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Variation in Soil Organic Carbon and Thickness of Soil Horizons within a Boreal Forest Stand – Effect of Trees and Implications for Sampling

Jari Liski

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Spatial variation in the density of soil organic carbon (kg/m^2) and the thickness of soil horizons (F/H, E) were investigated in a 6 m × 8 m area in a Scots pine (*Pinus sylvestris*) stand in southern Finland for designing an effective sampling for the C density and studying the effect of trees on the variation. The horizon thicknesses of the podzolized soil were measured on a total of 126 soil cores (50 cm deep) and the C density of the organic F/H and 0–10 cm, 10–20 cm and 20–40 cm mineral soil layers was analysed. The C density varied 3–5 fold within the layers and the coefficients of variation ranged from 22 % to 40 %. Considering the gain in confidence per sample, 8–10 samples were suggested for estimating the mean C density in the F/H and 0–40 cm layers, although about 30 samples are needed for 10 % confidence in the mean. The C densities and horizon thicknesses were spatially dependent within the distances of 1–8 m, the spatial dependence accounting for 43–86 % of the total variance. The F/H layer was thicker and contained more C within 1–3 m radius from trees. In the 10–20 cm and 20–40 cm layers (B horizon) the C density also increased towards the trees, but more pronouncedly in the immediate vicinity of the stems. Because the spatial patterning of the E horizon thickness was similar, the increase was attributed to stemflow and precipitation of organic compounds in the podzol B horizon.

Keywords soil carbon, soil formation, tree effects, spatial variation, geostatistics, soil sampling.
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1 Introduction

Properties of forest soils, both physical and chemical, vary considerably even within short distances of a few metres (Ilvesniemi 1991, Järvinen et al. 1993, Fournier et al. 1994). This small-scale variation sets high demands for soil sampling. In order to design effective sampling with pre-estimated precision, it is necessary to know the magnitude and spatial structure of the variation of the property in question. In addition, a thorough description of the variation, especially of the spatial aspects, may provide useful information on the processes generating this variation. Geostatistical tools offer effective means for interpreting the spatial aspects of the variation (Isaaks and Srivastava 1989).

Due to the considerable variation, a large number of replicates have been suggested for statistically satisfying results. For instance, hundreds of samples are needed for 10 % confidence in mean estimate (Fournier et al. 1994) and detecting 10 % changes (Ilvesniemi 1991) of several chemical soil properties. Traditional statistical tests also assume that the replicates are independent of each other. Soil properties have, however, been shown to be spatially dependent in various ecosystems at scales starting from a few metres (e.g. Robertson et al. 1988, Lechowicz and Bell 1991, Jackson and Caldwell 1993, Järvinen et al. 1993, Gonzalez and Zak 1994).

In forests, besides the geological factors, trees are important causes of variation in soil properties (Zinke 1962, Gersper and Holowaychuk 1970, Boettcher and Kalisz 1990). Zinke (1962) proposed, partly hypothetically, that trees induce spatial patterning which can be divided into three zones: (i) the zone closest to stems affected by stemflow and bark litter, (ii) the zone outside the inner one affected by leaf litter and drip from the foliage and (iii) an interspace between the affected zones receiving mainly unimpeded precipitation and little litter deposition. Gersper and Holowaychuk (1970) and Boettcher and Kalisz (1990) supported Zinke's ideas finding systematic variation in chemical soil properties, for instance in the concentration of organic carbon, according to the location of trees and attributed this variation to stemflow and litter deposition. Moreover, Gersper and Holowaychuk (1970) stated that the effect of trees was a definite soil forming factor.

Recently, due to the human-induced increase in the CO_2 concentration of the atmosphere, the soil of boreal forests has received increasing attention as an important store of organic C. Estimates of the actual size of the store are, however, not very precise, because of the lack of data and the large variation in the C density (kg/m^2) (Schlesinger 1977, Post et al. 1982, Liski and Westman 1995). To improve the confidence, accurate stand level estimates based on proper sampling for the mean C density are inevitably needed. In addition to the C balance consideration, other important properties in these soils, such as CEC and acidity, are closely associated with soil organic matter (Westman 1990). Results of the variation in the organic C density may therefore, to some extent at least, be applicable to the associated properties as well.

The objective of this study was to describe the spatial variation in the density of soil organic C and the thickness of soil horizons within a boreal forest stand to design effective sampling for the mean C density and investigate the effect of trees on the variation and soil formation.

2 Material and Methods

2.1 Study Site

The study site was located near the Helsinki University Forestry Station in Hyytiälä in southern Finland (61°48'N, 24°19'E, 150 m a.s.l). The annual mean temperature of the area is +2.9 °C and the yearly precipitation averages 709 mm (Climatological statistics... 1991).

The study site is situated on a glaciofluvially sorted coarse sand deposit that emerged from the Baltic some 10300 years ago after the most recent glacier in the area melted (Donner 1969, Kramer and Becker 1993). The topography of the site is flat. The soil is podzolized and there are no signs of artificial profile disturbance. Some properties of the soil, measured about 100 m away on the same deposit, are reported in Table 1. The site was classified as *Calluna* type according to the Finnish classification of forest types (Cajander 1925). Scots pine (*Pinus sylvestris* L.) is the dominant tree species on this low productivity type, where the total stemwood production of naturally developed (naturally regenerated and no forest harvest) pine stands averages 310 m^3/ha at the age of 100 years (Ilvessalo and Ilvessalo 1975). At the study site the tree stand consisted of naturally regenerated 100–130 years old Scots pines, whose mean height was 21.2 m and diameter 28 cm at 1.3 m height. The age, diameter and height of individual trees as well as approximated age (time since cutting) and diameter (for the youngest, measurable stumps only) of stumps in the area studied are reported in Fig. 1.

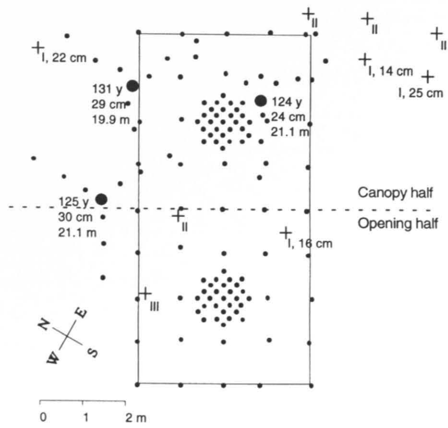


Fig. 1. Location of the sampling points (small dots), trees (large dots) and stumps (crosses) at the study site. The dashed line indicates the division of the site into the opening and canopy halves. Ages, diameters at 1.3 m height and heights of the trees are indicated. The stumps are divided into three approximate age classes (time since cutting): I 10–15 years, II 15–25 years and III more than 25 years; diameters indicated for the youngest class.

2.2 Soil Sampling

In order to investigate the effect of trees on the variation, a 4 × 8 m sampling grid was placed at the site so that one 4 × 4 m half lay in a small (80 m^2) within-stand opening and the other half under tree canopies (Fig. 1). Dense grids, with a minimum distance of 17 cm between samples, were established in the centre of each half for studying small-scale variation. A total of 99 soil cores (50 cm deep, 46 mm diameter) were taken from the sampling points using a steel corer that samples the profile in its natural form in a plastic tube (Westman 1995). To study the effect of trees in more detail, 27 additional cores were collected in three directions (0°, 120° and 240°) around three trees 20 cm, 80 cm and 160 cm from the stems. The division of the site into the opening and canopy halves is indicated in the Fig. 1; the samples on the line were included in the opening half to get a more balanced number of samples in the halves.

Table 1. General properties of the soil. B1 refers to the top half of the B horizon and B2 to the bottom half.

	F/H	E	B1	B2	C
Density, kg/dm^3	0.126	1.06	1.11	1.26	1.37
Silt conc., % [1]		9.17	10.8	10.6	1.36
pH_{CaCl_2} [2]	3.0	3.9	4.9	4.7	5.3
CECe, cmol(+)/kg [3]	9.6	1.5	0.55	0.72	0.28
Base saturation, % [4]	26	6.4	13	11	29

1) particle size fraction 2–60 µm; determined according to Elonen (1970)
2) soil : 0.01 M $CaCl_2$ = 1: 2.5 (v/v)
3) Ca + Mg + H + Al extracted by 1 M KCl
4) (Ca+Mg) / CECe

2.3 Measuring C Densities and Thicknesses of Soil Horizons

In the laboratory the plastic tubes were pulled off the soil cores and thicknesses of the organic F/H and mineral E and B horizons were measured on the cores, which were then divided into the organic F/H and 0–10 cm, 10–20 cm and 20–40 cm mineral soil layers. Since the thickness of the E horizon averaged 2.7 cm and that of the B horizon 28 cm, the 0–10 cm sample generally consisted of the E horizon and top layer of the B horizon, the 10–20 cm sample of the middle layer of the B horizon and the 20–40 cm sample of the bottom layer of the B horizon and top layer of parent material. The division by depth instead of horizon was applied, because in the fairly weakly developed soil the E horizon was usually very thin, defining the lower border of the B horizon was rather observer-dependent and, in addition, in a few cases the B horizon seemed to extend below the sampling depth. For these reasons, the B horizon thicknesses are not otherwise reported in this study. After the division, the samples were dried to a constant weight at room temperature (20°C) before they were sieved to <2 mm and weighed for calculating the density of the under 2 mm fraction (Db<2mm, kg/m^3).

Total C concentration (C_C, kg/kg), which equals the concentration of organic C in these acid soils, was measured using a Leco CSN-1000 analyser. In order to reduce analytical variability, the F/H sample and 50 ml of the < 2 mm fraction of the mineral soil samples were ground for the C analysis. The coefficient of variation for replicate measurements averaged 2.9 % in the F/H samples (3 samples of 200 mg tested, 5 replicates/sample) and 3.8 % in the mineral soil samples (10 samples of 500 mg tested, 5 replicates/sample). The mass of C per unit of surface area in a given soil layer, C density (kg/m^2), was calculated by multiplying the C_C by the Db<2mm and the thickness of the layer. For the 0–40 cm mineral soil layer the C density was obtained by totalling the amounts in the sublayers.

2.4 Data Processing

The structure of spatial dependence in the C densities and horizon thicknesses was studied using semivariograms, in which semivariances, g, are calculated for different distance intervals, h, in data and plotted against these lags:

$$\gamma(h) = \Sigma(z(xi) - z(xi + h))^2 / 2(N(h)),$$

where N(h) is the number of sample pairs in the lag h and z(xi) and z(xi+h) are data values at locations xi and xi + h, respectively (Isaaks and Srivastava 1989). In spatially dependent data, samples located close to each other tend to be more similar than samples located further away and consequently the semivariances increase with distance. The distance at which the increase levels off is the range of spatial dependence, a, and the corresponding semivariance is called the sill. Theoretically the semivariograms should start from zero, but experimental semivariograms generally do not. This nugget, C_0, the semivariance for distance equal to 0, is due to experimental error and spatial variation at distances shorter than the smallest distance of the sampling grid. The difference between C_0 and sill is called the structural variance, C, representing the variance accounted for by the spatial dependence.

Because the semivariances measure average squared differences between data locations, they are strongly influenced by unusually large or small data values (Rossi et al. 1992). The two exceptionally high C densities in the 20–40 cm layer (see Fig. 2d) altered the semivariogram structure remarkably. For instance, they increased the semivariance for the seventh lag nearly threefold (Fig. 3d). Since these two samples, for the most part, overrode the effect of the other samples, they were not thought to produce a representative picture of the spatial structure in the entire data and were therefore left out of the interpretations of the spatial dependence in the 20–40 cm layer.

To illustrate the spatial patterning, the C densities and horizon thicknesses were interpolated for 20 × 20 cm blocks using block kriging (Isaaks and Srivastava 1989). Models of the exponential form,

$$\gamma(h) = C_0 + C(1 - e^{-3h/a}),$$

were fitted in the semivariograms for the kriging. Distances used for the fitting depended on the semivariogram structure; exceptional semivariances at large distances (see Fig. 3) were excluded to obtain a good fit at the distances (less than 1.1–2.0 m depending on the variable) used in the kriging.

A cross-variogram was calculated for investigating the spatial relationship between the thickness of the E horizon and the C density in the 10–20 cm layer. The cross-variogram between two variables A and B separated by distance h is defined as:

$$\gamma AB(h) = \Sigma[(zA(xi) - zA(xi + h))(zB(xi) - zB(xi + h))] / 2(N(h)),$$

where N(h) is the number of sample pairs in the lag h, and zA(xi), zA(xi+h), zB(xi) and zB(xi+h) data values of variables A and B at locations xi and xi+h (Isaaks and Srivastava 1989).

The Geo-EAS program (Englund and Sparks 1988) was used for calculating the semivariograms and kriging. The cross-variogram was calculated using Geostat Toolbox (Froidevaux 1988) and the semivariogram models were fitted using SYSTAT (SYSTAT for Windows... 1992).

Number of samples, n, needed for a given confidence level, d, in the mean estimate of the C density in the F/H and 0–40 cm layers was assessed using the formula

$$n = (z_{0.95}\, s\, d^{-1})^2,$$

where $z_{0.95}$ is the 95 % fractile of the Student's t-distribution and s the standard deviation of spatially independent observations. Student's t-distribution was used instead of the normal distribution to account for uncertainty in s (e.g. Sokal and Rohlf 1981). Owing to the spatial dependence in the C densities, s was approximated on the basis of the sill value of the semivariogram. The use of the sill value is based on the definition of the semivariance as

$$\gamma(h) = C(0) - C(h),$$

where C(0) and C(h) are the covariances of observations separated by the distances of 0 and h, respectively. In spatially dependent data, in which widely separated observations do not depend on one another, C(h) reaches 0 with increasing h until the observations are independent of each other. Then C(h) = 0 and consequently $\gamma(h)$ = C(0). For such independent observations $\gamma(h)$ equals the sill value, which is thus the variance of the process producing the variation or the variance of the independent observations (Isaaks and Srivastava 1989, Cressie 1991). In practice, this variance was approximated by the sill values of the exponential models fitted in the semivariograms, and the square root was taken of the values to obtain s.

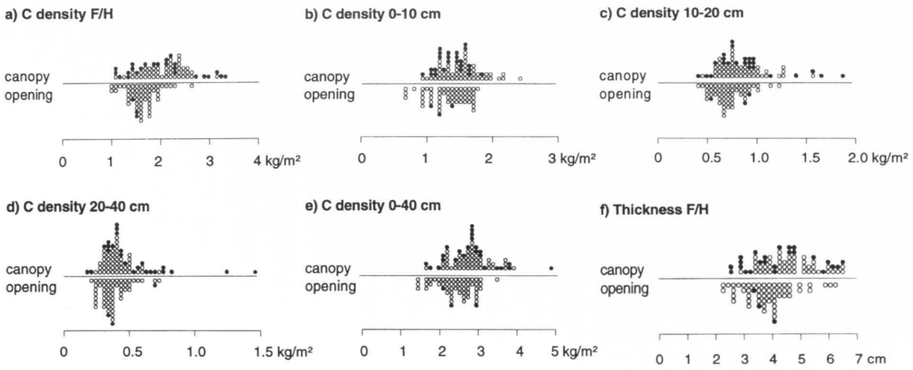
3 Results

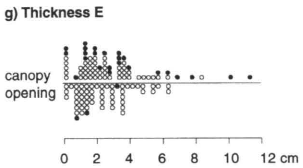
The C density varied 3–5 fold within the soil layers and the coefficients of variation ranged from 22 % to 40 %; for the compounded 0–40 cm layer the coefficient of variation was 21 % (Figs. 2a–e, Table 2). In each of the layers the C density varied more in the canopy half than in the opening, except in the 0–10 cm layer, in which both the standard deviations and coefficients of variation were almost equal in each half. In the F/H layer the larger variation of the canopy half was reflected in the wider normal shaped frequency distribution of the C densities. In the 10–20 cm and 20–40 cm layers the larger variation was mainly due to a few exceptionally high C densities in samples collected around the trees.

On average, the actual C density was also higher in each of the soil layers in the canopy half than in the opening (Table 2). The difference was largest for the F/H layer, in which the median C density was 33 % higher in the canopy half. For the 0–10 cm, 10–20 cm, 20–40 cm layers and compounded 0–40 cm layer the differences were 9 %, 16 %, 8 % and 14 %, respectively.

The thickness of the F/H horizon varied from 2.2 cm to 6.5 cm and the thickness of the E horizon substantially more, from 0 cm to 11.2 cm (Figs. 2f, g). The coefficients of variation were 25 % and 76 % for the F/H and E horizons, respectively (Table 2). The thicknesses of the F/H horizon were relatively normally distributed (Fig. 2f), whereas the frequency distribution for the E horizon thicknesses was strongly positively skewed and characterized by a few exceptionally large thicknesses located around the trees (Fig. 2g). Both the F/H and E horizons were 17 % thicker, comparing medians, in the canopy half than in the opening.

The semivariograms revealed clear spatial dependence both in the C densities and thicknesses of the soil horizons (Figs. 3a–g). The exponential models fitted well in the observed semivariances at the lags used; the fits, R^2, ranged from 81 % to 98 % (Table 3). Therefore, the model parameters reflected the structure of the spatial dependence similarly as would have been understood from the observed semivariograms alone.





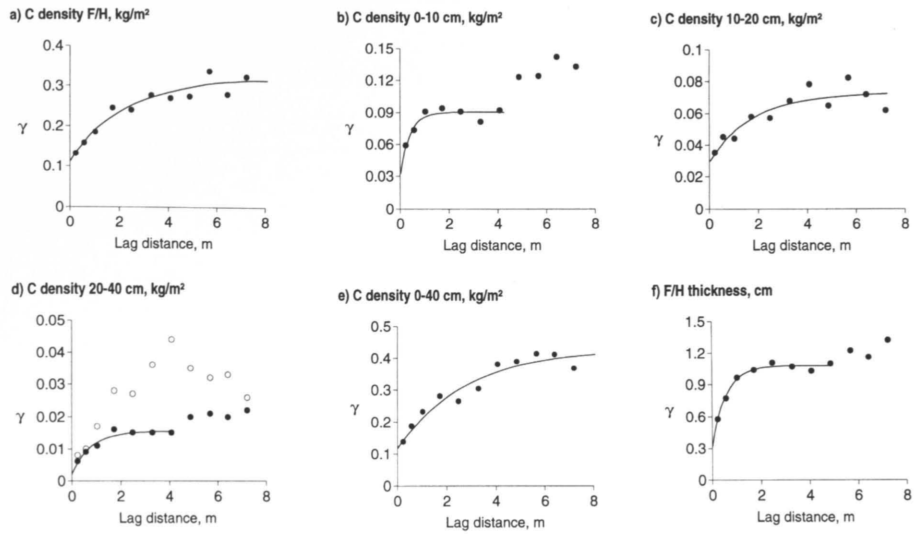
Figs. 2a–g. Frequency distributions for the carbon density and thickness of the soil horizons in the opening and canopy halves of the study site. The open dots represent samples taken from the grid (n = 99) and the filled dots samples taken with respect to the location of the trees (n = 27).

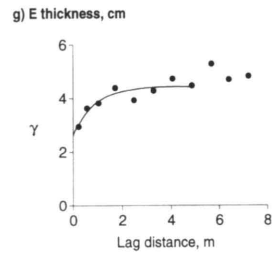
Table 2. Statistical parameters for the carbon density (kg/m^2) and the thickness of the soil horizons (cm) counting all the samples (n = 126), the samples in the opening half (n = 56) and the samples in the canopy half (n = 70). Coefficients of variation, cv, expressed as %.

	All samples				Opening				Canopy			
	mean	med	sd	cv	mean	med	sd	cv	mean	med	sd	cv
C density F/H	1.86	1.77	0.50	27	1.62	1.60	0.31	19	2.06	2.12	0.54	26
C density 0–10 cm	1.41	1.43	0.31	22	1.32	1.35	0.29	22	1.49	1.47	0.31	21
C density 10–20 cm	0.81	0.76	0.25	31	0.72	0.69	0.17	24	0.87	0.80	0.29	33
C density 20–40 cm	0.42	0.38	0.17	40	0.39	0.37	0.11	28	0.46	0.40	0.21	46
C density 0–40 cm	2.64	2.66	0.56	21	2.43	2.49	0.47	19	2.82	2.83	0.57	20
Thickness F/H	4.19	4.10	1.03	25	3.85	3.75	0.88	23	4.47	4.40	1.05	24
Thickness E	2.70	2.25	2.06	76	2.43	2.05	1.65	68	2.91	2.40	2.32	80

Table 3. Parameters for the exponential models fitted in the semivariograms of the carbon density (kg/m^2) and the thickness of the soil horizons (cm): semivariance, $\gamma(h) = C_0 + C(1 - e^{-3h/a})$.

Layer	Range (a), m	Nugget (C_0)	Structural variance (C)	Sill (C_0+C)	C/(C_0+C), %	R^2, %
C density F/H	6.5	0.11	0.20	0.31	65	92
C density 0–10 cm	1.1	0.029	0.061	0.090	68	86
C density 10–20 cm	5.2	0.029	0.044	0.073	60	81
C density 20–40 cm	2.3	0.0021	0.013	0.015	86	94
C density 0–40 cm	8.4	0.12	0.30	0.42	71	93
Thickness F/H	1.7	0.31	0.77	1.08	71	98
Thickness E	2.6	2.5	1.9	4.4	43	85





Figs. 3a–g. Semivariograms for the carbon density (kg/m^2) and thickness of the soil horizons (cm). The lines represent the models fitted in the semivariograms. In the semivariogram for the carbon density in the 20–40 cm layer, the open dots indicate semivariances including all the samples and the filled dots the semivariances excluding the two largest densities.

The distances within which the C densities were spatially dependent ranged from 1.1 m in the 0–10 cm layer to 8.4 m in the 0–40 cm layer. The proportion of the total variance accounted for by the spatial dependence varied from 60 % in the 10–20 cm layer to 86 % in the 20–40 cm layer. The F/H and E horizon thicknesses were spatially dependent at distances of less than 1.7 m and 2.6 m, respectively. The spatial dependence accounted for 71 % of the total variance in the F/H horizon thickness and 43 % of the total variance in the E horizon thickness. Exceptions to the good fits of the models were the high semivariances of the C densities in the 0–10 cm and 20–40 cm layers at distances larger than 5 m (Figs. 3b, d). These high semivariances were due to comparison of the 2–3 highest C densities in the canopy half with low values in the lower left corner of the dense grid in the opening.

The standard deviation of spatially independent observations, estimated as the square root of the sill value of the semivariogram (see Table 3), was 0.56 kg/m^2 in the F/H layer and 0.65 kg/m^2 in the 0–40 cm layer. The standard deviations of the whole data are a little smaller, 0.50 kg/m^2 in the F/H layer and 0.56 kg/m^2 in the 0–40 cm layer (Table 2), owing to the spatial dependence. On the basis of the standard deviations of the independent observations, 8–9 samples result in a mean estimate of the C density that differs by less than 0.5 kg/m^2 (21 % and 15 % of the mean in the F/H and 0–40 cm layers, respectively) from the true mean with 95 % probability in both of the layers (Fig. 4). Taking 10 samples of the F/H layer and 13 samples of the 0–40 cm layer increases the confidence to 0.4 kg/m^2. Sample numbers in excess of that increase the precision much less. For instance, 21 samples are needed to increase the confidence in the mean of the 0–40 cm layer by another 0.1 kg/m^2, to 0.3 kg/m^2. Both in the F/H and 0–40 cm layers about 30 samples are needed for a mean estimate that differs by less than 10 % of the true mean, i.e. 0.19 kg/m^2 in the F/H layer and 0.26 kg/m^2 in the 0–40 cm layer.

The F/H horizon was thicker and contained more C under the trees; the effect extended 1–3 m from the stems (Figs. 5a, e). The high C densities in the upper right corner of the map were associated with the decaying stump. In the 0–10 cm layer the C density was patchy and not closely associated with the location of the trees (Fig. 5b). On the other hand, the 10–20 cm and 20–40 cm layers contained more C within 1–2 m radius from the trees and the highest C densities were found in the immediate vicinity of the stems (Figs. 5c, d). The spatial patterning of the E horizon thickness was similar, especially to the 10–20 cm layer (Fig. 5f). This was also demonstrated by the cross-variogram between the E horizon thickness and C density in the 10–20 cm layer (Fig. 6). The positive values indicate that a thick E horizon is associated with high C density in the 10–20 cm layer and the increase with distance suggests that the difference between the thickness and the C density increases with increasing separation distance between the observations.

4 Discussion

In this study, variation in the soil C density and thicknesses of the soil horizons were investigated in a Scots pine (*Pinus sylvestris*) stand in southern Finland. The magnitude and spatial aspects of the variation were described using simple univariate statistics and geostatistical methods. The purposes of the description were to help design an effective soil sampling for estimating the mean C density and to investigate the effect of trees on the variation and soil formation.

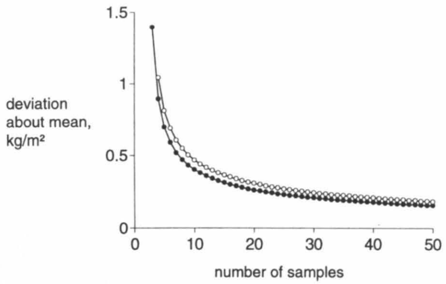
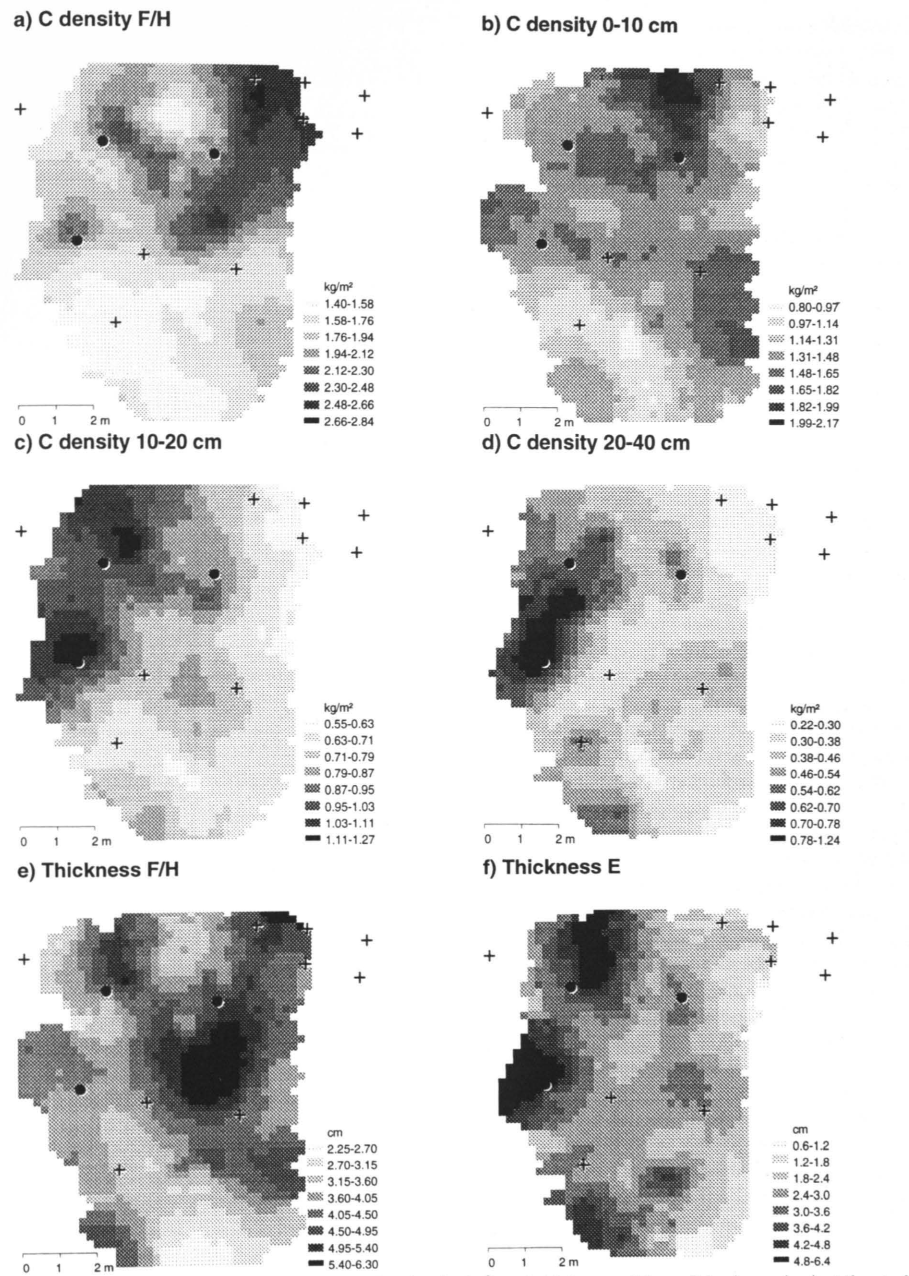


Fig. 4. 95 % confidence limits for the mean estimate of the carbon density in the organic F/H (filled dots) and 0–40 cm mineral soil (open dots) layers as a function of the number of samples.

The coefficients of variation for the C density ranged from 22 % to 40 %, depending on the soil layer. Comparing this magnitude of variation to other studies is not straightforward, since organic C has not been reported on either a volume (kg/m^3) or surface area (kg/m^2) basis in other studies on forest soil variation. Nevertheless, certain comparisons can be made using the coefficients of variation for loss-on-ignition (kg/kg) in mineral soil, because the loss-on-ignition is fairly linearly associated with the organic C concentration, which, for the most part, determines the C density in mineral soil (Huntington et al. 1989). In two forest stands in Canada the coefficients of variation for the loss-on-ignition were 55 % and 48 % in A horizon, 35 % and 41 % in B horizon and 32 % and 41 % in the parent material of a Ferro-Humic Podzol and Humo-Ferric Podzol, respectively (Fournier et al. 1994). Järvinen et al. (1993) reported a 20 % coefficient of variation for the loss-on-ignition in 10–15 cm mineral soil layer in a Scots pine (*Pinus sylvestris*) stand in eastern Finland. Thus the magnitude of variation measured in this study is of the same order.

Considering the gain in confidence per sample, 8–10 samples seem reasonable for estimating the mean C density in these forest stands, although as many as 30 samples are needed for a mean estimate that differs by less than 10 % of the true mean with 95 % probability both in the F/H and 0–40 cm layers. Fournier et al. (1994), with a larger variation, calculated that a total of 44–130 samples, depending on the soil horizon, are needed for a 10 % confidence in the mean



Figs. 5a–f. Interpolated maps for the carbon density (kg/m^2) and thickness of the soil horizons (cm) at the study site. The trees are indicated by the dots and the stumps by the crosses.

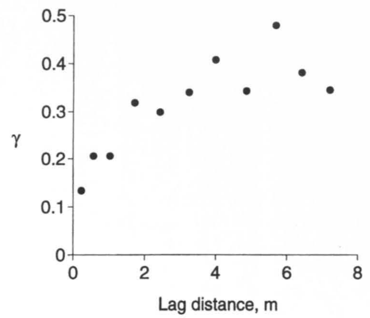


Fig. 6. Cross-variogram between the thickness of the E horizon (cm) and the carbon density of the 10–20 cm layer (kg/m^2).

estimate of the loss-on-ignition. Owing to the asymptotic dependence of the confidence on the number of samples, predetermined level of precision, for instance 10 % of the mean, may suggest that a large number of samples is needed, although even a considerable reduction in the number of samples would not seriously impair the precision of the mean. Therefore, to sample efficiently, one should rather consider the shape of the dependence of the confidence on the number of samples than calculate the number of samples needed only for one confidence level.

The C density was higher and generally varied more under the tree canopies than in the opening. Stratifying the site into internally more homogenous canopy and opening areas may therefore increase the precision of estimating the mean. The stratification, however, makes the sampling more laborious and expensive and complicates statistical analyses. It should probably be considered therefore only in special cases. Ruark and Zarnoch (1992) also found an increase in the C concentration and variability towards trees in the 5–10 cm mineral soil layer of a 35 year old pine plantation. However, they achieved only a little gain in precision for the mean estimate of the soil C by stratifying with respect to tree stems. They ended up suggesting that the stratification was needed only for ecosystems where stemflow and bark sloughing are considered large or are of primary interest of the investigator.

The C density of the layers and the thickness of the soil horizons were spatially dependent within distances varying from about 1 m to 8 m. These ranges of spatial dependence reflect the effect of the trees, which were situated 3–4 m from each other, on the properties and consequently the spatial patterning according to the location of the trees. The range of spatial dependence may therefore probably be predicted from the distance between trees in other forest sites also, where trees are major causes of spatial variation. Järvinen et al. (1993) did not detect any spatial dependence in a factor describing secondary soil properties, such as the loss-on-ignition, from a grid with minimum distance of 5 m between the samples. Therefore, it seems that most of the variation in the soil C density, and probably in the associated soil properties, can be found within a few metres distance in these stands. From the point of view of soil sampling, to fulfill the criteria of statistical independence, samples should be taken further from each other than the range of spatial dependence. On the other hand, to utilize the dependence in the kriging interpolation, samples should be taken closer than the range.

The F/H layer was 17 % thicker and its C density was 33 % higher in the canopy half than in the opening, comparing medians. These differences between the opening and canopy areas, were most likely due to differences in litter deposition and decomposition rates over some decades, which was the age of the opening judging by the stumps. On the basis of the illustrated maps, the effect of trees extended 1–3 m from the stems. That kind of spatial patterning supports Zinke's (1962) idea of the second zone of tree influence affected by leaf litter and drip from foliage (see Introduction). The 10–20 cm and 20–40 cm layers also contained more C near the trees, but the effect was more concentrated in the vicinity of the stems. The spatial patterning of the thickness of the E horizon was similar. The exceptionally thick E horizon near the stems was probably caused by stemflow rich in organic compounds leached from tree surfaces. The high C density in the B horizon (10–20 cm and 20–40 cm layers) below was, in turn, due to the organic compounds transported into soil by the stemflow. Owing to the podzolic properties, the organic compounds may have remained dissolved in water in the conditions of the E horizon and precipitated first in the B horizon. This explanation accords with Zinke's (1962) first zone of tree influence closest to stems, which he attributed to stemflow and bark litter. It seems that even if the volume of the stemflow is not more than 1–2 % of precipitation in Scots pine stands (Päivänen 1966), it still induces remarkable local variation in soil properties. This is probably due to concentrated routes of the stemflow into the soil (Gersper and Holowaychuck 1971) and high C concentration in the water, up to 350 mg/l in Scots pine stands (Jukka Laine pers. comm.), compared to an average of 26 mg/l in throughfall (Liski and Pumpanen 1994). These results reveal that trees also induce heterogeneity in mineral soil properties and remarkable alterations may develop fairly quickly, that is during about one hundred years, considering the usual time scale of soil formation.

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