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# Spatial Aspects of Forest and Forest Soil Management

Johan Stendahl

SWEDISH UNIVERSITY OF AGRICULTURAL SCIENCES



## Spatial Aspects of Forest and Forest Soil Management

**Johan Stendahl**

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### **Abstract**

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*Keywords:* Soil-site study, soil mineralogy, spatial variation, within-stand, geostatistics, kriging, forestry planning.

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*Department of Forest Soils*  
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# Abstract

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# Appendix

## Paper I-IV

This thesis is based on the following papers, which are referred to by their Roman numerals.

- I. Stendahl, J., Olsson, M.T., Snäll, S. & Holmgren, P. Influence of soil mineralogy and chemistry on site quality within geological regions in Sweden. Manuscript.
- II. Stendahl, J. & Oliver, M.A. Spatial variation in forest soil and the implications for soil management. Manuscript.
- III. Stendahl, J. Estimating the within-stand variation by means of geostatistical methods. Manuscript.
- IV. Stendahl, J. & Dahlin, B. Harvester-based forest inventory in thinnings: a pilot study. Manuscript.

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# Introduction

## Background

The spatial variation of forest attributes has become of increasing interest in many research fields such as ecology, soil science, and forestry operational research. Some reasons for this are, for example, the focus on spatial processes in ecological modelling, and in the understanding of ecosystem processes. In forestry, detailed spatial information might lead to better use of the forest resource and better information about the timber, which is extracted from the forests. More precise information will enable a better prediction of the outcome from forest operations, which is a requisite to meet the end-users requests. It will also enable management of the forests to be more adapted to site properties and to environmental issues.

It has been argued that the processes controlling spatial heterogeneity in forests at the tree-scale have large effects on the accumulation of standing crop and on successional species turnover (Pacala & Deutschmann 1995) for example. This implies that the spatial structure of the forests can be of great value in modelling processes related to the forest ecosystem. Also, knowledge of the forest stand structures might aid the simulation of virtual forest stands by computer (Pommerening *et al.* 2000).

At the country level the forest vegetation can be divided into physio-geographic regions, which are characterized by a certain climate, topography, geology etc (Ahti *et al.* 1968). At the landscape level smaller areas are considered, but its definition is not that strict. It can be defined either in biological, administrative or cultural terms. In forestry a landscape is often considered as a continuous piece of land of 5000 to 25000 ha (Stora Skog 1993). In most forests the management has divided the landscape into a mosaic of forest stands with sharp boundaries; this structure is at the stand-level. At the smallest scale the forest can be considered at the tree-level. Traditionally the stand has been the unit used in Swedish forestry, in planning and operations. The aim of stand-based forestry is to identify areas with similar conditions, i.e. they are assumed to be internally homogenous and spatially stable over time. However, it is often not the case that stands are internally homogenous. In response to differences in plant establishment and site conditions, such as soil properties and the physiography, trees will develop at varying rates, which will lead to the within-stand variation in tree attributes such as height and diameter (Ståhl 1992). Information on spatial structure might also provide a better description of reality, and a basis for better-designed experiments (Biondi *et al.* 1994).

The potential for using spatial information in forestry has improved through developments in the techniques of data collection and in data management and



analysis in e.g. geographical information systems (Holmgren 1995). Forestry planning systems, which enable spatially explicit models to be used in the planning process, have also been developed (Nelson & Brodie 1990; Nelson *et al.* 1991; Jamnick & Walters 1993). Some planning systems are not restricted to the forest stand structures and allow continuous spatial variation to be taken into account, for example a raster description of the forest (Hof & Joyce 1992, 1993; Hof *et al.* 1996; Holmgren & Thuresson 1997; Lu & Eriksson 2000). In these systems the formation of treatment units is made a part of the planning process to form *dynamic treatment units*, which are dynamic in time and space. The use of such units in forest planning can improve the economic outcome of forest management (Holmgren & Thuresson 1997), and may also take account of non-timber aspects of forest management, e.g. biodiversity and recreation (Helliwell 1987; Nalli *et al.* 1996). The difference in approach calls for new methods of collecting and handling information from the forests, and there is also the need to consider the spatial structure of the forests.

Geostatistics provides the tools to analyse and investigate the spatial structure of properties and to estimate the values of properties at unsampled locations. With the variogram, the central tool in geostatistics, it is possible to investigate the spatial scale or scales of variation that are the most important in an investigated area and to what extent the variation is spatially dependent, or correlated.

## **Spatial variation in forests**

Spatial variation is the change in the value of a property in terms of its location within an area. For most environmental properties there is some structure in the spatial variation that we observe as pattern. The latter can be described in terms of *spatial correlation* (or *spatial dependence*), i.e. that sites separated by short distances tend to be more similar than those further apart. A homogenous area has no discernible spatial structure, whereas a heterogeneous area has spatial organization of the values at some scale. It is important to note that homogeneity does not imply the absence of variation. On the contrary variation might exist, but no spatial organization of the values can be recognized (Bellehumeur & Legendre 1998). Foresters have long been aware of the existence of spatial correlation (Langsaeter 1926) and its implication to forest inventory was first addressed by Matérn (Matérn 1947, 1960).

The spatial structure of ecological phenomena can correspond to either physical features of the environment or to intrinsic characteristics of ecological processes and phenomena (Bellehumeur & Legendre 1998). The environmental influence on tree properties is from the site conditions, which is the combined effect of climate, topography, soil conditions and so on. These effects are characterized by structure at one or more spatial scales, which is subsequently reflected in the variation of tree properties. Different properties will be of different importance,

depending on which spatial scale that is considered. The intrinsic spatial variation of tree properties is characterized by the competition between individual trees, which cause small-scale variation. Processes within the stand such as gap dynamics and edge effects, as well as forest management will also affect the spatial structure of tree properties. Forest soil variability is related both to intrinsic properties of the parent material, such as soil texture and mineralogy, and to secondary processes in the soil formation. Here, the biota is one component and the trees will influence the soil properties by litter fall and stem flow (Zinke 1962) for example. This will affect the spatial pattern in soil pH and nutrient content, among other things. The soil-plant interaction in forests results in a complex system, for which the spatial pattern is not easily resolved.

To explore the spatial variation in forests involves many different techniques of spatial analysis. Since the trees are discrete entities their distribution in space can be analysed by *point pattern* analysis (Ripley 1981), which examine any clustering among them and any interaction between neighbouring trees (Wälder & Stoyan 1996; Hanus *et al.* 1998). The trees also possess attributes such as diameter and height, which among other things are a function of environmental processes that vary continuously in space. Such environmental processes also affect the attributes of trees, and will result in some degree of continuity in their variation (Wälder & Stoyan 1996). The observed properties can be regarded as regionalized variables, which because of the complexity in their variation, can be treated as random variables. These regionalized variables can be analysed by geostatistical methods. Tree properties are both the result of point pattern processes and continuous random fields and this may affect the behaviour of the variogram when applied on discrete entities such as tree. Stoyan and Wälder investigated this topic by comparing the variogram with the mark variogram and used tree data as an example (Wälder & Stoyan 1996; Stoyan & Wälder 2000). This review focuses on the continuous aspects of spatial variation in forests at the sub-stand level, and especially on the applications of geostatistics to trees and forest soil data.

### *Natural forests*

Natural forests are characterized by the asymmetrical competition between neighbouring trees, i.e. trees are either dominating or suppressed by their neighbours. Disturbances within the forest are also considered as major sources of variation. This can be small-scale disturbance caused by tree fall (Hyttborn *et al.* 1991; Kuuluvainen *et al.* 1998b), or large-scale disturbance caused by forest fires (Zackrisson 1977) or storm fellings (Hyttborn *et al.* 1987). The regeneration pattern is also an important factor in the spatial structure of all forests, and this interacts with the other sources of variation.

Several investigations have been made on spatial variation in natural forests at the tree level (cf. below). The purpose has been mostly to investigate spatial scales and structures in the variation from an ecological point of view. The spatial

pattern in natural forests is characterized by short scale variability in tree size arising from competition between neighbouring trees as well as small and large-scale disturbances.

In a natural mature *Pinus sylvestris* forest in eastern Finland, Kuuluvainen *et al.* (1998) found a fairly strong autocorrelation in tree height with a range of 35 m. This reflected the spatial scale in patches of regeneration in the understory. When only the height of the canopy trees was investigated, the spatial correlation was weak. They also found evidence of asymmetrical competition between neighbouring trees, i.e. that large trees suppress smaller trees. The asymmetrical competition was shown in the variogram as a variance peak at short distances. This pattern was also found in an old pristine *Picea abies* forest in southern Finland (Kuuluvainen *et al.* 1996); the spatial correlation was weak up to 6 m for diameter and height, and there was a variance peak at very small distances (<1 m). Kuuluvainen *et al.* (1998) concluded that natural *Pinus sylvestris* forests exhibit complex small-scale patterns of spatial heterogeneity and correlation in tree size. This is important for stand-scale habitat diversity, which could have aggregated effects on ecosystem dynamics at the larger spatial scale. In another investigation of a large relatively homogenous area of pristine *Picea abies* taiga in southern Ural (Kuuluvainen *et al.* 1998b), the forest was characterized by pronounced small-scale spatial variation, whereas it was relatively homogenous at a larger scale. This was related to the small-scale mosaic of patches at different stages of recovery from small-scale disturbances such as tree-fall. The small-scale variability seemed to dominate large-scale variation from fire disturbances etc., which is considered as important sources of variability in natural forests (Zackrisson 1977). In a very old (>615 years) natural forest of *Pinus ponderosa* in Arizona, Biondi *et al.* (1994) investigated spatial and temporal patterns in tree dimensions and basal area increment (BAI). The range of spatial correlation was about 30 m for diameter and basal area. This structure mainly reflected clusters of trees of different size, i.e. regeneration patches. Further, they found that the spatial pattern was preserved over a 70-year time span except for BAI, whose spatial correlation decreased with time. In a tropical Malaysian forest the spatial distribution of the density of *Macaranga lowii* (Bellehumeur & Legendre 1998) showed nested spatial variation with scales of variation at 50 m and at 500 m. The short-scale variation accounted for 47% of the total variation, whereas the large-scale variation was less important.

### *Managed forests*

In managed forests the spatial structure can be attributed to natural processes as well as to forest management practises. In stand-based forestry the stand structure will develop the landscape over time into a mosaic of forest stands at different stages of development. This is the major source of variation. Forest operations such as thinning will result in spatial variation of forest properties at a smaller scale, i.e. within the stand. One aim of thinning is to reduce the variation in basal area and to make the distribution of trees more even within the stand. Most

investigations of spatial variation in managed forest stands are at the large scale, over large estates for example, and aim to estimate the forest resource.

In a comparison of the spatial structure of a managed and an unmanaged spruce forest in southern Finland (Kuuluvainen *et al.* 1996), strong spatial correlation occurred at 10 to 30 m for both tree diameter and height in the 105 year old managed stand. This was due mainly to the contrast between dominant trees and patches of regenerated trees; when only the dominant trees were analysed the spatial correlation was non-existent. The stem density was 1360 stems ha<sup>-1</sup>, but only 400 stems ha<sup>-1</sup> belonged to the dominant layer. The distribution of trees was regular, with a separating distance of 4 m for the managed stand, whereas it was random for the unmanaged stand. In a German investigation (Pommerening 2000) the spatial structure of one old natural forest and one tree plantation was investigated. In the plantation a regular pattern was found which corresponded to the rows of planted trees.

Gunnarsson *et al.* (1998) attempted to estimate the forest resource on a continuous grid in a 400 ha intensely managed forest estate in southern Sweden using geostatistical estimation, kriging. Before the kriging, the data was stratified according to age class, in order to maintain the stand boundaries in the kriged map. Hardwood trees were evenly distributed within the estate. The variograms of forest volume, site quality, age etc. had ranges of spatial variation of 150 to 400 m, which corresponded with the mean size of the stands. Thus, the most important source of variation was the stand structure. A comparison by regression between the kriged estimates and the validation data was modest and 44% of the variation was explained ( $r^2 = 0.44$ ). Spatial interpolation of forest data was also applied in a Canadian mixed fir/birch forest within two areas of 20 ha and 1500 ha (Gilbert & Lowell 1997). Despite significant autocorrelation tests (Moran's I and Geary's *c*) in the smaller area, kriging interpolation of the forest volume gave poor results. The confidence interval was about 85% of the mean and only 16% of the variation in the validation data was explained ( $r^2 = 0.16$ ) by a 50 m sampling grid. An Indian investigation (Samra *et al.* 1989) of a 0.5 ha Dharek plantation (*Melia azerdarach L.*) showed that 70 to 77% of the variation in tree height and height increment were spatially correlated, and the ranges of spatial variation were 16 m and 27 m respectively. Kriging was used to evaluate of the forest resource. Kriging the tree height resulted in an error variance of 9% of the mean height. The variation in tree height could be attributed to variation in soil properties.

Estimation of the forest resource by kriging has been made at the large-scale by some investigators (Hock *et al.* 1993; Payn *et al.* 1999). Large-scale investigations of forest spatial structure have also been made using remotely sensed data (St-Onge 1997), as well as forest resource estimates from ground data together with remotely sensed data (Nunes *et. al* 2000; Pereira *et. al* 2000).

## *Forest soils*

A fundamental reason for soil heterogeneity is large- and small-scale variation in bedrock mineral composition (Reiche, 1950 in Järvinen *et al.* 1993), which has a significant influence on the weathering of rocks. Spatial variation in soil texture depends to an important extent on the genesis of the parent material, i.e. whether it was deposited by water or as glacial drift, or if it was formed *in situ* for example. Many soil properties are secondary, i.e. the result of other properties and processes. For example, soil texture, mineralogy, topography, ground water table, and vegetation give rise to the variation in properties such as pH and the depth of the organic horizon. The influence of trees on soil properties by litterfall and throughfall has long been known (Zinke 1962; Gersper & Holowaychuk 1970; Boettcher & Kalisz 1990), and so tree influence itself is also considered a soil forming factor (Gersper & Holowaychuk 1970).

The soil is a complex system, which is also evident in the complexity of the spatial variation in soil properties. Properties of the soil such as texture, depth, and chemistry are all characterized by spatial structure at some particular scale, but it is difficult to know beforehand the scale of variation that is likely to be the most important for different soil features in an investigation.

Many investigations have focused on the spatial variation in forest soil properties at the tree level. The purpose has been monitoring and the design of sampling schemes (Liski 1995; Bringmark & Bringmark 1998). Spatial approaches to ecological issues have also been addressed, such as tree-species influence on soil properties (Nykqvist & Skyllberg 1989; Liski 1995; Saetre 1999; Saetre & Baath 2000). As pointed out by Järvinen *et al.* (1993) the spatial variation in primary properties of the soil has been given less attention in the literature than secondary soil properties and the processes giving rise to the latter.

In southern Finland the spatial variation in the properties of the mineral soil was investigated in a 1 ha *Pinus sylvestris* stand on a sorted glacial deposit (Järvinen *et al.* 1993). A factor analysis resulted, after rotation by Varimax, in a soil texture factor and a soil mineral factor, which exhibited ranges of spatial correlation of approximately 20 m. The existence of spatial correlation indicated gradual variation from place to place in these soil properties. The mineral soil was weakly correlated to seedling establishment at the site (Kuuluvainen *et al.* 1993). At the same site, Hokkanen *et al.* (1995) investigated the spatial variation in topsoil properties and the relation to mineral soil properties. The variables investigated were carbon and nitrogen content, respiration, humus thickness, loss on ignition, electrical conductivity, and pH. The topsoil properties showed weak spatial dependence, although some relation with the influence of trees could be seen. No correlation between topsoil and mineral soil properties was evident. They concluded that the influence of larger trees was the main cause of topsoil heterogeneity in the investigated area (Zinke 1962; Riha *et al.* 1986), and that the spatial correlation in soil pH was too short a scale (<1 m) to be identified.

In a semi-natural forest in England the average range of autocorrelation for sand, clay, silt, hue and mottling at four profile depths was 40 m (Oliver & Webster 1987). A nested survey, with sampling intervals ranging from 6 m to 600 m showed that approximately 80% of the variation occurred over distances less than 60 m. In addition they found that the variation in the topsoil was more gradual than that of the subsoil. Topsoil variation seemed to have been smoothed by periglacial processes. The variation in the subsoil showed a closer association with changes in the underlying lithology. For pH the pattern was the reversed and there was more variation in the topsoil, because of the marked effect of the trees by stem flow for example.

In an investigation of coniferous stands in northern Sweden, Nykvist and Skyllberg (1989) concluded that the pH of the mor layer was very variable within the stands, and that all of the variation was found within 2 m<sup>2</sup> plots.

## Objectives

The general objectives of this thesis are to estimate the degree of within stand variation in forest stands, as well as the interaction between soil and forest properties at both the small and large scale.

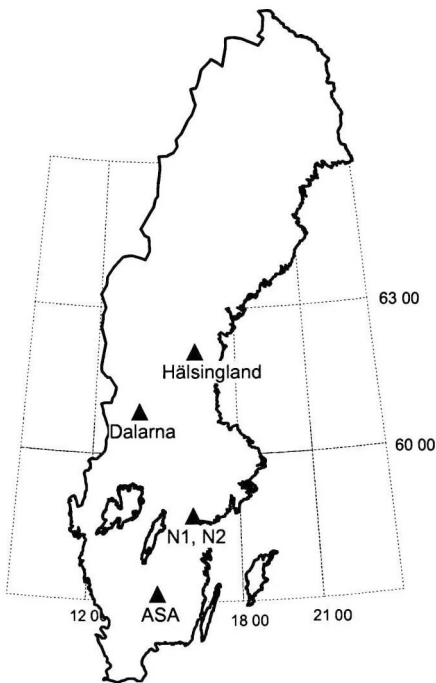
The specific objectives are:

1. To estimate the regional influence of forest soil mineralogy on site quality and to assess the feasibility of predicting forest site quality from the mineralogy in the C horizon and the relations with soil chemical properties in the upper part of the soil (O, A, E, upper B and lower B horizon) (Paper I).
2. To quantify the within-stand variation in the properties of the forest and mineral soil, and the relations between these for a forest stand (Paper II). In addition, to compare the within stand variation in forest properties of three managed stands at different stages of development, and to assess the effort needed for mapping forest properties within the stands (Paper III).
3. To evaluate the potential use of data collected by the harvester at thinnings to estimate the forest resource after thinning. The aim is to estimate stand mean values and a spatially continuous model of various forest properties (Paper IV).

# Material and methods

## The investigations

Two approaches were taken to meet with the objectives defined above. A regional survey of soil and forest properties was made to determine the importance of soil mineralogy on the regional variation in site properties (Paper I). Secondly, intensive sampling was made in three forest stands of different ages to determine the amount of within-stand variation, the extent to which it is spatially structured, the scales at which spatial variation exists, and the effort needed to resolve it (Paper II-IV). The relationship between soil and forest properties within stands was also studied (Paper II).



**Figure 1.** Map of the investigated sites. Paper I involves forty sites in the Dalarna and Hälsingland areas. Paper II the site in Asa (ASA), Paper III the site in Asa and two sites near Norrköping (N1, N2), and Paper IV one site in Norrköping (N2)

### *Regional survey of forest and soil properties, Paper I*

Forty sampling sites were chosen with the aim of keeping all environmental parameters as similar as possible except for soil mineralogy. The sites were evenly distributed within two areas in Dalarna and Hälsingland in mid Sweden (Fig. 1). The geology of the Dalarna area is dominated by sandstone, sometimes covered by basalt beds, and some porphyry and porphyrite. In the Hälsingland



area the bedrock was characterized by granitoids that merged with mafic sedimentary rocks, and some dolerites. In essence, the mineralogy of the Dalarna area was poor whereas for the Hälsingland area it was rich. The sites were located in mature managed forest stands on podzolised tills. The site quality was estimated from the expected dominant height at the age of 100 years, i.e. *site index*. The height of the current stand was translated to the expected height at 100 years from height development curves (Hägglund 1973, 1974). The site index was larger in the Hälsingland area than in the Dalarna area.

At each site a sample was taken from each of the following soil horizons: O, A, E, upper B (B<sub>1</sub>), lower B (B<sub>2</sub>), and C. In the upper soil horizons (O to B<sub>2</sub>) several soil chemical properties were determined: exchangeable cations, pH, and total content of carbon and nitrogen. In the C horizon the elemental composition was determined by ICP (plasma emission spectrometry) after: (1) fusion with LiBO<sub>2</sub> to obtain total elemental composition, and (2) extraction by *aqua regia*. The soil mineralogy was estimated by a normative mineralogical assessment (see Paper I) (Hjelmqvist 1966), which is based on knowledge of the elemental composition of various soil minerals and how they are dissolved. It takes into account the total elemental composition, the *aqua regia* extractable amounts, and the X-ray diffraction pattern (XRD). Soil texture and the depth of the horizons was also determined for each horizon at each sampling location.

The multivariate structure in the soil mineralogy was analysed by principal component analysis, PCA (Webster & Oliver 1990), and the relationships between soil and forest growth potential was investigated by correlation analysis and multiple step-wise regressions between different soil properties and forest site index.

#### *Intensive sampling in forest stands, Paper II-IV*

An intensive sampling was made in three stands in the south of Sweden. The sampling included an inventory of all trees larger than 5 cm in diameter at 1.3 m height. For each tree the diameter and the location was determined, and in addition, tree height was determined in two of the stands. In one stand a detailed soil survey was made.

The stands were (Table 1, Fig. 1): a mature mixed Scots pine (*Pinus sylvestris* (L.)) and Norway spruce (*Picea abies* (L.) Karst.) stand near Norrköping (N1), an unthinned Scots pine stand near Norrköping (N2), and an unthinned Norway spruce stand near Asa (ASA). The geology for N1 was older commonly foliated granite to tonalite, and the soils were podzolised sandy till or thin soil on superficial bedrock. The N2 site was located on younger, coarse porphyric granite, and the area had rock outcrops where the soil was shallow, and in the depressions sediments or organic soils. N1 and N2 are located below the highest post-glacial shoreline.

**Table 1.** Descriptive statistics of investigated forest stands. (N1=mature mixed pine-spruce stand, N2=unthinned pine stand, ASA=unthinned spruce stand)

Variable	Unit	N1	N2	ASA
Area	(ha)	5.1	1.9	2.4
Age	(year <sub>1.3m</sub> )	95	40	31
Pine	(%)	38	92	6
Spruce	(%)	58	8	91
Diameter	(mm)	264	185	161
Height	(cm)	225	157	-
Basal area	(m <sup>2</sup> ha <sup>-1</sup> )	30	26	28
Stem density	(stems ha <sup>-1</sup> )	453	913	1294

The geology for ASA is dominated by acid volcanites of rhyolitic composition, with small areas of mafic diorite and gabbro. The soil is mainly podzolised tills and it is located above the highest post-glacial shoreline.

The tree diameter was determined using a calliper, and for N1 and N2 the height of 25% of the trees was determined also. At the ASA site the height was determined for a small subsample of trees. The position of each tree was determined in relation to a 25 m-reference grid by measuring distance and azimuth from the nodes of the grid. The reference grid was located by DGPS. Mean diameter, basal area and stem density was calculated for circular plots, which were formed in the computer. In N1, plots with a radius of 7.98 m (200 m<sup>2</sup>) were used, and in N2 and ASA the plots had a radius of 5.64 m (100 m<sup>2</sup>). The plots were distributed as square grids of different cell size in Paper II, III, and IV.

For Paper IV each tree was also given an ID tag. After the inventory the trees at the N2 site were thinned with a one-grip harvester. The machine was equipped with a GPS that recorded the coordinates of the strip roads. It was not equipped to record the position of the felling head, and hence not the position of the removed trees. Therefore the ID number of each harvested tree was recorded and the database of the original trees was updated with information on which trees that had been removed. This methodology was adopted to imitate data that would be produced if the harvester had been properly equipped.

A buffer analysis was carried out to investigate the selectivity in the thinning operation. Buffers were created along the strip roads in a GIS to a distance of 5 m from the strip road centre line. Ten buffer zones were created and each zone was 0.5 m wide. The properties of the trees located within each buffer zone were calculated for the original trees, the removed trees and the remaining trees after the thinning.

At ASA stand, an intensive soil survey was carried out. Soil samples were taken from the upper 10 cm of the B horizon at 120 locations based on a nested sampling grid, designed to detect spatial variation at distances >10 m. At each sampling location soil was taken from each corner of a 5 m triangle centred on the sampling point and the three subsamples were then bulked to form a composite or bulked sample. The aim of bulking was to reduce natural locally erratic variation in soil properties, and the influence of single trees on the soil. The relative ground elevation was determined by levelling. Each sample was analysed for pH, total amounts of carbon, nitrogen and sulphur, and soil particle size distribution in five classes. Duplicate samples of 0.035 g soil were analysed separately for carbon, nitrogen and sulphur, and averaged to minimize the effects of laboratory error and the random variation due to the small weight of the sample analysed. The soil properties were analysed by PCA (Webster & Oliver 1990) and the first two components were further rotated using Varimax rotation (Kaiser 1958). The two rotated components were used further in the spatial analysis.

To quantify the within-stand variation in forest and soil properties a geostatistical analysis was carried out. To assist the reader, some fundamental geostatistical theory and nomenclature are given as an introduction to the topic below.

## Geostatistics

### *Background*

Geostatistics deals with phenomena that vary in space or time (Olea 1992). Matheron (Matheron 1963, 1965) formulated the theoretical base of geostatistics in the Theory of Regionalized Variables. A *regionalized variable* can be any property that takes a value at every location within an area in space (or time). It is similar to the *random field* in classical statistical literature (Wälder & Stoyan 1996).

Geostatistics is based on a probabilistic approach for describing spatial variation; at each point the value is considered as a realization of a stochastic process or *random function*. In reality there is only one possible value of a property, or outcome of the random function, at each location. Therefore, we assume that the property is repeating itself in space to provide multiple realisations. For this assumption to hold the random function must be *stationary*, i.e. it has some characteristics that are the same everywhere. This is necessary to characterize the random function and make inference for the area investigated.

The random process  $Z(\mathbf{x})$  can be represented by the following model of spatial variation:

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

where  $\mu$  is the mean of a property and  $\varepsilon(\mathbf{x})$  is a spatially correlated random component at a location  $\mathbf{x}$ .

Second-order stationarity is the strongest assumption we make about the random function. For it to hold the expected values of the property,  $E[Z(\mathbf{x})] = \mu$ , must be the constant and finite over the investigated area. This implies the absence of trend, deterministic variation. Further, the covariance and variance between two points depends only on the separating distance  $\mathbf{h}$  between two locations,  $(\mathbf{x})$  and  $(\mathbf{x}+\mathbf{h})$ , and not on their absolute location in the investigated area:

$$C(\mathbf{h}) = E[\varepsilon(\mathbf{x})\varepsilon(\mathbf{x} + \mathbf{h})]$$

where  $C(\mathbf{h})$  is the covariance,  $\varepsilon(\mathbf{x})$  and  $\varepsilon(\mathbf{x}+\mathbf{h})$  are a spatially correlated random components at a location  $\mathbf{x}$  and  $\mathbf{x}+\mathbf{h}$ . For many situations, second-order stationarity cannot be assumed, for example when the mean changes over an area and the variance continues to increase as the area becomes larger. To overcome this Matheron, formulated the *intrinsic hypothesis*, with weaker assumptions of stationarity. This states that the expected difference is zero and the variance of the *increments*,  $[z(\mathbf{x})-z(\mathbf{x}+\mathbf{h})]$ , must be stationary, i.e. it must depend only on the distance and direction between two locations  $(\mathbf{x})$  and  $(\mathbf{x}+\mathbf{h})$ , and not on their actual location within an area:

$$\text{Var}[(\mathbf{x}) - (\mathbf{x} + \mathbf{h})] = E\{[(\mathbf{x}) - (\mathbf{x} + \mathbf{h})]^2\} = 2\gamma(\mathbf{h})$$

where  $\gamma(\mathbf{h})$  is the semivariance for lag distance  $\mathbf{h}$ . The intrinsic hypothesis is more general and hence the variogram has become the central tool of geostatistics for many applications. Under the intrinsic hypothesis the covariance can no longer be defined, but for second order stationary processes the semivariance and covariance are equivalent:

$$\gamma(\mathbf{h}) = C(\mathbf{0}) - C(\mathbf{h})$$

In practice we can restrict the assumptions of stationarity further to consider only small areas. These assumptions are those of *quasi stationarity*. In kriging for example (cf. below), we only use the data from a small neighbourhoods to make spatial estimation, and quasi stationarity will suffice.

### The variogram

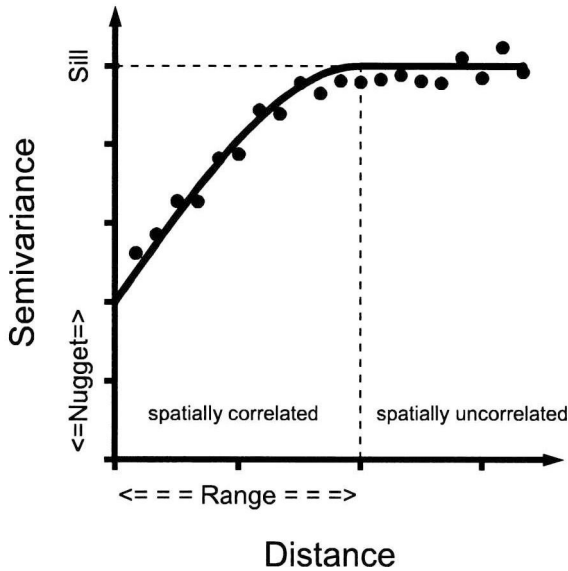
The spatial variation of the random function can be described in terms of spatial (*auto*)*correlation*, i.e. points separated by short distances tend to be more similar than those separated by longer ones. The random function can be characterized by the variogram, which is a pair-wise variance function. It summarizes the semivariance,  $\gamma(\mathbf{h})$ , for pairs of points separated by a distance  $\mathbf{h}$ , the lag:

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

where  $\hat{\gamma}(\mathbf{h})$  is the estimated semivariance,  $M$  the number of pairs of comparisons for the distance vector  $\mathbf{h}$ , and  $z(\mathbf{x})$  and  $z(\mathbf{x}+\mathbf{h})$  are the values of a property at locations  $(\mathbf{x})$  and  $(\mathbf{x}+\mathbf{h})$ , separated by  $\mathbf{h}$ . The semivariance is calculated for a sequence of separating distances or lag intervals and this series constitutes the experimental variogram.

The variogram (Fig. 2) can describe both the spatially structured part of the variation and the spatially uncorrelated variation. It generally features a monotonic initial slope that often flattens to an upper bound at a distance known as the *range*. The range is the limit of spatial autocorrelation or dependence in the data and corresponds to the average size of the patches in the spatial structure, or pattern. The semivariance at which the variogram flattens or reaches an asymptote is known as the *sill* variance. There is often a discontinuity on the ordinate at zero lag, which is called the *nugget* variance. The spatially correlated part of the variation and the nugget variance comprise the sill variance. The nugget variance represents the spatially uncorrelated variation at the scale of sampling. It is the unresolved variation of the property, which can arise from variation at distances less than the lag interval (the main source), measurement error or purely random variation.

A mathematical function is fitted to the experimental semivariances; it is a theoretical model of spatial variation for the random variable. This must be an *authorized* model that fulfils the assumptions of conditional negative semi-definiteness (CNSD) (Webster & Oliver 2001). The authorized models have different shapes to fit the different forms of the experimental variogram. More than one model may also be combined into *nested* models, which implies that the property might have more than one distinct scale of spatial variation. Examples of models can be found in Papers II and III. The variogram model of a second order stationary property is *bounded*, i.e. the sill exists and is reached, and its value corresponds to the variance of the sample. Properties with variograms that are *unbounded*, i.e. never reach a sill, do not fulfil the assumptions of second order stationarity and are intrinsic only, i.e. they fulfil the intrinsic hypothesis.



**Figure 2.** The variogram. Along the ordinate is the semivariance and along the abscissa is the distance between points. The *range* is the range of spatial correlation and the *sill* is the variance at distances longer than the range. The *nugget* is the spatially uncorrelated variation, whereas the difference between the sill and the nugget is the spatially correlated, or structured variation

### *Kriging*

Kriging is a method of estimating values at unsampled places using the variogram model and the data. Estimates can be made for points or over blocks, i.e. the support of the target point. Kriging is a generic term that embraces many techniques (Goovaerts 1997); the type most commonly used is *ordinary kriging*. The basic function for ordinary kriging shows that it is essentially a form of locally weighted average. For kriging at a point (punctual kriging) the equation is:

$$\hat{z}(\mathbf{x}_0) = \sum_{i=1}^N \lambda_i z(\mathbf{x}_i)$$

where  $\hat{z}(\mathbf{x}_0)$  is the estimated value at a location  $\mathbf{x}_i$ ,  $\lambda_i$  are the *kriging weights*, and  $N$  is the number of sample sites.  $N$  is usually reduced to a subsample  $n$ ,  $n \ll N$ , which is the number of sample sites in the kriging neighbourhood. It is the kriging weights that make kriging different from other methods of interpolation, which use arbitrary functions for weighting. The weights,  $\lambda_i$ , depend on the model of spatial variation and on the configuration of the data points. They are also a function of the distance between each point in the neighbourhood ( $N$ ), the distance between each point and the target point or block to be estimated, and their spatial distribution. This results in less weight being given to data points that are clustered or grouped together and to those that are screened by other data values closer to the target point. Points nearest to the target point get the most weight, i.e. kriging is local. The sum of  $\lambda_i$  is constrained to sum to 1 to ensure that the estimates are unbiased:

$$\sum_{i=1}^N \lambda_i = 1$$

The weights are derived in such a way as to minimize the estimation or kriging variance, which is given by:

$$\sigma^2(\mathbf{x}_0) = 2 \sum_{i=1}^N \lambda_i \gamma(\mathbf{x}_i, \mathbf{x}_0) - \sum_{i=1}^N \sum_{j=1}^N \lambda_i \lambda_j \gamma(\mathbf{x}_i, \mathbf{x}_j)$$

For kriging over blocks there is an additional term in the equation for the kriging variance:

$$\sigma^2(\mathbf{x}_B) = 2 \sum_{i=1}^N \lambda_i \bar{\gamma}(\mathbf{x}_i, B) - \sum_{i=1}^N \sum_{j=1}^N \lambda_i \lambda_j \gamma(\mathbf{x}_i, \mathbf{x}_j) - \bar{\gamma}(B, B)$$

where  $\gamma(\mathbf{x}_i, \mathbf{x}_j)$  is the semivariance between points  $\mathbf{x}_i$  and  $\mathbf{x}_j$ ,  $\gamma(\mathbf{x}_i, \mathbf{x}_0)$  is the average semivariance between data point  $\mathbf{x}_i$  and the target point  $\mathbf{x}_0$ ,  $\bar{\gamma}(\mathbf{x}_i, B)$  is the average semivariance between data point  $\mathbf{x}_i$  and the block  $B$ , and  $\bar{\gamma}(B, B)$  is the within block variance. For point estimates (point kriging) the last term is omitted. All semivariances are derived from the variogram model.

The value of  $\sigma^2(\mathbf{x}_0)$  is least when:

$$\sum_{i=1}^N \lambda_i \gamma(\mathbf{x}_i, \mathbf{x}_j) + \psi = \gamma(\mathbf{x}_i, \mathbf{x}_0) \quad \text{for all } j$$

and:

$$\sum_{i=1}^N \lambda_i = 1$$

The Lagrange multiplier,  $\psi$ , is introduced to achieve minimization and the sum of the weights is constrained to 1. Thus kriging is an optimal unbiased estimator.

For a more detailed introduction to geostatistics, consult more extensive literature on the subject (Isaaks & Srivastava 1989; Goovaerts 1997; Kitanidis 1997; Webster & Oliver 2001).

## Results and discussion

### Regional influence of soil mineralogy on site index, Paper I

The two regions investigated in Dalarna and Hälsingland, respectively, formed two distinct sub-populations based on the mineralogy. This conclusion was based on results of the PCA analysis of the mineralogy. It suggested that the mineralogy of the two regions was different, mainly with respect to quartz content and also different within-region mineralogy. In Paper I the components are described in detail.

The correlation between soil minerals and forest site index differed between the two regions (Table 2). In the Dalarna area the correlations between forest site index and soil minerals were strongest for chlorite, epidote and amphiboles. In the Hälsingland area K-feldspar, epidote, amphiboles and quartz were the most strongly correlated with forest site index. It was noteworthy that the site index was independent of chlorite in the Hälsingland area. For some minerals the correlations with forest site index were the opposite in the two areas. Biotite, for example, was positively correlated with forest fertility in the Hälsingland area, whereas in the Dalarna area it was negatively correlated. Similarly, plagioclase was positively correlated with forest site index at Dalarna and negatively correlated at Hälsingland. When the two regions were analysed together epidote and amphiboles correlated most strongly with forest site index together with quartz and titanite (Table 2).



Separate regressions were made between forest site index and the different soil properties for each region (see Paper I), which are here summarized. The sign of the coefficients are given within brackets (). In the Hälsingland area plagioclase (+), K-feldspar (-) and chlorite (-) had the largest coefficients in the regression function, which explained 61% ( $r^2=0.61$ ). In the Dalarna area the minerals with the largest coefficients were chlorite (+) and, to a smaller degree, iron oxides ( $\text{Fe}_2\text{O}_3$ ) (+). It was noteworthy that amphibole, which is easily weathered, had a negative influence in the regression. The regression function for the Dalarna area explained 37% ( $r^2=0.37$ ). The regressions based on soil texture explained 48% ( $r^2=0.48$ ) of forest site index in the Hälsingland area, whereas in the Dalarna area no variation was explained ( $r^2=0.01$ ).

The general pattern was that site quality related positively to the easily weathered minerals, such as epidote, amphibole, chlorite and biotite. But not all minerals were consistently related in the same way to site index for the two geological regions. Chlorite was important for site index in the Dalarna area where the mineralogy was poor in other magnesium bearing minerals. In the Hälsingland area where the magnesium could be supplied from other minerals the relation between chlorite and site index was weak. A balance of the base cations seems to be important the forest site quality, and which minerals that are important for site quality seem to depend on the total mineralogical composition. The regional variation in site quality could be estimated to some extent from mineralogy in the C horizon. The regression functions benefited from dividing the data according to geological region.

The regression between site index and chemical properties in the O to B horizon explained 53% to 80% for the Hälsingland area. In the O horizon the nitrogen was positively related (+) and hydrogen negatively related (-) to site index and had large coefficients in the regression function. For the A and B horizons coefficients were large for the base cations, mainly for calcium (+). There was a tendency that the regression functions based on soil chemistry in the O to B horizon explained systematically less of the variation (had smaller  $r^2$  values) in site index the deeper the horizon. In the Dalarna area the regression between site index and properties in the O to B horizon explained 18% to 68% of the variation. Nitrogen had the largest coefficient (+) in the regressions for most soil horizons (O, A and B<sub>1</sub>), and pH (+) as well for the O and B<sub>2</sub> horizons. For the E horizon, calcium (-) and hydrogen (+) had the largest coefficients in the function.

The regressions between the soil properties and site index accounted for a larger amount of variation in site index for the Hälsingland area than for Dalarna area. One exception was the data from the E horizon. The associations were stronger between topsoil properties and the site index, than for mineralogy, due to the interaction between the forest stand and the upper soil horizons by nutrient

**Table 2.** Correlation between site index ( $H_{100}$ ) and soil mineralogy in the C horizon

Mineral	All data	$H_{100}$	
		Hälsingland	Dalarna
Quartz	-0.48	0.33	-0.28
Plagioclase	0.48	-0.21	0.31
K-feldspar	0.01	-0.56	-0.03
Biotite	0.37	0.19	0.00
Muscovite	0.03	0.13	0.08
Chlorite	0.44	-0.09	0.54
Vermiculite	0.11	0.15	0
Amphibole	0.56	0.33	0.35
Epidote	0.55	0.33	0.47
Titanite	0.43	0.29	0.39
Rutile	0.27	0.28	0.11
Apatite	0.30	0.00	0.21
Fe <sub>2</sub> O <sub>3</sub>	0.29	-0.01	0.22
Al <sub>2</sub> O <sub>3</sub>	-0.13	0.17	0.06

cycling. Topsoil properties are not independent of the forest stand and should therefore not be used to estimate site index at non-forested sites.

## Forest-soil interaction at the small-scale, Paper II

The principal component analysis extracted two general features of the soil data: general soil chemistry (1<sup>st</sup> principal component, PC1), and general soil texture (2<sup>nd</sup> principal component, PC2). Experimental variograms were computed and models fitted to the PC scores of PCs 1 and 2. This was also done for the individual variables. The models fitted were bounded, i.e. the processes examined within the study area were second order stationary (Webster & Oliver 2001).

Among the soil variables investigated in Paper II, three major scales of variation were detected at about 40 m, 80 m, and >100 m. The first group had ranges of 29 m to 44 m (total carbon, nitrogen and sulphur, medium sand, coarse sand, and PC1); the second group had ranges of 69 m to 92 m (tree basal area, silt and clay content, altitude, PC2 and pH); and the third group had a range of 100 m to 122 m (total carbon, gravel, fine sand, and PC1). The variograms for total carbon and PC1 were nested with ranges of 30 m and 122 m, and 30 m and 112 m, respectively.

Carbon and nitrogen were strongly correlated ( $r=0.89$ ) and had similar spatial patterns. Carbon had a nested spatial structure, i.e. two distinct scales of spatial variation, which was seen in the small- and large-scale patchiness of the carbon when mapped. The short-scale variation reflected the joint distribution of carbon and nitrogen. The organic nature of carbon and nitrogen implies that there might be an interaction with the forest stand, but the spatial scales of the forest



**Figure 3.** Maps of basal area, pH and carbon content in the B horizon, and 2nd principal component (corresponding to soil texture)

properties were different from those of the soil. This suggests that the variation in carbon and nitrogen might be more related to textural and drainage effects or other components of the soil ecosystem. The terrain in the area was gently undulating and there was a depression that in the middle of the stand, which might cause water accumulation. Such wetter conditions favour the accumulation of organic matter and large values for carbon and nitrogen. For pH the spatial distribution was not as variable as for carbon and nitrogen.

The basal area varied considerably within the stand (Fig. 3). The maximum basal area was in a distinct patch that coincided with an area where pH was also at its maximum. A similar area was also evident in the maps of texture (PC 2), carbon and nitrogen (Fig. 3). The C-N ratio of this area was small (minimum 13),

which indicates better quality organic matter. This will decompose in the topsoil easily and the values for total carbon and nitrogen in the B horizon were small. In other areas where a larger content of carbon and nitrogen was found, the C-N ratio large (maximum 28), which indicates the presence of humic substances. These are recalcitrant and will be transported down in the soil profile and the carbon content will be large. The general picture was that the basal area is positively related to pH and fine soil texture, whereas it was negatively related to carbon and nitrogen, but there were exceptions to this pattern in some parts of the stand. The property showing the most consistent relation with basal area in the study area was fine soil texture.

In stand-based forestry inhomogeneous stands will lead to suboptimal economic output for some parts of the stand. A system that can create homogeneous management units is needed to optimise production, in much the same way as that proposed in the field of precision agriculture. In this study the range of spatial autocorrelation for basal area was 70 m. To identify the spatial structures (patterns) of basal area, and thus potentially homogeneous management units, the sampling interval would need to be just less than 35 m. This result suggests that the management units for productivity related forest planning should be about 0.4 hectare for the assumptions of homogeneity to hold.

### **Within-stand variation in forest properties, Paper III**

The diameter of individual trees was highly variable in all three stands (CV=29.6 to 35.9%), whereas the tree height was less so in the two stands (N1 and N2) where height was measured intensively (CV=15.3 and 17.6%). The variability in the plot mean diameter was considerably less than for individual trees (CV=12.5% to 16.1%). Basal area was highly variable in all stands (CV=30.1% to 36.9%), and so was stem density as well (CV=29.0% to 35.6%).

The spatial correlation for the diameter of individual trees was weak as expected: the spatially correlated variation was 11.6% to 26.5% of the sill variance in the variogram models (cf. Fig. 2 and Table 3:  $c/c_0+c$ ). For the mature N1 stand there was a substantial difference when the variogram was calculated for pine and spruce trees separately, and the spatially correlated variation for pine was 61.3% and for spruce 45.4%. For tree height the spatial correlation was stronger than for tree diameter: the spatially correlated variation was 50.4% for N1 and 36.3% for N2 respectively. For basal area the variograms were somewhat erratic, but approximately 30% to 40% of the variation seemed to be spatially correlated. The spatial variation in stem density was very different for each of the three stands. The spatially correlated variation varied and was 27.3% in N1, 48.2% in N2, and 7.4% in ASA stand, i.e. it lacked any spatial correlation.

The variogram analysis of N1 indicated ranges of spatial variation at shorter distances of 9 m to 38 m, and at longer distances of 120 m to 170 m. In N2 the spatial correlation was weak, but ranges of spatial variation of 10 m to 37 m were defined, except for plot mean diameter, which had a range at 91 m. In ASA the ranges were consistently between 67 m and 83 m. Generally for the three stands, the strongest spatial correlation was found for plot mean diameter and tree height, whereas for basal area and stem density it was found to be weak.

The stands investigated were all managed, and compared to natural stands they lacked the asymmetric competition, i.e. the pattern of dominant and suppressed neighbouring trees, which is characteristic of natural boreal forests (Kuuluvainen *et al.* 1996, 1998a-b). This was seen in the absence of a variance peak in the variogram for diameter at short distances. This probably reflects the effect of thinning, which makes the tree distribution more regular, and regeneration by planting, which is made in a regular way. The spatial correlation in tree diameter was weak. This is probably due to the influence of inter-plant competition, however not as pronounced as the asymmetrical competition evident in natural forests. For the mature N1 stand it was interesting to note that the spatial correlation was rather strong for tree diameter, when the diameter for pine and spruce trees were studied separately. This was due to layering by tree species, where large pines seemed to coexist with small, suppressed, spruces and vice versa.

The tree height generally had a more continuous spatial structure than the diameter. This may be explained by the symmetric competition between neighbouring canopy trees, i.e. that trees must grow as large as their neighbours to avoid unfavourable shading for example. In the mature N1 stand the spatial variation was more continuous for the pines than for the spruces. It is more crucial for the pine to belong to the canopy since most of the green biomass is allocated there. The spruce is more adapted to shady conditions.

For basal area and stem density the spatial correlation was weak in general (Table 3:  $c/c_0+c$ ). These properties are affected directly by the management, e.g. by thinnings, which aim at reducing the within stand variation. This may explain the weak spatial autocorrelation in the mature managed stand, but this was evident for the two unthinned stands as well. Perhaps the explanation lies in early measures in the stands like cleaning and pre-commercial thinning, which reduce the number of thickets and make the stems evenly distributed in the stand. Homogenous site condition could also be the cause, but in ASA this was apparently not the case (Paper II).

The influence of site factors is the most probable cause of variation in forest properties in the ASA stand. The scale of variation was approximately 70m to 80m, which was the scale of variation for texture and pH in the ASA stand (Paper II). Similar scales of variation in soil were also found in other investigations

(Oliver & Webster 1987). In the mature stand (N1) a short-scale of variation (<20 m) was determined for several forest properties, which was not seen in the younger unthinned stands, N2 and ASA, for which the ranges were generally larger. This could be caused by short-scale variation in soil properties or patch-wise thinning, which has left trees of similar size in patches.

Estimation by kriging was made for different sampling intensities (Paper III) to investigate at which effort the spatial variation could be estimated. For N1 the kriging of the local mean diameter explained the spatial variation to some extent for the shortest sampling interval (25 m interval,  $r^2=0.24$ ). This was not the case for basal area, which could not be estimated well for any sampling interval (35 m, 50 m, or 70 m) and the kriging was no better than using the global mean value for the local estimation. The tree height could be estimated fairly well from the largest sampling intensity (20 stems per ha,  $r^2=0.32$ ), but also for smaller sampling intensities (15, 10, 5 and 3 stems per ha) the kriging explained the variation in tree height to some extent. For the N2 stand, where the spatial correlation was weak, the kriging was not successful. Only a small part of the variation in mean diameter could be estimated by kriging, even for the shortest sampling interval ( $r^2=0.14$ , 18 m interval). For the longer sampling intervals (25 m to 70 m) the kriging was pointless. For basal area no variogram model could be fitted and hence no kriging was made. The kriging of tree height in N2 was more successful than for the other parameters, but still only about 18% of the variability could be explained from the largest sampling intensity (20 stems per ha). For the ASA stand about 27% of the spatial variation in mean diameter was explained by the kriging for the short sampling interval (Table 4, 18 m interval), whereas considerably less variation could be explained for the 25 m sampling interval ( $r^2=0.18$ ). The basal area could not be estimated by kriging at any sampling intensity.

Kriging the forest properties produced rather poor results in most cases. Even the most intensive sampling did not explain more than approximately 30% of the variation in the stand for any of the properties: basal area, local mean diameter and tree height. The best result was obtained for tree height in the N1 stand, whereas for basal area the kriging was pointless in all stands no matter the sampling interval. Some variation of the local mean diameter could be explained for in N1 and ASA, but only for very intense sampling scheme. Field sampling at the largest intensity proposed is not realistic, and some alternative approach must be taken in data collection if we want to interpolate the values of forest properties across the stand.

**Table 3.** Variogram models for the investigated properties in the three stands (N1=mature mixed pine-spruce stand, N2=unthinned pine stand, ASA=unthinned spruce stand). The model parameters are the nugget variance ( $c_0$ ), the sill variance ( $c$  for single models,  $c_1$  and  $c_2$  for nested models) and the effective range ( $a$  for single models,  $a_1$  and  $a_2$  for nested models), where  $a=3 \cdot r$  for the exponential model

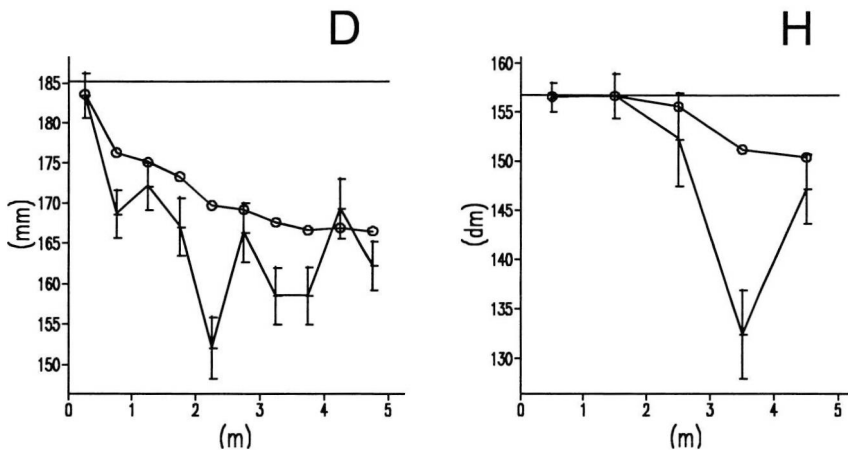
Variable	Model type	$c_0$	$c_1$	$c_2$	$c/c_0+c^a$ (%)	$a_1$ (m)	$a_2$ (m)	$r^2$ (%)
Diameter <sub>N1</sub>	Exponential	7206	1579		18.0	65.3		94.1
Diameter <sub>pine, N1</sub>	Exponential	1998	3171		61.3	16.2		79.3
Diameter <sub>spruce, N1</sub>	Double spherical	4697	1654	2249	45.4	9.2	50	92.2
Diameter <sub>N2</sub>	Spherical	1582	248.9	321	26.5	9.8	91	95.8
Diameter <sub>ASA</sub>	Double spherical	2010	416		17.1	80		97.8
Height <sub>N1</sub>	Double spherical	734	286	460	50.4	25.4	133	95.1
Height <sub>pine, N1</sub>	Double spherical	288	317	606	76.2	30.1	162	94.7
Height <sub>spruce, N1</sub>	Exponential	975	751		43.5	21.9		74.2
Height <sub>N2</sub>	Spherical	355	203		36.3	26.1		75.6
Mean diam. <sub>N1</sub>	Double spherical	441	1033	690	79.6	38.2	170	89.8
Mean diam. <sub>N2</sub>	Spherical	515	208.2		28.8	118		68.7
Mean diam. <sub>ASA</sub>	Spherical	202	232.7		53.5	67.1		97.2
BA <sub>N1</sub>	Spherical	58.9	45.6		43.6	35.8		70.7
BA <sub>N2</sub>	-	-	-	-	-	-	-	-
BA <sub>ASA</sub>	Spherical	54.7	26.5		32.6	81.7		75.4
Stem density <sub>N1</sub>	Spherical	18674	7001		27.3	120		62.2
Stem density <sub>N2</sub>	Spherical	60404	56265		48.2	36.8		91.3
Stem density <sub>ASA</sub>	Spherical	131382	10565		7.4	82.8		5.4

<sup>a</sup>  $c$  equals  $c_1$  for single models and  $c_1+c_2$  for nested models. The ratio is given as percent

## Harvester based forest inventory, Paper IV

The thinning of the stand investigated was made selectively by removing the smaller trees, since the mean diameter of the trees removed was smaller than the mean value before thinning. Approximately 30% of the basal area was removed in the thinning, which is a normal value for a Swedish thinning.

The analysis of the buffer zones showed the selectivity in tree size in the vicinity of the strip roads. The buffer analysis was made on the original trees to determine how representative the strip road trees were for the whole stand. The mean diameter and tree height of the original trees near the strip road centre was close to the mean value of the stand before the thinning (Table 4, original trees). This was not the case for basal area and stem density, which was smaller at distances <1.5 m from the strip road centre line (Table 4). There was a peak in basal area and stem density for the 2 m to 3 m buffer zones, which is the zone just outside the strip road. The strip road was located to a representative part of the



**Figure 4.** Near-strip road statistics of mean diameter (D), and mean tree height (H) vs. distance from strip road centre for trees removed by thinning. The horizontal solid line is the mean for the original trees before thinning. Vertical error bars indicate SEM and the circle line (o) is the cumulative mean value

stand as seen from the 0 to 5 m buffer zones which in total has just about the same tree diameter, tree density and basal area as the stand average. The results indicate that the selectivity in basal area and stem density was due to winding of the strip road, to avoid felling of target trees (trees that are preferred to be left). The central zone in the strip road (<0.5 m from the strip road centre) seem to form a representative sample of the original stand before thinning for mean diameter and height, whereas for basal area and stem density the values were smaller than for the original stand before thinning.

The variogram analysis showed the spatial structure of the different forest properties. The mean diameter before thinning was spatially correlated to a distance of 80 m and for the mean tree height to 30 m. Basal area and stem density had weak spatial correlation, and it decreased after thinning, whereas for mean diameter and mean height it remained the same. In general there was weak spatial correlation in the stand and the spatially uncorrelated component was large.

The mean diameter of the removed trees was asymptotically reaching the mean of the original trees towards the strip road centre line (Fig. 4, removed trees). Therefore the zone around the strip road centre line (<0.5 m) was assumed to be a representative sample of the stand before thinning. The data from the 0.5 m buffer zone was used to generate a continuous spatial model of the tree diameter in the stand before thinning. A variogram model was fitted to the data, and the range of spatial correlation of tree diameter within the 0.5 m buffer zone was 42 m. This was quite different from the variogram for the diameter for all trees, which was nested with two ranges of variation at 10 m and 91 m.



Spatial estimation of the mean diameter was made by kriging from: (1) the sample of trees within the 0.5 m buffer zone, and (2) all trees before thinning as a reference. Both sets of predictions were made over 10 m by 10 m blocks. The first kriging (using trees from the 0.5 m buffer zone) underestimated the mean of the reference slightly, and the RMSE was 14.3 mm. The correlation between the two was moderate ( $r^2=0.27$ ).

**Table 4.** Summary of the buffer analysis. Values of basal area (BA), stem density (N), mean diameter (D) and mean tree height (H), within buffer zones at increasing distance from the strip road for the original, removed and remaining trees

Buffer (m)	Original trees					Removed trees				Remaining trees			
	Area (m <sup>2</sup> ·100)	BA (m <sup>2</sup> ·ha <sup>-1</sup> )	N (stems ha <sup>-1</sup> )	D (mm)	H (dm)	BA (m <sup>2</sup> ·ha <sup>-1</sup> )	N (stems ha <sup>-1</sup> )	D (mm)	H (dm)	BA (m <sup>2</sup> ·ha <sup>-1</sup> )	N (stems ha <sup>-1</sup> )	D (mm)	H (dm)
0.5	14.6	11.3	397	185		10.5	376	184		0.8 <sub>a</sub>	21 <sub>a</sub>	216 <sub>a</sub>	
1.0	14.1	10.5	418	173	156	8.8	368	169	157	1.8 <sub>b</sub>	50 <sub>b</sub>	201 <sub>b</sub>	153 <sub>c</sub>
1.5	13.7	13.3	460	186		8.4	343	172		4.9	117	226	
2.0	13.2	37.1	1162	193	163	8.3	347	167	157	28.8	815	204	166
2.5	12.8	46.0	1446	193		6.4	320	152		39.6	1125	204	
3.0	12.3	33.8	1113	189	163	7.8	333	166	152	26.0	780	199	165
3.5	11.8	28.6	953	187		8.8	408	159		19.8	544	208	
4.0	11.1	23.6	874	178	154	8.5	397	159	133	15.1	478	195	161
4.5	10.5	28.3	960	186		9.5	390	169		18.9	571	197	
5.0	10.0	27.9	1010	181	154	8.5	390	162	147	19.4	620	192	156
0 to 5	124	25.5	859	187	159	8.6	366	167	150	17.0	494	202	162
Original stand:		25.0	854	185	157	7.3	321	164	148	17.7	533	198	160

<sup>a</sup> Number of observations=3

<sup>b</sup> Number of observations=7

<sup>c</sup> Number of observations=4

## General remarks and conclusions

The variation in site quality at a regional scale can be described to a large degree by variation in soil mineralogy. Site quality generally benefits from easily weathered minerals like epidote, amphibole and chlorite, although the relationship between site quality and soil mineralogy is complex and depend on the overall geology. The potential to predict site quality from soil mineralogy is improved if it is made within geological regions.

The results indicate that there is substantial variation within forest stands in both tree and soil properties. For many properties the variation is spatially organized to a large degree in patches at several scales of variation, from 10 m to 170 m. For the soil properties in the B horizon there were three distinct scales of variation at 40 m, 80 m, and >100 m. For tree diameter the spatial correlation was weak, which probably reflects the influence of inter-plant competition on the tree diameter distribution. However, this pattern is not as pronounced as in natural forests, which are characterized by strong competition between neighbouring trees that results in dominant and suppressed trees. In mature stands the spatial pattern in tree diameter and height seem to interact with tree species. The spatial correlation within managed forest stands is weak for basal area and stem density. This is obvious for mature thinned stand, since the thinnings aim at reducing variability for these properties. This pattern is also evident in unthinned stands, which might be related to early measurements like cleaning or variation in plant establishment. For local mean diameter and tree height the spatial patterns are rather strong and they seem to remain after thinnings. The within-stand pattern in forest properties seem to be related to variation in site factors such as soil texture and terrain.

The gain in describing the forests at a smaller scale than the stand, depends on (1) the magnitude and structure of the within-stand variation, (2) which properties of the forest that are considered, and (3) how the information at sub-stand level can be handled. The result from this work indicates that spatially related variation differs for different properties. For basal area and stem density the spatial structures seem to be weak, whereas for height and local mean diameter the structures are more evident. In case the information about the forest at tree level can be handled in forestry planning and in the stage of the forest production chain the benefit from a small-scale description of the forest is evident.

In forest planning the use of smaller description units may be a prerequisite for reaching goals set up, by e.g. forest policy makers, concerning biodiversity and other non-timber purposes of the forests. Ultimately, a raster model of the forest can describe the forest continuously. The economical output might increase by making the formation of treatment units a part of the planning process. In this case there is a need for new planning systems and the development of high-resolution data collection methods for the forests.

To create continuous descriptions of the forest, by e.g. kriging, will require detailed data at a level, which is not practically feasible by field inventory. An exception may be properties with continuous spatial variation, such as tree height. Alternative methods of data collection must be considered to replace or complement traditional sampling in the field, but the methods must not be too costly. Harvester based inventory is one approach that can be applied, but there are also other possibilities. New methods for remote sensing such as lidar (light detection and ranging) and SAR (synthetic aperture radar) may provide additional sources of information to be used alone or in combination with field sampling. In any case the sub-stand spatial structure of forest properties will need to be considered. The appropriate size of the units for forest planning and management may be determined on the basis of the scale of variation for different properties.

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