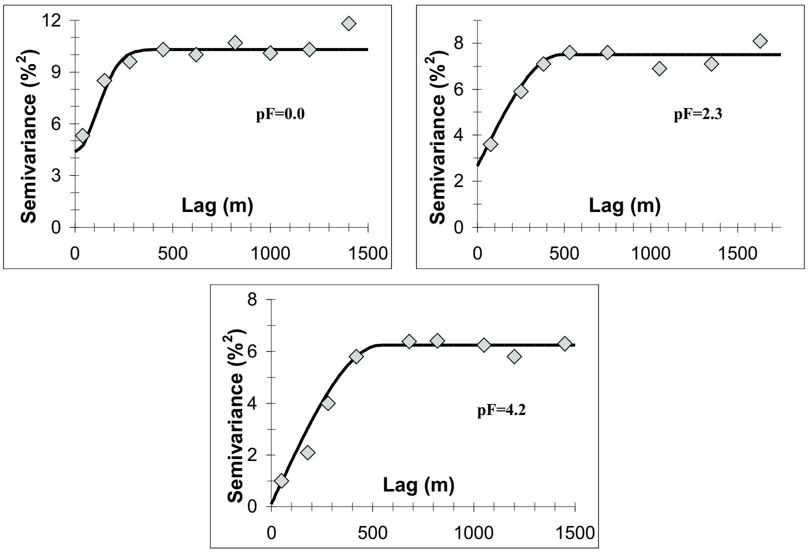

Figure 8.1: Experimental (points) and theoretical (lines) semi-variograms, calculated for the characteristic points of the soil water retention curves

characteristics from the clay content as well as by increasing of other soil effects (e.g. compactness, soil structural status, soil cultivation etc.). Spatial patterns of the saturated soil water content ($\Theta_{pF=0.0}$), field capacity ($\Theta_{pF=2.3}$) and wilting point ($\Theta_{pF=4.2}$) soil water contents are given in Fig. 8.2-8.4. We found, that the spatial variability of the $\Theta_{pF=0.0}$ was higher in maize and wheat fields than that of alfalfa and grass fields.

The field capacity water content values, measured at the experimental sites ranged within a relatively small interval of 10%. Thus, no valuable differences between the land use types were found. The effect of soil tillage could be found in higher SD values of tilled fields. The spatial pattern of the wilting point soil water contents reflected the relief and the land use types of the territory. As it was shown by the statistical evaluation of the spatial data, the clay and the organic matter contents depend on the elevation and the land use. Thus, the spatial pattern of the wilting point can be related to the spatial pattern of the clay- and organic matter contents of the soil. Consequently, fields belonging to the same land use types can be considered homogeneous in soil texture as well as in the high suction part of the soil water retention curve.

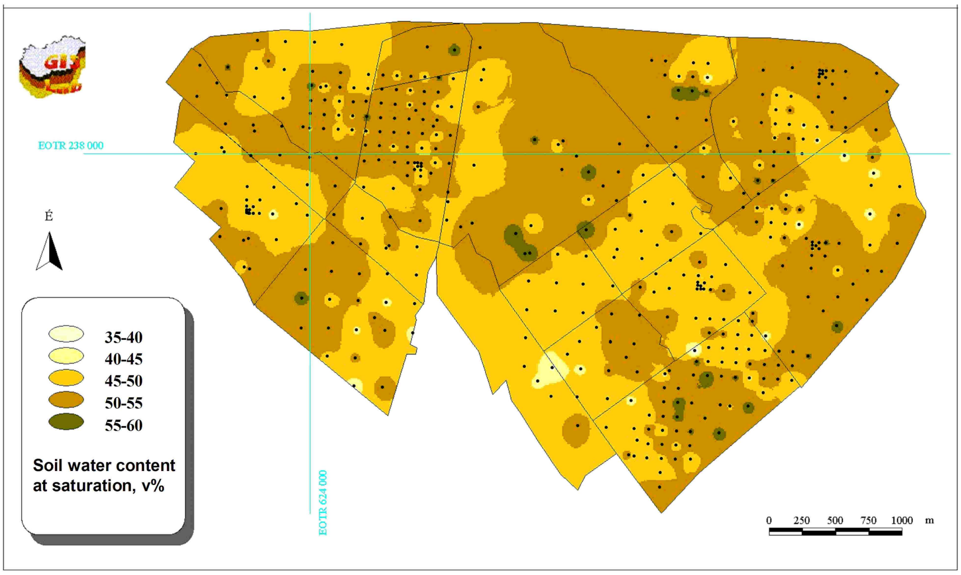

Figure 8.2: The total water capacity water content pattern of the Herceghalom study area

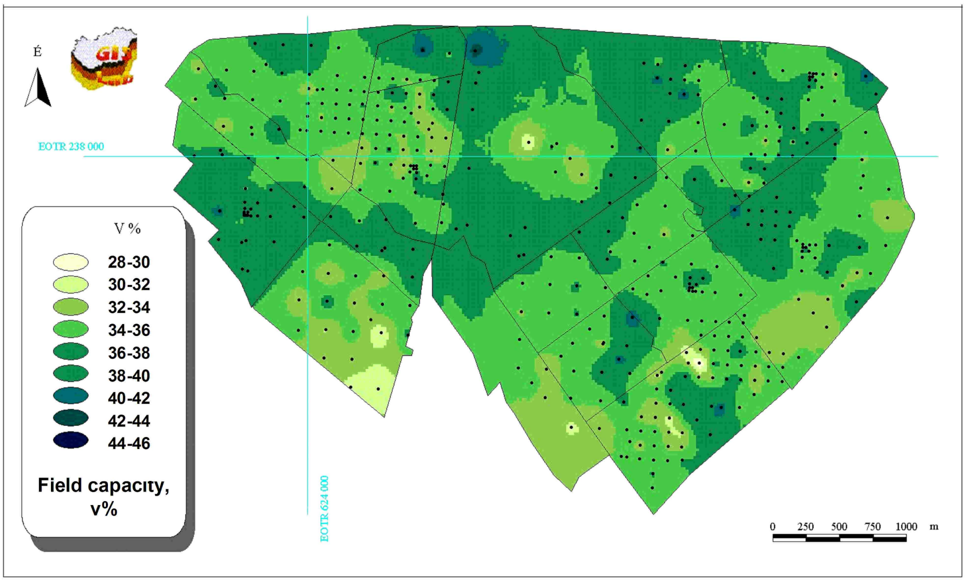

Figure 8.3: The field capacity soil water content pattern of the Herceghalom study area

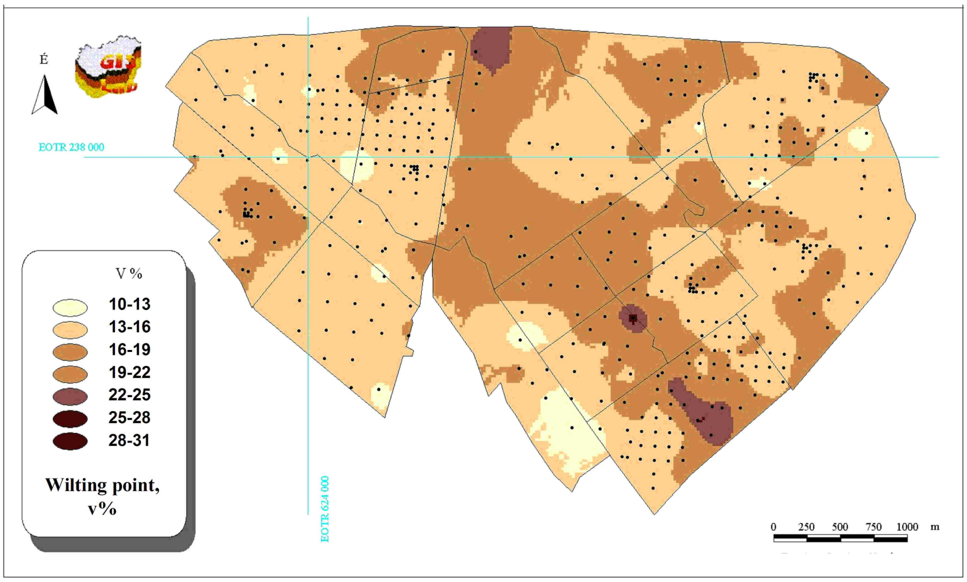

Figure 8.4: The witling point water content pattern of the Herceghalom study area

Calibration of the soil water balance simulation models

Calibration of the SOIL model

The simulated soil water content dynamics were in good agreement with the measured ones for the wheat field (Fig. 8.5). Similar results were obtained (not shown) for the maize field.

The main difference between the two years consisted of the amount of precipitation during spring. In March and April it was 27 and 96 mm for 1993 and 1994, respectively. Consequently, the soil was dry at the beginning of the growing season in 1993, and it was drying out until August without any increase in soil water content. In 1994 several rainfalls followed the relatively wet spring, so drying and wetting periods could be observed.

We concluded, that the estimation of the soil water content dynamics using the SOIL model was successful, and the model described the soil water flow and its redistribution in different weather conditions.

Calibration of the SWAP model

The measured and calculated volumetric soil water content profiles for 6 days are presented in Fig. 8.6. Figures show that predicted soil water content profiles do not differ much from the measured ones, so the simulation can be qualified as good. The difference between the two increases next to the soil surface and at the bottom of the profile, especially in case of wheat. The model calibration for the uppermost layer is more difficult compared to lower ones, because of the more complex nature of the water movement and redistribution phenomena (Zsembeli, 2000). On the other hand, the relative error of the capacitive probe, used for soil water content

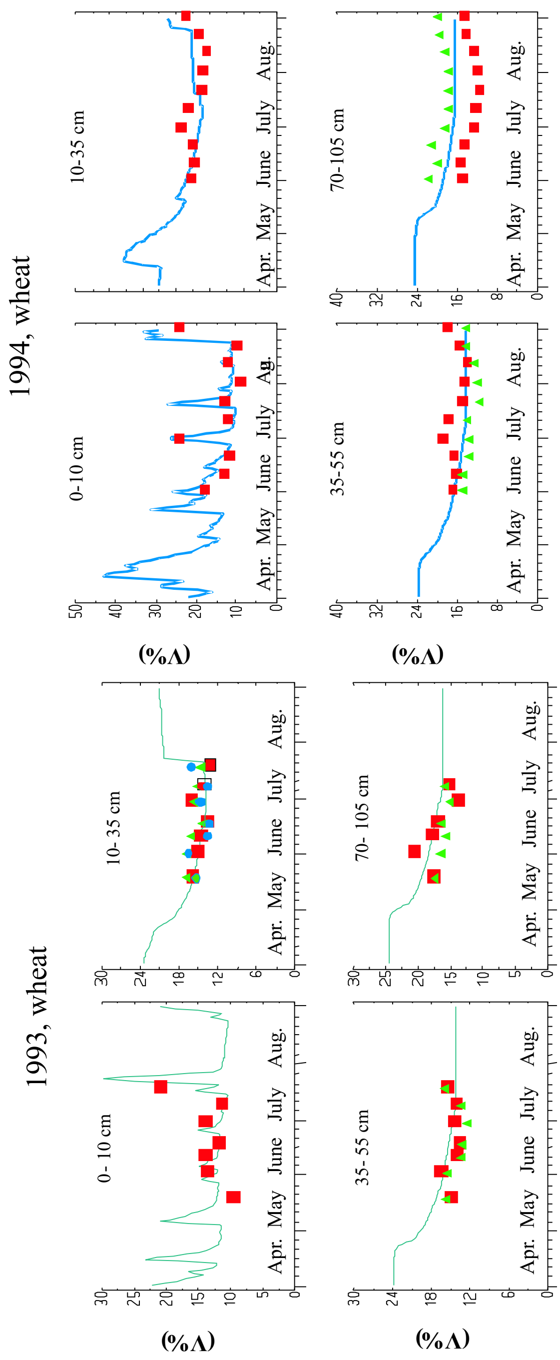

Figure 8.5: Measured (points) and simulated (lines) with the SOIL model soil water content values for a dry (1993, left side) and relatively wet (1994, right side) year. Squares/triangles show the soil water content values, measured at depths of 40-50/50-60 cm (for 35-55 cm layer) and 70-80/90-100 cm (for 70-105 cm layer), respectively.

measurements, increases towards the soil surface. This might also be the reason of the less precise calibration of the model for the upper 15 cm layer of soil. At the lower boundary of the soil profile a rather thick (70-150 cm) layer was considered to be homogeneous and represented with one set of soil hydrophysical parameters. This could cause a higher inaccuracy of the simulated soil water content values in the 80-110 cm layer.

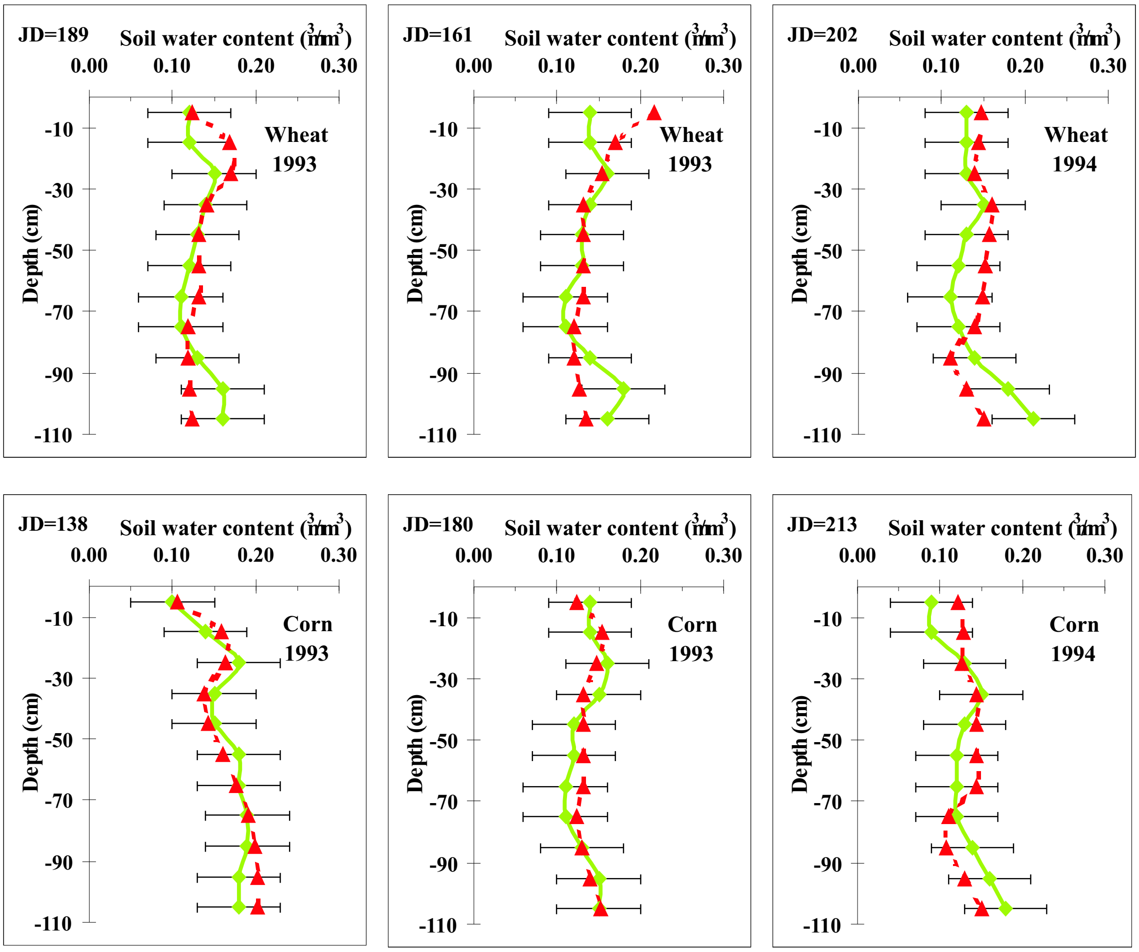

Figure 8.6: Measured (dashed) and simulated (solid) soil water content profiles (JD refers for Julian Days; the error bars are also indicated)

The analyses of the model accuracy according to Addiscott (1993) are presented in Table 8.6. We concluded, that the model calibration was successful in general. The differences between the simulated and observed soil water contents can also be explained by seasonal changes of soil physical properties caused by biological activity and weather conditions. Farkas et al. (1999) reported about strong seasonal variability of soil hydrophysical properties of an agricultural soil and proofed the sensitivity of the SWAP model to this variability (Farkas et al., 2000). They established that considering the seasonal variability of soil physical properties using seasonally different parameters improved the simulation accuracy significantly.

Table 8.6: The mean difference (M) between the simulated (SWAP) and observed soil water content values and the percentage of cases (K%), when the difference does not exceed the accuracy level p=5%. N refers to the number of cases.

Wheat						Corn					
1993			1994			1993			1994		
M	K	N	M	K	N	M	K	N	M	K	N
0.030	77	90	0.047	83	132	0.015	100	110	0.034	85	132

Spatial extension of the simulation models

Spatial extension of the SOIL model, using a regression technique

Based on regression analyses, the soil water content at saturation ($\Theta_{pF=0}$) was found to be the most important soil property, influencing the simulated actual evapotranspiration (ET) and, consequently, the root water uptake. Fig. 8.7. demonstrates the relationship between the simulated evapotranspiration values and the $\Theta_{pF=0}$values, corresponding to the 5 water retention curve groups (Table 8.2) used to represent the spatial variability of soil hydrophysical properties.

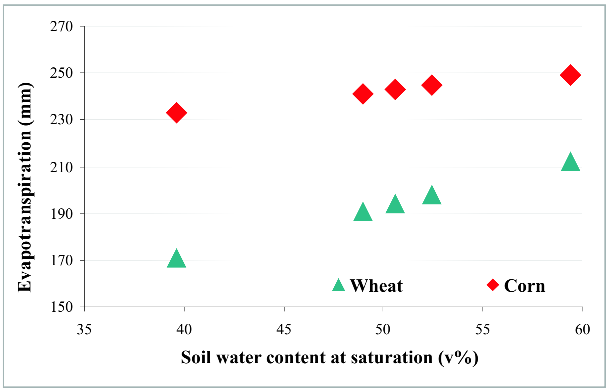

Figure 8.7: Relationship between the $\Theta_{pF=0}$ values of the five soil water retention curve groups and the simulated evapotranspiration

The regression equations, used for spatial extension of the SOIL model results were as follows:

$$ET = 88.212 + 2.097 * \Theta_{pF=0}(\text{wheat}); \quad (8.2)$$

and

$$ET = 190.01 + 1.030 * \Theta_{pF=0}(\text{corn}) \quad (8.3)$$

The spatial pattern of the ET values for wheat and corn are given in Fig. 8.8 and 8.9, respectively. Block kriging was used for the interpolation of the ET values, derived for each measurement point, assuming, that wheat (or corn) was grown in the whole area of the farm and that the nutrition support was uniform through the area.

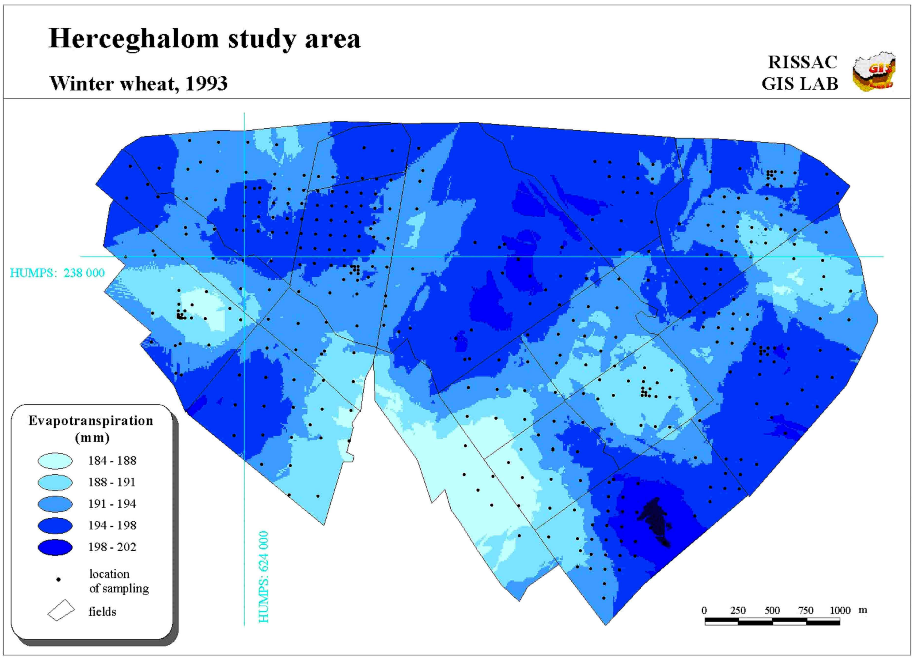

Figure 8.8: Spatial pattern of the SOIL model simulated evapotranspiration of wheat (1993)

Since the actual transpiration is strongly related to the plant water uptake, we assume that areas with high wheat/corn yield are marked with dark colour.

Maps were created for an extremely dry vegetation period (year 1993). After the wheat was harvested, rains started, so the corn could get water from the soil. This means, that the drought stress for wheat was bigger than that for corn, and the spatial distribution of the ET values was more uniform for corn than that of wheat (Figs. 8.8-8.9).

Spatial extension of the SWAP model, using the scaling method

The spatial pattern of the simulated transpiration ratio for wheat is presented in Fig. 8.10-8.11 for 1993 and 1994, respectively. The amount of precipitation differed a lot between the two years. 1993 was an extremely dry year with a total of 158 mm precipitation in the vegetation period. The following year was relatively wet with 302 mm of total rainfall during the growing season.

The spatial pattern of the simulated transpiration ratio for 1993 and 1994 was rather similar, but less uniform in the dry year. The transpiration range, (not shown)

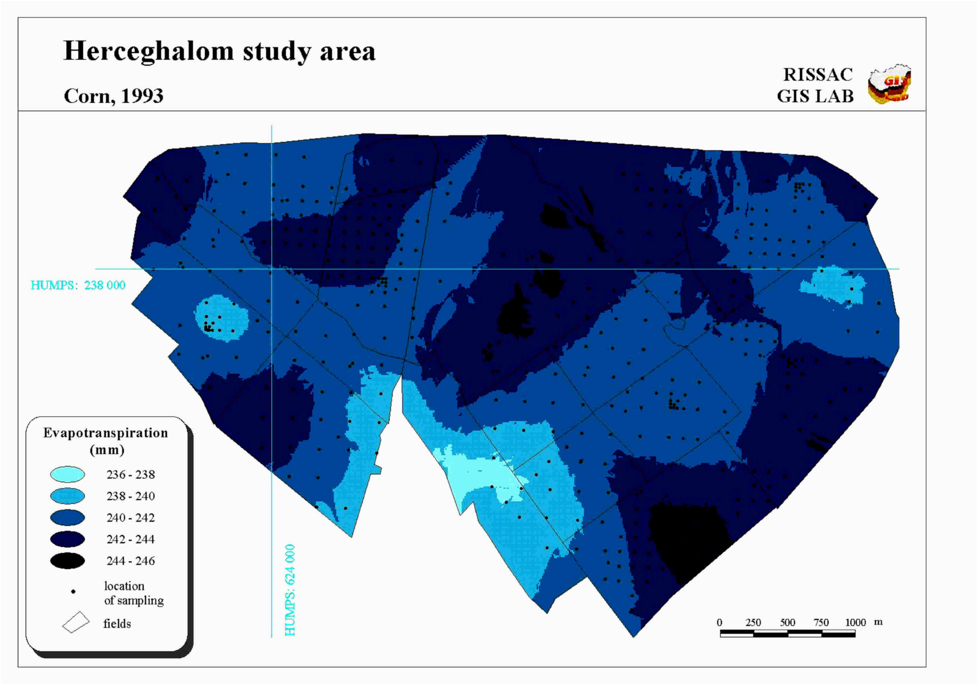

Figure 8.9: Spatial pattern of the SOIL model simulated evapotranspiration of maize (1993)

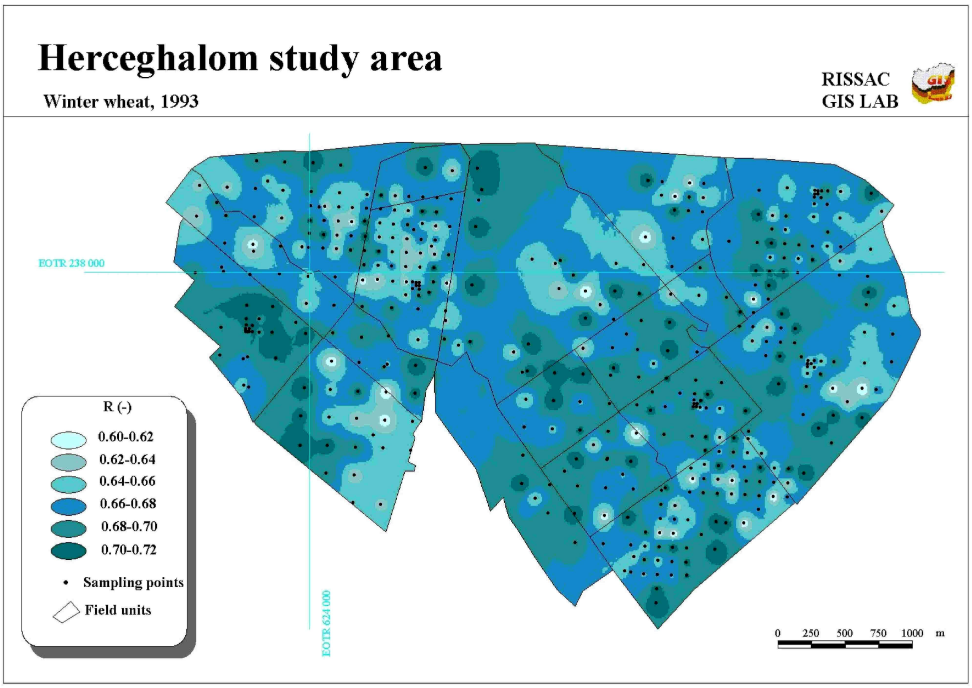

Figure 8.10: Spatial pattern of the simulated transpiration ratio R (-) for wheat (1993)

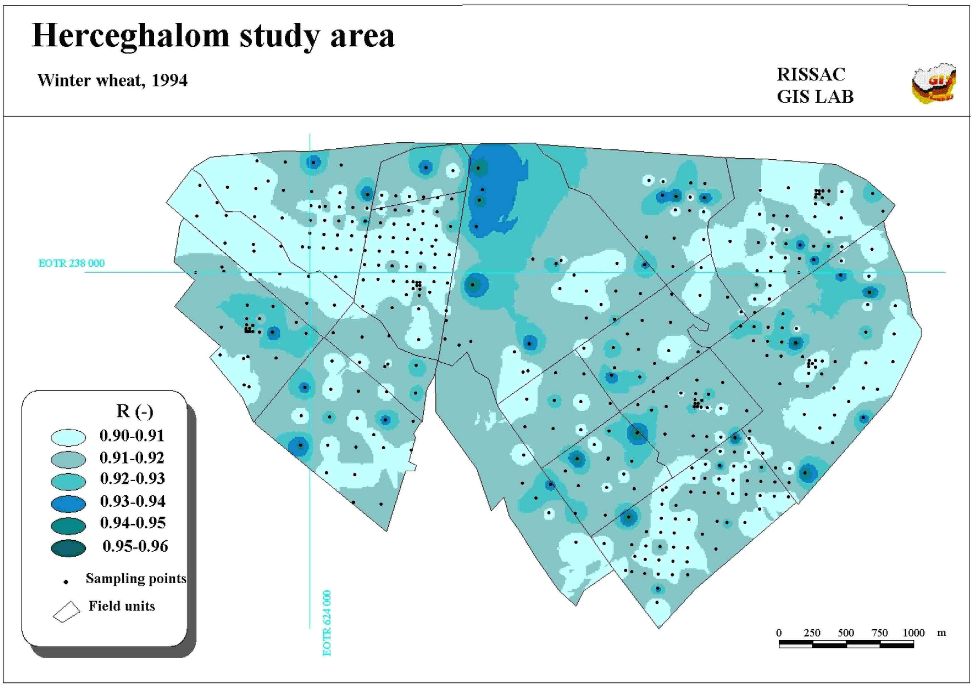

Figure 8.11: Spatial pattern of the simulated transpiration ratio R (-) for wheat (1994)

was twice as big (62 mm/growing season) in 1993 than in 1994 (27 mm/growing season), the coefficients of variation were 6.8% and 1.8%, respectively. The bigger range and less uniform spatial pattern of the transpiration ratio in the dry year indicates, that in case of less favourable conditions a stronger effect of the spatial variability of soil hydrophysical properties on the spatial pattern of soil water balance can be expected.

Similar conclusions can be drawn regarding the spatial pattern of the simulated transpiration ratio for corn (not shown). The transpiration ranges for the vegetation period in this case were 59 and 22 mm/growing season, the coefficients of variation 5.3% and 1.5% in 1993 and 1994, respectively.

Note, that in this study neither the spatial pattern of the crop parameters nor the adaptation of the vegetation to unfavourable environmental conditions were taken into account. No conclusions can be drawn for territories, where no sampling points appear.

Conclusions

The adaptation of the SOIL and SWAP simulation models to the Herceghalom study area was successful. We found, that the spatial variability of the soil hydrophysical properties influences the spatial pattern of the soil water balance elements, especially in dry, unfavourable weather conditions.

The applied methods, used for spatial extension of the profile-based simulation models are appropriate for optimisation purposes and suitable for precision agriculture aspects. They make possible to analyse the integrated effect of the variability of different soil physical properties on the soil water balance for a given crop and weather scenario. Moreover, this type of simulation allows selecting the most appropriate land use pattern on the area.

Acknowledgement

This paper presents results of research programs supported by the Hungarian Ministry of Education (NKFP NKFP6-00079/2005 and NKFP 4/064/2004), the Hungarian National Scientific Foundation (OTKA T062436, T042996 and T048302). Csilla Farkas is the grantee of the János Bolyai Research Scholarship of the HAS. Authors wish to thank the contribution of J. Denaeghel in the paper.

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Chapter 9

The continuum dilemma in pedometrics and pedology

J.-J. Ibáñez, A. Saldaña

A conflict between doctrines is not a disaster
but a great challenge
(Prigogine and Stengers, 1988:
Entre le temps et l'eternité)

Abstract [1]

This chapter deals with a controversial matter within the community of soil scientists. In the last years classical pedology has been questioned about the concept of soil as a natural body on the landscape and also about how soils are classified and mapped. Main criticisms coming from pedometricians regard the ability of classical pedology to describe properly soil variability. Aspects under analysis regard the discussion about continuum-discrete entities, the natural-artificial classification, the objectivity of the soil classifications, the basic-applied nature of pedology and the need of universal classifications. It is shown here that many criticisms are similar to those that have been already overcome by other sciences. The conclusion is that according to the philosophy of science, the quantitative (geostatistics) and the qualitative (classical pedology) approaches are not incompatible and it should be possible to analyse the soil cover using both of them.

Introduction

Soil spatial variety and variability are crucial elements to quantify the pedogenic concepts and better understand the causal factors of soil distribution patterns and landscape evolution (Wilding and Drees, 1983). On a classical soil map, variation is displayed using geomorphic and soil knowledge (Hudson, 1992), mainly in terms of

[1] This chapter is an extended and improved translation of the text published in Russian in "Geostatistics and Soil Geography", Moscow, Nauka Publ., P. 109-120.

systematic variation, which according to Jenny (1941) entails any gradual or marked change in soil properties as a function of landforms, soil-forming factors and/or soil management.

In the last years classical pedology has been questioned about the concept of soil as a natural body on the landscape and also about how soils are classified and mapped. Main criticisms coming from pedometricians regard the ability of classical pedology to describe properly soil variability. Grunwald (2003) opened a very interesting debate asking whether it is possible to reconcile the two approximations to soils analysis: quantitative/mathematical versus taxonomy.

This chapter deals with a controversial matter within the community of soil scientists. Many pedometricians claim against classical approaches to the analysis of the pedosphere continuum. Most criticisms regard: (1) the separation of soils into hard classes due to the inherent large variability of soil properties; (2) the application of hierarchical classifications to soil systems in the same way they are used for biological systems; (3) do classical soil scientists (particularly in the United States) have such a narrow focus on Soil Taxonomy, as suggested by Grunwald (2003)?; (4) classical pedology is viewed by some geostatisticians as really obsolete, like fossils of a "*dark age*" (Heuvelink and Webster, 2001).

In few words, are we talking about two different paradigms? We think that both pedologists' schools could learn a lot from this controversy if the current intuitive attacks were replaced by constructive statements based on conceptual tools provided by other branches of knowledge. Other scientific disciplines such as biological taxonomies, biodiversity analysis or geomorphology (Rhoads and Thorn, 1996) are involved nowadays in similar controversies.

Arguments to defend classical pedology

Continuum versus discrete entities

One of the main criticisms arriving from pedometricians concerns the continuous nature of the soil mantle with fuzzy boundaries (e.g., Odeh, 1998 and *personal communication*; McBratney and De Gruijter, 1992). And not only: they are also "adjacent" (Ibáñez et al., 2005a). Compared to most of biological organisms, soil bodies are usually not separated by non-soil bodies, and this makes it difficult to detect different soil classes. However, novel approaches in biology show that the horizontal gene flow and other biological mechanisms are very important and then, the separation of different biotaxa in hard classes is also (at least in many instances) questionable (Ghiselin, 1974; Sattler, 1986 and references therein). Thus, biological individuals are discrete only in appearance or in some features. Novel trends in biology claim that the species are the true individuals, whereas the termed biological "individuals" of a given species are only mere "organisms" of the formers (the species) (Ghiselin, 1974). Since there are not two identical organisms, it is impossible to quantify the inner genomic variability of a single species without sampling all his variability (all individuals) and then, the central concept of species is intrinsically vague. Many philosophers (Rosenberg, Williams, etc.) and reputed biologists (e.g., Mayr, Eldredge, Willmann, and so on) have embraced the Ghiselin conjecture as the only one compatible with the Darwinian evolution (see Mosterín, 2000 and references therein). In our context, we could say that pedotaxa or soil types are "vague individuals" constituted by "dispersed organisms" with distinct genetic constitution (intrinsic variability). And then, what is the response of pedometricians to this new challenge?

Yaalon (2003), using mainly empirical arguments, also reacted to the criticisms by Grunwald (2003) against "classical" pedology. He mentioned that two of the soil forming factors (i.e., parent material and topography) do frequently change abruptly over small distance. His experience indicates that for most medium and large scale maps it would be between one quarter and one half of the soil boundary lines drawn on them. He mentions two examples (tectonically active and non-glaciated regions) but Phillips (1999) provides more examples (e.g., biological induced discontinuities, such as nano-podzols under certain tree types and less developed soil bodies after that a tree fall in a given forest). Such lithologic, geomorphic and biotic spatial discontinuities and abrupt delineations obviously confirm that there are well recognized pedological individuals or soil bodies, together with others that have more fuzzy boundaries, included in the same polygon or soil association. Pedometrics is essentially a tool for the study of soils observed and for data analysis and need not to be considered a challenge or in contradiction with soil taxonomies. So, the notion of soil continuum should be carefully examined and then applied in a proper way (Yaalon, 2003). This idea supports the patterned continuum concept in biology (Sattler, 1986) and pedology (Ibáñez and Boixadera, 2002; Ibáñez et al., 2005a). Yaalon's comments disprove pedometricians arguments to attack other approaches to pedology.

It is recommendable to remember that geostatisticians started with these criticisms against classical pedology. Geostatistics is just one element of pedometrics, which also includes experts who work with other mathematical tools, such as non-linear dynamics, fractals and multifractals, and pedodiversity measurements. Since the latter have not participated in this debate, it is more appropriate to say that the controversy concerns to some pedometricians and not to all of them as Grunwald (2003), among others, claims.

Natural-artificial classifications

Many geostatisticians have the opinion that biotaxa are natural bodies while pedotaxa are artificial (but see Sattler, 1986; Ibáñez and Boixadera, 2002; Ibáñez et al., 2005a,b,c). The reason is that the pedosphere is a continuum and soil types have to be defined according to the expert judgement of soil taxonomists. This could cause conspicuous structural differences between both taxonomies as information systems (e.g., Burlando, 1990 and 1993; Minelli, 1993; Minelli et al., 1991; Odeh, *personal communication*). This issue relates to the *Naturalia/Artifitialia* dilemma of biological classifications going back to the 18^{th} century (Ibáñez and Boixadera, 2002; Ibáñez et al., 2005a; Mosterín, 2000).

Objective-subjective classifications

To some pedometricians, current soil classification schemes such as USDA-Soil Taxonomy and WRB, split the soil continuum into "subjective" hard classes. They prefer fuzzy partitions together with numerical taxonomy procedures (e.g., Odeh, 1998) as more "objective" methods. These arguments are similar to those used in biology several decades ago. However, these approaches only allow "to break the soil continuum" in *ad hoc* soil classes. In addition, the selection of the soil properties to be considered in numerical classifications is also "subjective" (i.e., purpose oriented), as well as the choice of the algorithms utilised to such partitions (Ibáñez et al., 2005a). Therefore, this approach is not "more objective", although it must be acknowledged that subjectivity (i.e., a priori criteria) is easier to analyse when it is presented in a mathematical format. Since such methods only produce "*ad hoc* partitions" the results obtained in different areas, environments and biomes (or pedomes) are not comparable. However, the comparability of results is important to provide pedologists with useful techniques to analyse the soil cover mantle. To end this section, it is worthy to note that "breaking the continuum" regards not only Pedology but also live sciences because sometimes the "objective" delimitation of species is impossible in certain taxa such as the genus *Quercus* (oaks) because hybridisation is very frequent. Other biological organisms could be considered porous, for example the fungi of the *Armillaria* genus that form vagueness-porous of mycelia networks that spread along hectares and weight several tons (Bollock, 1992; Smith et al., 1992), or some aspens (Eldredge, 1998).

Basic versus applied science

Most pedologists think as applied scientists rather than basic scientists. The best to "sell" a purpose oriented product is not necessarily the best way to make a scientific discipline to progress. There is not applied without basic science. Basic science demands and works with theoretical structures including a clear definition of natural resources involved, their characterisation, and a universal classification as a consensual language among specialists. However, current soil classifications, as well as biological ones (Mosterín, 2000; Ereshefsky, 2001; Hey, 2001) have several biases and shortcomings and are not good for certain purposes (e.g., some environmental ones). The soil, as any other natural resource, is part of the natural heritage and should be conserved, either for human use or in as pristine state as possible to establish networks of natural reserves (Ibáñez et al., 2003). The European Commission (2002) recognises this fact in the framework of the EU Future Directive on Soil Protection.

The need of universal classifications

Classification is an essential part of the data reduction process, whereby complex sets of observations are made understandable. Universal classifications are needed in all scientific disciplines (Mosterín, 2000). Although all classifications involve a loss of information, a good classification not only aims to reduce information loss to a minimum, but provides a convenient means of information transfer by identifying natural groups of individuals that have common properties (Burrough, 1989). Psychological proofs have demonstrated that the human mind carries unconsciously hierarchical classifications to understand how nature works (Hey, 2001; Rosch, 1978; Roch et al., 1976; Houdé, 1998). Categorization is an important adaptive behaviour that humans use to break the physical and social realities (social cognition). Its cognitive function is to create categories (of objects, individuals, etc.) useful for the conceptual transition from continuous entities to discrete ones (Houdé, 1998). Even the best classification system reflects not only the order of nature but also the classification method. It would be naive to believe that there is one methodology that is in total harmony with nature lacking of bias and limitations (Sattler, 1986; Mosterín, 2000; Ereshefsky, 2001).

Early soil classifications were largely based on extrinsic soil forming factors. These were replaced by other approaches such as Soil Taxonomy, where classes are rigidly defined in terms of measurable diagnostic soil horizons and properties with genetic meaning. In this type of classification model, it is implicitly assumed that all changes between classes take place at the class boundaries and that little genetic change of importance occurs within classes. Nevertheless, most classical soil surveyors also accept the variability of many soil properties within a single taxa and the difficulty of considering them in classical classifications (Arnold, *personal communication*).

Some pedometricians (e.g., Odeh, *personal communication*) wonder whether hierarchical classifications are as applicable to soil systems as to biological systems. In our opinion the main differences between biological and pedological classifications obey to the distinct social practices and applications in both disciplines as well as their respective bias like in the case of the classical soil maps with agronomic purpose. While biotaxonomists recognise that they only have identified less that the 2% of the world species, pedologists were forced, from the beginning, to split the whole soil "patterned continuum" into discernible classes, using different (i.e., national) schools. This historical contingency is of supreme importance to understand the state of the art in both disciplines (i.e., different histories involve different scientific traditions). Homogenisation and harmonisation of soil surveys data from different sources and/or traditions require consensual hierarchical classification systems (national or international depending of the objective and geographical area involved) (Krasilnikov, 2002).

Classifications are not only scientific tools. Human mind and children apprenticeship follow a cognitive process that requires hard categorization or partition (reify), as occur in all natural languages (Mosterín, 2000, Rosch, 1978; Rosch et al., 1976). Thus, the introduction of the fuzzy logic is not a trivial question and requires a deep study if we prefer to use it in a user friendly way. A classification is an iterative fragmentation of a given continuum in discernible classes (Houdé, 1998; Ibáñez et al., 2005a). Most pedologists agree that a fuzzy categorization could be, in some aspects, a better alternative than hard ones. It is possible to think in this way but it is very difficult to reach a consensus to put in practice this procedure in universal classifications.

Ibáñez et al. (2005b, c) compared the mathematical structure of biological and pedological taxonomies (Soil Survey Staff, 1996 and 1998). Their results must be surprising to many geostatisticians: both classifications show similar structures after the analysis of statistical distribution models, entropy analysis to assess their respective qualities as retrieval information systems, fractal and multi-fractal analysis. Both taxonomies follow the MaxEnt Principle of thermodynamics (Jaines, 1957) and the Mayr criterion (Mayr, 1995). The MaxEnt Principle states that the least biased and most likely probability assignment is the one which maximizes the total entropy subject to the constraints imposed on the system. On the other hand, Mayr argues that a low number of large taxa size and an excessive number of monotypic taxa reduce the usefulness of taxonomy as an information retrieval system. Thus, if each taxa of any taxonomic category is subdivided into the same number of subtaxa along all the hierarchy, a perfect fractal is obtained (the most efficient retrieval information system). Obviously the taxonomies tested by Ibáñez et al. (2005c) show a higher variability of taxon sizes, as consequence of cognitive and utilitarian biases (Rosch, 1978; Rosch et al., 1976), but the system is close to its maximum efficiency. Thus, the results obtained by these authors are then in agreement with the above mentioned principle and criterion respect to the efficiency in the information flow. To provide a more detailed mathematical analysis Ibáñez et al. (2005c) made use of fractal and multifractal formalism. The reason is that fractal trees imply hierarchies that optimise matter, energy, and/or information flow (Pastor-Satorras and Wagensberg, 1998; Solé and Manrubia, 1996) and thus, they are in agreement with the MaxEnt Principle and the Mayr criterion for systems with a finite number of elements. This analysis showed that both classifications are multifractal efficient information systems according to the above mentioned principles.

Therefore, it seems that in order to maximize the economy of information flow, human mind seems to adopt the same principles: it emulates nature when it has the same purpose. For these reasons it is very difficult to know if biological taxonomies are something "natural", if this term has sense in science.

Then the question is: how is it possible that "natural" and "artificial" taxonomies show the same structure using different mathematical tests? Ibáñez et al., (2005a,b,c), with a strong empirical support, conjecture that: (i) the *Natu-*

ralia/Artificialia dilemma is not the driving force for the detected differences; (ii) the idiosyncratic taxonomic practices and bias produce the minor detected differences; (iii) the structure of the biological taxonomies has no biological significance as they are products of our cognitive structure (see also Mosterín, 2000); and (iv) all efficient (in physical and information terms) classifications are hierarchical and try to get fractal structures, but cognitive and purpose oriented biases divert these to multifractal structures (Ibáñez et al., 2005c).

Another analogy between biological and pedological polemics regards the concept of taxa (see also Ruellan, 2002). In a recent publication, Wilding et al. (2002) noted that some pedons could be multi-taxa (e.g., Vertisols), while Van Valen (1976) defended that some biotaxa, such as the genus *Quercus* did not consist of different species but of single multispecies. There exist intergrades also in biological classifications in contrast to pedometricians naive perception (e.g., Van Valen, 1976; Hey, 2001; Ereshefsky, 2001). For instance, the International Code of Botanical Nomenclature recognises also that there are numerous interbreeding hybrid taxa in nature. In order to formalize and classify these biological entities, biotaxonomist use specific terms, as "reticulation" and nothotaxa. Reticulation is the union of separate lineages in a phylogenetic tree, generally through hybridization or through lateral gene transfer (mainly common in certain land plant clades and microorganisms). Hybridity is indicated by the use of the multiplication sign "×" or by the addition of the prefix "notho-" (nothotaxa) to the term denoting the rank of the taxon (all the information concerning to the International Code of Botanical Nomenclature is available in Internet). Therefore, it is clear that biologists have similar problems to the ones of pedologists (intergrades) and they solve them without appealing to fuzzy logic tools.

Some possibilities of soil quantification

Geostatistics

Currently, the main stream of pedometrics is concerned with geostatistics, fuzzy sets and some aspects of numerical classifications. The main success of geostatistics relates to the quantification and prediction of single soil properties. In this way geostatisticians put in evidence the shortcomings of traditional soil maps for some purposes that require this type of information (e.g., precision farming, assessment of soil and water quality, etc.). However soil types, soil bodies and soilscapes are very complex natural entities. For many purposes, expert knowledge can not be replaced with better measures and mathematical data treatment. This is true not only for earth sciences but also for biological systematic, biological classifications, ecology, conservation biology and so on (Ibáñez et al., 2005a,c).

According to the standards of the philosophy of science, many geostatisticians fail to distinguish between the predictive power of theories and getting the best fit for single soil property of a given area using geostatistical tools. Pedometrics does not provide us with any scientific sound alternative to the classical approach but only with *ad hoc* purpose oriented maps. This is the reason why geostatisticians (e.g., Grunwald, 2003) consider that spatial variation of soil properties must be included in a new generation of soil maps. Many "traditional" soil scientists certainly agree with that, and also with the fact that there is a certain degree of arbitrariness in classical soil taxonomies (Arnold, *personal communication*), as also occurs in the biological ones (Ibáñez and Boixadera, 2002; Ibáñez et al., 2005a,b,c). However, the uncritical use of geostatistics in soil survey has several drawbacks. Just to mention three of them, (a) the large number of data required to estimate a variogram and the assumptions regarding stationarity of the variation, necessary to measure spatial variation from a single set of observations, restrict the application of the variogram to small sections of landscape for particular purposes (e.g., precision farming). At coarse and medium scales this is very time consuming and in most cases the price is prohibitive for the decision-makers; (b) data interpolation yields maps of single properties at one depth; (c) geostatistical tools minimise the existence of small or rare soil singularities (but important in some aspects), in opposition to pedodiversity tools (Pachepsky, *personal communication*). This has important implications from a conceptual point of view because the idea of the soil as a complex self-organised system disappears, and from a practical point of view because every soil attribute should be sampled at different distances and depths. This fact hinders soil comparison within regions and among regions for scientific and technological knowledge transfer.

Chaos and complexity sciences, predict that although there might be chaos at a given level, order might arise at higher levels of taxonomic hierarchy and spatial organization. From this perspective, it is wrong to translate the laws and/or regularities of a given pedological hierarchy level to higher ones. In other words, geostatistics is concerned with the study of the spatial variation of single soil properties, while classical taxonomists work with complex systems at higher levels of the pedological hierarchy. The latter are systems that comprise many interacting parts with the ability to generate a new quality of macroscopic collective behaviour through self-organization (e.g., the spontaneous formation of temporal and spatial structures). The recognition that the collective behaviour of the whole system cannot be simply inferred from the understanding of the behaviour of the individual components, has led to various new concepts and sophisticated tools of complexity. Therefore, it is surprising that Lark and Webster (2005) claim that: "*we have been led to believe that the soil at any one place was determined by five soil-forming factors and that the laws of physics must hold*" when, so far, no one doubts that all scientific laws must be reduced to the physical ones.

According to the conception of Heuvelink and Webster (2001) "soil varies at all scales with great complexity, and there is no way that we can capture the full extent of its variation in a deterministic model". We agree with them. Exploring the variability of a single biological species requires also sampling all the population. There are not two identical individuals (or organisms according to the Ghiselin proposition of species concept). In a similar way, Heuvelink and Webster (2001) state that "*a geostatistician models soil properties as if they were realizations of random field*". The corollary of this assertion is that the pedology must disappear as science, if we bear in mind the standards premises of the philosophy of science. This is not a paradigm shift (the logic to the reduction to other disciplines), as we will see in section 4. It is easy to show that if the pedosphere is considered as random fields of single soil properties, the fuzzy logic and the numerical taxonomy do not provide any solution to the continuum analysis. The existence of intergrades exists also in biological classifications as already mentioned in section 2.5. Besides, if the pedosphere is considered as a set of random fields, then, the categorization processes using fuzzy logic and numerical procedures is at least as arbitrary as classical approaches to soil classification. Thus, geostatisticians do not show the way neither to solve the continuum dilemma nor to offer a novel generation of taxonomies.

Pedodiversity

Pedodiversity is another way to quantify and understand the structure of the soil mantle. After the seminal papers of Ibáñez et al. (1990, 1995 and 1998a) pedodiversity analysis has become a growing industry. Some pedometricians attack typological pedodiversity analysis because there are no soil individuals (e.g., Odeh, 1998). Several authors (e.g., Phillips, 1999, 2001a, b; Guo et al., 2003; Saldaña and Ibáñez, 2004; Ibáñez et al., 2005d) have detected strong similarities between spatial biological and pedological assemblages using different tests. It must be highlighted that these studies quantified the pedotaxa composition of soil maps at very disparate scales. Even at world wide level, the number of pedotaxa using FAO keys and the number of biological species increase simultaneously with country areas, and pedodiversity and biodiversity are strongly correlated between them (Ibáñez et al., 2004). These results reveal that pedotaxa and biotaxa follow the same pattern. The conclusion here is that fine classical soil maps represent quite well the nature and structure of the soil mantle and that the objection related to the problem of soil individuals does not hold (Ibáñez et al., 2005a).

In fact, experts in biodiversity studies recognise the shortcomings of the intrinsic problems to categorization (reify), as we can see in the following definition of diversity:

"*The concept of diversity has two primary components, and two unavoidable value judgements. The primary components are statistical properties that are common to any mixture of different objects, whether the objects are balls of different colours, segments of DNA that code for different proteins, species or higher taxonomic levels, or* ***soil types*** *or habitat patches on a landscape. Each of these groups* *of items has two fundamental properties: 1. the number of different types of objects (e.g., species*, ***soil types****) in the mixture or sample; and 2. the relative number or amount of each different type of object. The value judgements are 1. whether the selected classes are different enough to be considered separate types of objects; and 2. whether the objects in a particular class are similar enough to be considered the same type. On these distinctions hangs the quantification of biological diversity*". (Huston, 1994, pp. 65).

Tables 9.1 and 9.2 show that pedodiversity tools have a plethora of mathematical tools and numerous applications, such as spatial pattern analysis and soil geography (Ibáñez et al., 1998a and b, 2004), soil genesis (Phillips, 1999, 2001a. b; Saldana and Ibáñez, 2004), among others, while geostatistical analyses have not shown from their results whether it is possible to obtain regularities and discernible repetitive patterns in the pedosphere structure.

Table 9.1: Some mathematical analysis and procedures related with pedodoversity analysis (synthesized from Ibáñez et al., 2003, with some additional items)

Mathematical tools
Pedorichness measurement and estimations
Pedodiversity measurement and estimation (including dominance, evenness, etc.)
Abundance distribution models
Spatial soil pattern analysis
Pedorichness and pedodiversity-area relationships
Pedorichness and pedodiversity-time relationships
Pedorichness and pedodiversity-energy relationships
Complementarity algorithms (selecting areas to design networks of soil reserves)
Nestedness analysis
Species-range size distribution
Scale invariance (fractals and multifractals)
Non-equilibrium thermodynamics in soil genesis
Convergent vs. divergent pedogenesis
Diversity inventory: mathematical analysis of taxonomical structures
Comparing spatial patterns with biological resources and non-biological ones (e.g., earth surface systems)
Learning of cognitive rules bias in scientific activities

Is a paradigm shift of pedology feasible?

Pedology has become a science after the seminal work of Dokuchaev, who recognised for the first time that soil is a natural body with its laws of self-organisation. If

Table 9.2: Summary of some of the patterns of principal concern to macroecologists and corroboration in the field of the pedology (assuming that biotaxa and pedotaxa could be considered in a similar way) (modified from Gaston and Blackburn, 2000 by Ibáñez et al., 2005d with some corrections)

Pattern	*Age*	*Scaling relation*	*Experts consensus*	*Corroborated in pedology*
Species (taxa)-area relationships	Old	Yes	Very high	Yes
Species richness-isolation relationship	Old	Yes	Low	No
Peninsular effect	Medium	Yes	Low	?
Local-regional richness relationships	New	Yes	Debatable	Exist evidences
Latitudinal gradient in species richness	Old	No pertinent	Debatable	Yes
Species richness-free energy relationship	Medium	?	Debatable	?
Longitudinal gradient in species richness	Medium	?	Debatable	Yes
Altitudinal Gradient in species richness	Old	Yes	Very high	Yes
Species-range size relationships	New	Yes	High	Yes
Geographical range structure	Old	Yes	Very high	Yes
Range-size-niche breadth relationship	New	Yes	Debatable	Exist evidences
Extinction-range size relationship	New	Yes	Debatable	?
Speciation-range size relationship	Medium	Yes	Debatable	No pertinent
Nestedness of species occurrence	New	Yes	High	Yes
Spatial turnover in species identities	Old	Yes	High	yes
Latitudinal gradient in geographical range size (Rapoport's rule)	Medium	?	Medium	?
Abundance-range size distribution	New	Yes	Medium	Yes
Abundance-niche breadth relationship	Medium	Yes	Yes	Exist evidences
Latitudinal gradient in abundance	Old	No pertinent	High	Yes
Species-abundance distribution	Old	Yes	Very high	Yes
Species-body size distribution	Medium	Yes	High	? (soil bodies instead of soil profiles)
Extinction-body size relationship	Medium	Yes	Debatable	? (soil bodies instead of soil profiles)
Speciation body size relationship	Medium	Yes	Debatable	No pertinent
Range size-body size relationship	New	Yes	Debatable	?
Latitudinal gradient in body size (Bergmann' rule)	Medium	No pertinent	Debatable	No
Abundance-body size relationship	Medium	Yes	High	?

the latter were not correct, then pedology would not be a true science, but a knowledge area governed by the laws for physics, chemistry and other basic disciplines (Ibáñez and Boixadera, 2002), against the comments of Lark and Webster (2005).

The main progress of geostatistics has to do with the spatial variability of soil properties, while "classical" inventories and new typological pedometric approaches (e.g., pedodiversity analysis) focus their attention on soil types or pedotaxa. As we can see in Figure 9.1. it is frequent that the same pedosphere segment is considered chaotic (random field) by geostatisticians but deterministic by "classical" pedologists and soil surveyors (but see also Saldaña and Ibáñez, 2007) Therefore we are dealing with different levels of the pedological hierarchy, and the conclusions are not contradictory but probably complementary. It should be clear that "classical" pedologists are also concerned with the spatial variation of pedotaxa and soil properties, but their approach is theoretically different. The paper by Wilding et al. (2002) is a very interesting example of a more "qualitative" approach, which does not exclude geostatistical tools as recognized by the authors.

According to Kuhn (1970) a paradigm shift is a dramatic change in the cosmovision of a given discipline. It is mainly conceptual and not technological in principle. A new paradigm must explain the scientific principles inherited from the old paradigm and, additionally, offer novel ideas. The inclusion of new instrumental or mathematical tools does not constitute a paradigm shift in itself.

In the last years several pedologists have proposed novel ways of classifying soils and other innovations (e.g., Buol, 1994; Richter and Markewitz, 1995; Paton et al., 1995; Ollier and Pain, 1996; Phillips, 1999; Tonkonogov et al., 2002; Ibáñez and Boixadera, 2002; Nachtergaele, 2003; Targulian and Goryachkin, 2004). The convergence of opinions, according to sociology of science (Merton, 1973) is not an unusual fact and probably occurs when a scientific community feels that something is going to happen. In other words, these contributions may indicate that there is a real need for a change in pedology as a scientific discipline, i.e. a paradigm shift, as already claimed by several pedologists (Ibáñez and Boixadera, 2002; Targulian and Goryachkin, 2004). However a true paradigm shift requires gathering and merging not only geostatistics progress but also others such as those mentioned previously.

Conclusions

Geostatistics is a growing industry. Pedologists must not have any doubt that the mathematical tools applied or developed by geostatistics in the last decades have been of paramount importance to the development of soil science. The scientific rigour, novel approaches, and the progress done in the quantification of many (but not all) soil patterns and processes (at level of single soil properties) have been impressive, although also biased towards certain mathematical tools, overlooking others. Other pedometric tools work well with typological units (e.g., pedotaxa) and hard classes (Boolean) partitions (Saldaña and Ibáñez, 2004; Ibáñez et al. 2005d).

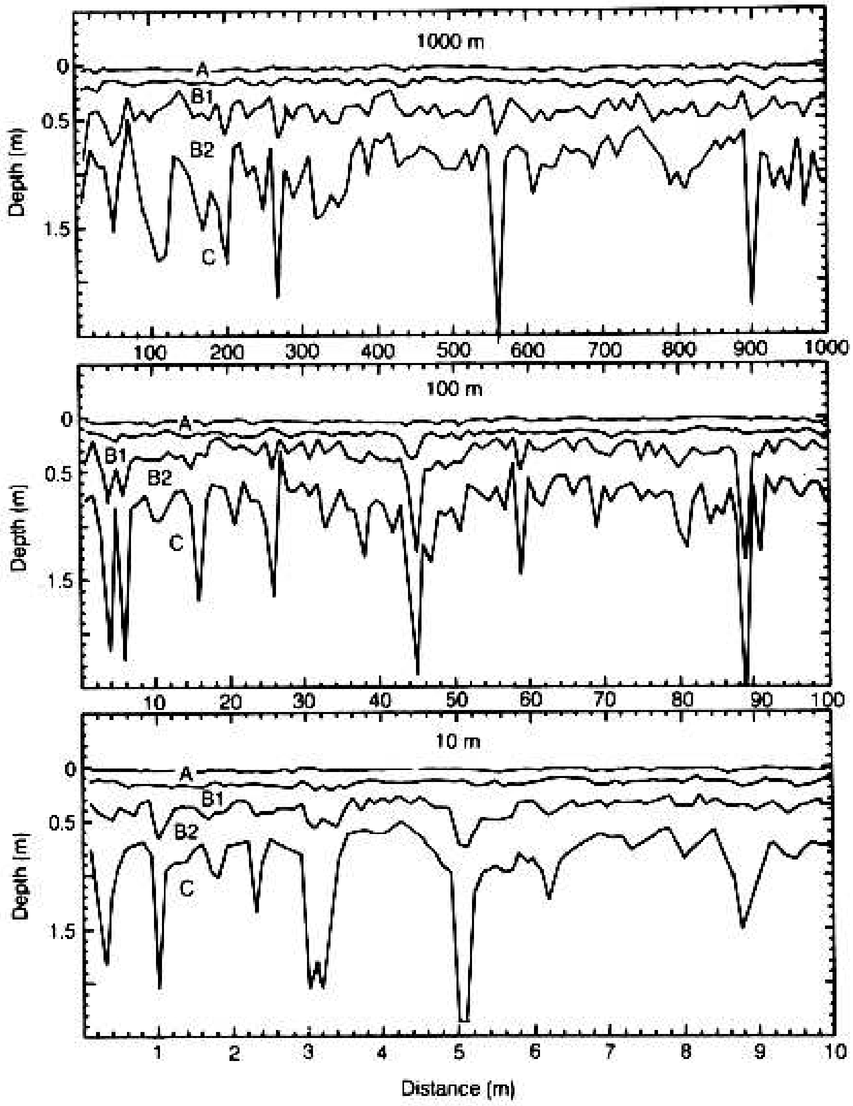

Figure 9.1: Horizon thickness for three scales of observation for the Delhi forest transects. Note that a "geostatistical analysis" at standard depths in the transition zone between different soil horizons could fit a nugget effect while at the same time for classical" pedologists there is a deterministic pattern since A horizon is always below a B horizon, and in the most of the transect C horizon is always below a B one (after Figure 9.1 from Kachanoski, 1988)

Thus, against Grunwald's opinion, a conflict between doctrines should not be a disaster but a great challenge (Prigogine and Stengers, 1988).

In the last years some geostatisticians, but not all pedometricians, -as the former claim-, have attacked hardly the classical schools concerning soil taxonomy and soil survey activities, as well as other novel typological pedometric tools (e.g., pedodoversity, and some fractal and multifractal results)
when the latter work with classical pedotaxa or another type of soil hard classes partitions. Some of the criticisms about the nature of soils and their classification are based on comparisons with biological systems. It has been shown that problems to classify any natural resource, breaking the continuum, are similar. In fact biological and pedological taxonomies have very comparable mathematical structures. The latter seems the product of cognitive bias and thermodynamic principles, but not of idiosyncratic properties of the natural body under analysis. The continuum dilemma appears in all sciences concerning natural resources. The same is true for the *Naturalia/Artificialia dilemma*. Despite the opinion of some soil scientists, neither quantification in pedology, nor the so called soil quality paradigm, represent true changes of paradigms. Geostatisticians' arguments against classical approaches only offer the ending of pedology as a scientific discipline, i.e., the recognition that the soil is a complex self-organized natural system with its own and idiosyncratic laws.

The soil has a polystructural and polyfunctional nature, and thus, requires a healthy epistemological pluralism. In other words, different approaches from different perspectives are needed (the dialectic aspects of science). In addition, as suggested by Sattler (1986), it is not that one of the approaches is superior as far as adequacy is concerned; they may in fact be equally adequate representing complementary aspects of the *patterned continuum of nature*.

To end, we would like to emphasize that, according to the philosophy of science, both perceptions of the natural world are not incompatible (see Mosterín, 2000 and references therein). The antonyms natural-artificial, objective-subjective, and continuous-discrete, among others, are utilised uncritically as suggested by Levy-Leblond (1996). This author shows that these antonyms, from a scientific point of view, are relative and blurred (confused) distinctions, and it is possible to construct a continuum with innumerable meanings among the "idealised" end points, from "pure continuous" to and "pure discrete" or from "pure natural" to "pure artificial". The dilemma of the continuum is also found in Borhr's Principle of Complementarity Wave-Particle (duality) (Ibáñez et al., 1998b). Following this principle, the soil mantle can be viewed as a continuum field (pedosphere) that comprises numerous aggregates of "artificial" or "natural" entities (pedotaxa). In fact, years ago, Fridland (1976) also defended the "discrete-continuous" nature of the soil mantle. At the date, geostatisticians do not provide to us with a theory that refutes the classical ones. They only show that with a huge number of samples and geostatistical tools it is possible to get good purpose oriented products. However, we think that with the necessary funds, novel technologies of proximal soil sensing (Brown, 2005) and sampling efforts, classical pedologists could also get fine predictions of soil distribution along the same landscape. So, they only offer a complementary, interesting and useful perspective to mapping and predicting pedological entities at low levels of the pedological hierarchy.

Therefore, the continuum is not conceptually incompatible with discrete units, as geostatisticians claim. It should be the possible to analyse the soil cover using the two approaches, as it is already done in plant ecology, where phytosociological and gradient analyses approaches, are not considered rivals but complementary approaches (e.g., Biondi et al., 2004).

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Abstract
Geostatistics are a useful tool for understanding and mapping the variation of soil properties across the landscapes. They can be applied at different scales regarding the initial punctual datasets the soil scientist has been provided, and regarding the target resolution of the study. This report is a collection of various studies, all dealing with geostatistical methods, which have been done in Hungary, Russia and Mexico, with the financial support of various research grants. It provides also a chapter about the general concepts of geostatistics and a discussion about limitations of geostatistics with an opening discussion on the usage of pedodiversity index. This report is then particularly recommended to soil scientists who are not so familiar with geostatistics and who need support for applying geostatistics in specific conditions.

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