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# Carbon storage in forest soil of Finland

## *2. Size and regional patterns*

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**Abstract.** For confidently estimating the amount of carbon stored in boreal forest soil, better knowledge of smaller regions is needed. In order to estimate the amount of soil C in forests on mineral soil in Finland, i.e. excluding peatland forests, and illustrate the regional patterns of the storage, statistical models were first made for the C densities of the organic and 0–1 m mineral soil layers. A forest type, which indicated site productivity, and the effective temperature sum were used as explanatory variables of the models. In addition, a constant C density was applied for the soil layer below the depth of 1 m on sorted sediments. Using these models the C densities were calculated for a total of 46673 sites of the National Forest Inventory (NFI). The amount of the soil C was then calculated in two ways: 1) weighting the C densities of the NFI sites by the land area represented by these sites and 2) interpolating the C densities of the NFI sites for 4 ha blocks to cover the whole land area of Finland and summing up the blocks on forested mineral soil. The soil C storage totalled 1109 Tg and 1315 Tg, when calculated by the areal weighting and the interpolated blocks, respectively. Of that storage, 28% was in the organic layer, 68% in the 0–1 m mineral soil layer and 4% in the layer below 1 m. The total soil C equals more than two times the amount of C in tree biomass and 20% of the amount of C in peat in Finland. Soil C maps made using the interpolated blocks indicated that the largest soil C reserves are located in central parts of southern Finland. The C storage of the organic layer was assessed to be overestimated at largest by 13% and that of the 0–1 m mineral soil layer by 29%. The largest error in the organic layer estimate is associated with the effects of forest harvesting and in the mineral soil estimate with the stone content of the soil.

## 1. Introduction

Soil of boreal forests is estimated to contain about 15% of the global soil carbon storage, excluding wetlands (Schlesinger 1977; Post et al. 1982). The large quantity is due to the large land area covered by boreal forests and the high amount of C stored per the land area in these soils. The soil C density, however, varies considerably within the boreal zone (Schlesinger 1977; Post et al. 1982) impairing the confidence of the estimates made in the worldwide studies by extrapolating a mean C density over the land area covered by boreal forests. The present amount of C stored in different soils is one of the most essential factors when assessing changes in the soil C storage in response to climatic warming. For improving the confidence of the estimates of the boreal soil C storage, more detailed knowledge of the soil C reserves in smaller regions is needed.

Post et al. (1982) related the variation in the soil C density to factors such as aspect, topography, parent material, soil age, vegetation and climate. Schlesinger (1977) mentioned differences in site productivities and ecosystem structures as causes for this variation. Such factors, which are associated with the soil C density, but which are easier to measure and for which more data is available, could provide means for stratifying sites into internally less variable groups to more accurately estimate the C reserves in different regions and investigate the spatial distribution of the soil C. For example, Burke et al. (1989) used climatic factors and certain soil properties to map the soil C density in the Central Plains Grasslands in the U.S.A. Davidson & Lefebvre (1993) and Stone et al. (1993) stratified sites on the basis of soil classification. Grigal & Ohmann (1992) showed that the soil C density of moist temperate forests is related to forest type in the U.S.A. In boreal forests in Finland, the soil C density has been found to be associated with forest types which indicate site productivity, and within the forest types the soil C density of the 0–1 m mineral soil layer has been observed to increase with the effective temperature sum (Liski & Westman 1995, 1997).

In the present study, we used the forest type and the temperature sum to explain the C density of the organic and 0–1 m mineral soil layers in forests on mineral soil in Finland; forests on peatlands were excluded from this study. In addition, a constant C density was applied for layers below the depth of 1 m on sorted sediments. By these means, we estimated the amount of C in these soil layers in the forests of Finland and illustrated regional patterns of the soil C storage.

## 2. Materials and methods

Models for the C densities of the organic (F/H) and 0–1 mineral soil layers were first made for the forest types used in the National Forest Inventory (NFI) to estimate the C densities at the 46673 NFI sites situated on forested mineral soil (Table 1). The NFI sites are located in clusters in a systematic grid which covers the whole country. The distance between the clusters ranges from 7 km to 8 km and the distance between the sites in a cluster from 200 m to 750 m. The maximum number of sites in a cluster varies from 8 to 21. The forest types used in the NFI represent different site productivities.

The C density of the organic layer was explained by the forest type and that of the 0–1 m mineral soil layer by the forest type and the effective temperature sum (+5 °C threshold), according to our earlier studies (Liski

*Table 1*. Models for the C densities (kg $m^{-2}$) of the organic and 0–1 m mineral soil layers in different forest type classes (tsum refers to the effective temperature sum using +5 °C threshold, expressed in degree-days).

| Forest type | Organic layer | Mineral soil layer |
|---|---|---|
| *Oxalis-Maianthemum* type and corresponding types | 2.20[1)] | 0.00266 tsum + 4.09[1)] |
| *Oxalis-Myrtillus* type and corresponding types | 2.20[2)] | 0.00266 tsum + 4.09 [5)] |
| *Myrtillus* type and corresponding types | 1.91[3)] | 0.00266 tsum + 2.69[3)] |
| *Vaccinium* type and corresponding types | 1.90[2)] | 0.00266 tsum + 0.790[6)] |
| *Calluna* type and corresponding types | 1.20[3)] | 0.00266 tsum + 0.218[3)] |
| *Cladina* type and corresponding types | 1.20[4)] | 0.00266 tsum + 0.218[4)] |
| Rocky ground, where stemwood production $>1$ $m^3$ $ha^{-1}$ $a^{-1}$ | 1.20[4)] | 0.00266 tsum + 0.218[4)] |
| Rocky ground, sandy soils and arctic hills, where stemwood production $<1$ $m^3$ $ha^{-1}$ $a^{-1}$ | 1.20[4)] | 0 |

[1)] assumed equal to *Oxalis-Myrtillus* type
[2)] from Liski & Westman 1995
[3)] from Liski & Westman 1997
[4)] assumed equal to *Calluna* type
[5)] 1.4 kg $m^{-2}$ more than at *Myrtillus* type (Liski & Westman 1995)
[6)] 1.9 kg $m^{-2}$ less than at *Myrtillus* type (Liski & Westman 1995)

& Westman 1995, 1997) (Table 1). In both soil layers the C density was assumed to increase with the productivity of the forest type. In addition, the C density of the 0–1 m mineral soil layer was assumed to increase linearly with the temperature sum. The same regression slope was applied for all the forest types, because the association between the C density and the temperature sum has not been found to differ among the forest types (Liski & Westman 1997).

At both ends of the productivity range we had to extrapolate our measurements for forest types not studied (Table 1). The C densities of the organic and 0–1 m mineral soil layers in the most productive *Oxalis-Maianthemum* type were assumed equal to the next productive *Oxalis-Myrtillus* type. At the other end of the productivity range, the C density of the organic layer in the least fertile studied type, the *Calluna* type, was applied for all the types of lower productivity, because forest floor was thought to exist in all forests. The C density of the 0–1 m mineral soil layer in the *Cladina* type was assumed equal to the *Calluna* type. At the more productive rocky sites the C density was assumed equal to the *Calluna* type, and at the less productive rocky sites the C density was set equal to zero. We think these extrapolations do not cause a large overall error in our estimates, because the extrapolated densities are probably fairly close to the actual densities and the unstudied forest types cover quite a small proportion of the forest area on mineral soil in the country. The *Oxalis-Maianthemum* type covers about 1% of the forest area, the *Cladina* type about 0.1%, the more productive rocky sites about 4% and the less productive rocky sites about 9% (calculated from the NFI data).

Using the models (Table 1), the C densities of the organic and 0–1 m mineral soil layers were calculated for all the 46673 NFI sites situated on forest land on mineral soil. The models give the C densities for stoneless soil and we assumed that the mineral soil was at least 1 m deep at all of the sites. The temperature sum, needed to calculate the C densities of the mineral soil, has been interpolated for the NFI sites by the Finnish Forest Research Institute from temperature measurements at meteorological stations using the method by Ojansuu & Henttonen (1983).

The amount of C in the organic and 0–1 m mineral soil layers in forests on mineral soil in Finland was estimated in two ways. One estimate of the C amount, the areal weighting estimate, was calculated by weighting the C densities of the systematically located NFI sites by the land area represented by the individual sites. To calculate the other estimate of the C amount, the block interpolated estimate, and to illustrate the spatial distribution of the soil C, the C densities of the NFI sites were first interpolated for 2 km × 2 km squares to cover the whole land area of Finland. A block kriging method was used for the interpolation (Isaaks & Srivastava 1989). This interpolation method utilizes spatial dependence to interpolate the values, and the structure of the spatial dependence is described by semivariograms, Because the structure of spatial dependence was found to vary with latitude in the country, the interpolation was carried out in five separate bands. Each band was 200 km wide from south to north, except the northernmost band, which was nearly 400 km wide. This division was thought to be appropriate for accurate interpolation. The northernmost region needed to be larger, because the grid of the NFI sites is sparser in the north, and, consequently, the larger size was needed to obtain enough sites for calculating valid semivariograms. For the interpolation, models of the exponential form (Isaaks & Srivastava 1989) were fitted in the isotropic semivariograms using the NONLIN procedure of SYSTAT (Anonymous 1992). The interpolation was done using GS + program (Anonymous 1993). After the interpolation, the 2 km × 2 km squares were divided into 200 m × 200 m squares to match the resolution of the satellite image based land use and forest classification data produced by the National Land Survey of Finland. The blocks on forested mineral soil were summed up for the estimates of the soil C and maps were made to illustrate regional patterns of the storages.

We also estimated the C storage in the soil layer between the depth of 1 m and ground water level in Finland, because this layer may contain 18–28% of the total amount of soil C in waterpermeable sorted sediments (Liski & Westman 1995). For the C content of these deep layers in till no data was available. We think that the accumulation of the post quaternary organic carbon in the very tight deep layers of till in significant quantities is improbable, because the tightness prevents root growth and vertical water movement that would transport organic matter into these layers. Therefore, a mean C density of 2.25 kg $m^{-2}$ (Liski & Westman 1995) was applied for the layer only in forests on sorted sediments. Such sediments were found by combining the information of the land use data and the data of quaternary deposits in Finland at the 200 m $\times$ 200 m resolution. The quaternary deposit data originated from the Geological Survey of Finland.

## 3. Results and discussion

The amount of soil C totalled 1109 Tg, when estimated by the areal weighting, and about 19% more, 1315 Tg, when estimated by the interpolated blocks (Table 2). The difference is mostly due to the approximately 12% larger land area of forests on mineral soil in the latter estimate, 199 129 $km^2$ compared to 177 898 $km^2$, and, for a smaller part, to the interpolation method. The difference in the land area of forests on mineral soil is in turn mainly caused by different definitions of peatland. In the land use and forest classification data, used for the larger estimate, sites classified as paludifying in topographic maps have been included in the land area on mineral soil. In contrast, the NFI sites have been classified as peatland if either the organic layer on top of mineral soil is peat or more than 75% of ground vegetation consists of peatland species. Which of the C estimates is more correct is difficult judge, since the estimates are essentially for different land areas. As an interpolation method, the block kriging used for the interpolated blocks estimate is usually more accurate than the areal weighting used for the areal weighting estimate (Isaaks & Srivastava 1989).

According to both estimates, 28% of the total soil C storage was in the organic layer, nearly 70% in the 0–1 m mineral soil layer and only a few percent in mineral soil below the depth of 1 m (Table 2). The similar division of the total C storage in the soil layers in both estimates is a result of the same models used for calculating the C densities at the NFI sites.

The amount of C in soil organic matter equals about two times the amount of C in tree biomass in Finland, which is 620 Tg altogether in forests on mineral soil and peatland (Kauppi et al. 1995). The organic layer alone contains about the same amount of C as the stemwood, about 360 Tg (Kauppi et al. 1995). Still, peat is nationally the largest C storage containing about five

*Table 2.* The amount of C in the different soil layers in forests on mineral soil in Finland. The areal weighting estimate is calculated by weighing the C densities of the sites of the National Forest Inventory (NFI) by the land area represented by the sites. The interpolated blocks estimate is calculated by interpolating the C densities of the NFI sites for 4 ha blocks to cover the whole land area and summing up the blocks on forested mineral soil. The amount of C in the layer below the depth of 1 m is for forests on sorted sediments in both estimates.

| Soil layer | Areal weighting estimate | | Interpolated blocks estimate | |
|---|---|---|---|---|
| | Tg | % | Tg | % |
| Organic | 315 | 28 | 370 | 28 |
| Mineral soil 0–1 m | 754 | 68 | 905 | 69 |
| Mineral soil below 1 m | 40 | 4 | 40 | 3 |
| Total | 1109 | 100 | 1315 | 100 |

times as much C as the soil of forests on mineral material, namely 6250 Tg (Ahlholm & Silvola 1990).

Earlier, Karjalainen & Kellomäki (1993) estimated the amount of C in the organic and 0–30 cm mineral soil layers in forests on mineral soil in Finland. In the study, they converted mean soil organic matter contents of different forest types in southern Finland, reported in Tamminen (1991), to organic C and multiplied the values by the land area covered by the forest types in Finland; the total land area was 162 900 km$^2$. Their estimate for the organic layer, 244 Tg, is 23% smaller than the smaller one of our estimates calculated by the areal weighting (Table 2). This difference is partly due to the 8% smaller land area of forests on mineral soil used in their study. For the 0–30 cm mineral soil layer they estimated 759 Tg, which is about as much as our estimate for the thicker 0–1 m soil layer (Table 2). One reason for their equal estimate for the shallower 0–30 cm soil layer, which contains 60–85% of the C storage in the 0–1 m layer (Liski & Westman 1995), is the lack of temperature association in their C densities, which were from southern Finland only.

The C storage of the organic layer was distributed quite evenly throughout the country (Figure 1a). The even distribution is due to the independence of the C density on temperature and to the densities applied for the most frequent forest types, *Vaccinium* and *Myrtillus* types and their corresponding types, which were very similar to each other (Table 1). Only the areas around the lakes in southern Finland were distinguished as having a higher (more than 2 kg m$^{-2}$) and the south-west coast and northernmost Lapland as having a lower (less than 1.6 kg m$^{-2}$) C density in the layer than the rest of the country. On the basis of the spatial distribution, the C storage exposed to potential losses of C from the organic layer as a consequence of forest harvest (Aber et al. 1978; Covington 1981) is similar in different parts of the country.

In the 0–1 m mineral soil layer, the C density generally decreased towards the north reflecting the association of the density with temperature (Figure 1b). The highest C densities (more than 5.0 kg $m^{-2}$) were found in the lake district in southern Finland, owing both to the temperature effect and to the location of the region of the most productive forest types in the country. Therefore, if the present coniferous are replaced by broadleaved forests as a consequence of climatic warming in southernmost Finland (Kellomäki & Kolström 1992), potential losses of soil C due to the replacement (Anderson 1992; Van Cleve & Powers 1995) will occur in regions where the present soil C density is the highest in the country. The C density was in turn lowest (less than 3 kg $m^{-2}$) in the south-west coast and northernmost Lapland. These low C densities are due to rocky and shallow soils of low productivity in the area, which is reflected in the forest type, and in Lapland also to the cold climate. In addition, local minimums in the C density tended to occur on the sorted sediments (Figure 1c). These sorted sediments are formed by glaciofluvial action during the retreat of the most recent glacier, and they are scattered all over the country. The forested sorted sediments are often very coarse, consisting of sand and gravel, and, therefore, covered by low productivity forest types with low soil C density.

The confidence in the estimates of the soil C storages and the regional patterns can not be calculated statistically, because, aside the uncertainty in the C density models and the interpolation methods, the error is caused by applying the models for types of sites not originally studied for the models. Such are sites with stony and shallow soils, sites with soils of different age, sites with different tree species and stand ages, sites with different past events, and sites with soils of different hydrological properties. We approximated the potential error caused by each of these factors separately to assess the overall uncertainty in the C storage estimates and the regional patterns.

The average volume of stones in the topmost 30 cm mineral soil layer in Finland is estimated to be as high as 42% (Viro 1958). To affect the soil C density, the stones should affect the processes of the soil C balance, namely net primary production of plants and decomposition of organic matter in soil. Therefore, it is improbable that the stones affect the soil C density to the whole extent of the stone volume. Assuming 42% stone volume for the whole 0–1 m mineral soil layer and that the stones reduce the soil C density by half of their volume decreases the estimate of the C storage in this layer by 21% (Table 3).

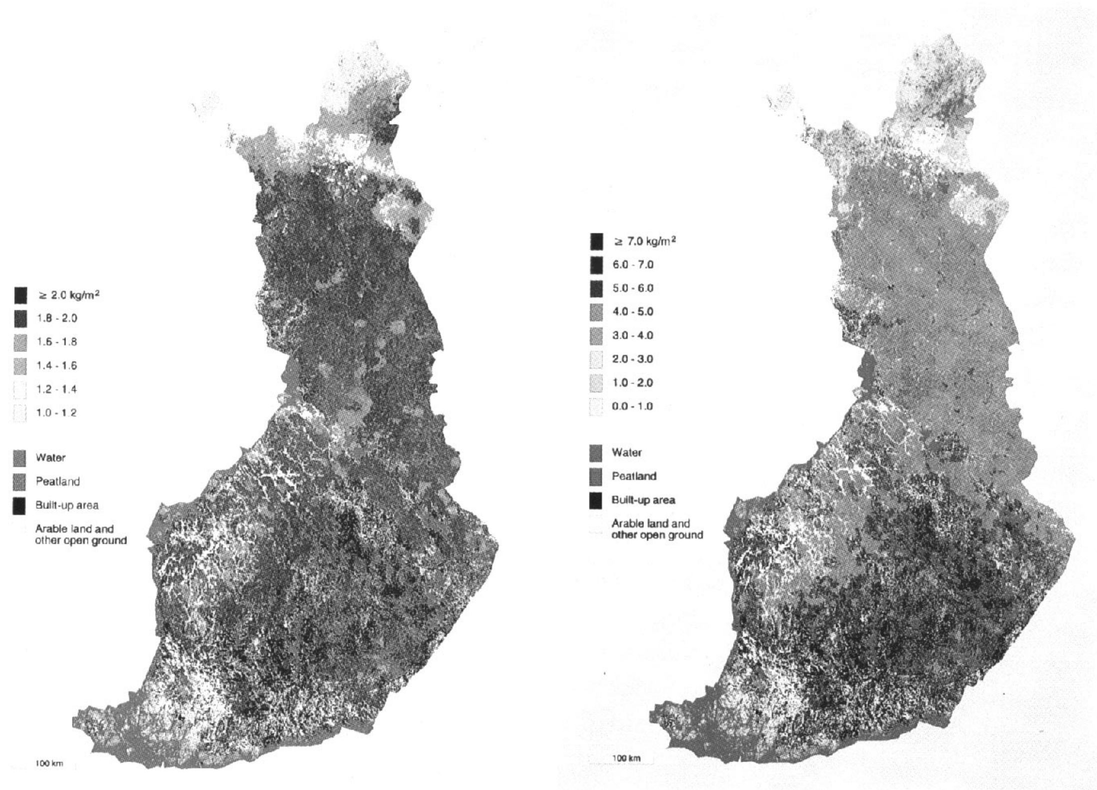


*Figure 1*. The C density of a) the organic layer, b) the 0–1 m mineral soil layer and c) the mineral soil layer below the depth of 1 m in forests on mineral soil in Finland.

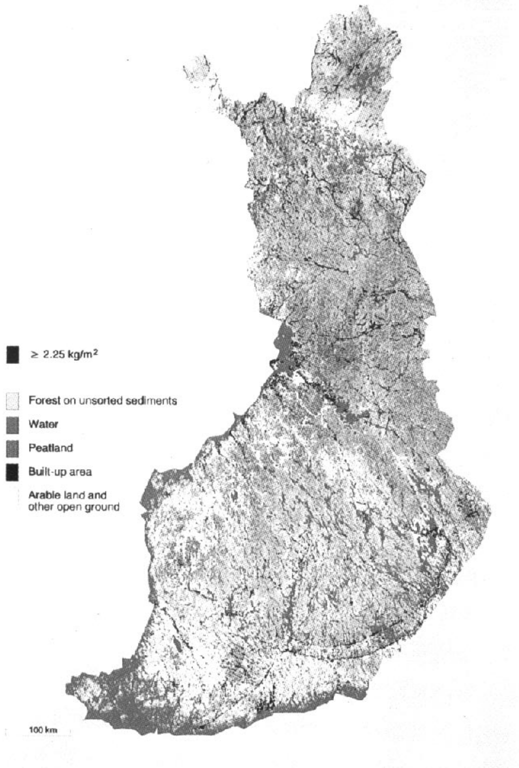


*Figure 1*. Continued.

*Table 3*. The potential error (%) in the C storage estimates for the organic and 0–1 m mineral soil layers of forests on mineral soil in Finland associated with different error sources. Negative and positive values indicate that the error source respectively decreases and increases the C storage estimates.

| Error source | Organic layer | Mineral soil layer |
|---|---|---|
| Stoniness of soil | 0 | −21 |
| Shallowness of soil | 0 | −7 |
| Dominance of broadleaved trees | −3 | −3 |
| Forest harvesting | −16 | 0 |
| Slash and burn cultivation | 0 | −4 |
| Drainage properties of soil | +6 | +6 |

The drift on the bedrock is less than 1 m thick on about 14% of the land area of the forests on mineral soil (calculated from the data on land use, forest classification and quaternary deposits). Most of this area is located on the southwestern coast and in northern Lapland, where the estimated C densities are low. The low C densities indicate that the shallowness of the soil layer is reflected in the forest type indicating site productivity, which reduces the potential overestimation. The rocky areas are also found in southeastern parts of the country where the estimated C densities were highest. There the shallowness of the soil layer has likely caused local overestimates of the C densities. Assuming 50% lower C content for all the shallow soils leads to, on the average, 7% smaller estimate for the C storage in the 0–1 m mineral soil layer (Table 3).

The C density models were made using soil C measurements of approximately 10 000 year old soils, and then applied for the whole of Finland. This soil age is close to the maximum in Finland, where the most recent glacier retreated some 11 000 years ago. Still, a majority of the soils in Finland are older than 7000 years, and only a negligible proportion of the land area, about 1% situated on the west coast, is younger than 2000 years (Eronen et al. 1995). On a 5000 year chronosequence of soils on the west coast of central Finland, the soil C density of the 0–30 cm mineral soil layer increased until a soil age of about 1500 years, after which the C content stabilized (Starr 1991, the C data unpublished). $^{14}$C datings of organic matter in A and B horizons of similar soils in Sweden suggest that the mean residence time for the C in the soils is some hundreds of years (Tamm & Östlund 1960; Tamm & Holmen 1967). On these bases, the soil C storage has reached equilibrium with the soil age in a great majority of soils in Finland, and, therefore, the differences in the soil age do not cause a significant error either in the C storage estimates or in the regional patterns.

At the sites studied for the C density models, tree stands were mature and dominated by Scots pine and Norway spruce. These tree species dominate in about 90% of the forest area in Finland (Anonymous 1994). The rest of the area is dominated mainly by birches. In these locations the models may overestimate the soil C density, since litter of broadleaved trees is more easily decomposable than litter of conifers, which in turn may decrease the soil C content (Flanagan & Van Cleve 1983). Assuming that the dominance of birches reduces the soil C density both in the organic and 0–1 m mineral soil layers by 25% compared with conifer sites reduces the C storage estimates for both soil layers on the average by 3% (Table 3). Forest harvest and especially clear cuttings have been estimated to lead to a 20–50% reduction in the C content of the organic layer in northern hardwood stands, and the recovery may take a few decades (Aber et al. 1978; Covington 1981). In mineral soil the effects of forest harvest on the C density are negligible, if forest vegetation is reestablished soon after harvest (Cooper 1983). In Finland this is most often the case. Assuming that the organic layer contained 50% less C in the 32%

of the forest area where the stands were less than 40 years old in 1983–1993 (Anonymous 1994) leads to a 16% smaller estimate for C storage of the organic layer (Table 3). The effect on the regional pattern of the storage is unimportant, since the harvested areas are distributed quite evenly throughout the country.

Some 30% of the total forest area has been under slash and burn cultivation in Finland between the years 1654–1861 (Heikinheimo 1915). This cultivation was most common in eastern Finland, whereas in western Finland it had mostly ceased in the early 19th century and in northern parts of the country it was not practised at all. In the latter half of the 19th century slash and burn cultivation started to become rarer and rarer also in eastern Finland, until it practically ceased at the beginning of 20th century. According to Kivekäs (1939), slash and burn cultivation reduces the amount of organic matter in top mineral soil, and this reduction is still observable 50 years after cultivation ceases. The effects on the present soil C storage have not been studied, but in a majority of the forest area once under the slash and burn cultivation the soils have had more than 100 years to recover. Assuming 25% lower C density in the 0–1 m mineral soil layer for half of the once cultivated forest area decreases the estimate of the C storage in this layer on the average by 4% (Table 3). This decrease is largest in eastern Finland, where the cultivation was most frequent.

Forest fires and prescribed burning for forest regeneration may also have reduced the soil C storage. There is, however, no reason to doubt that the sites studied for the models have been affected by forest fires at the normal intensity and frequency. The effects of the prescribed burning are insignificant, since it has been practised only on about 2% of the forest area and most frequently in the 1950s (Anonymous 1994).

Soils at the sites studied for the C density models were all well-drained podzolized soils. In poorly drained soils the C density may be much higher because frequent water-logging slows down decomposition. Such soils are often found around peatlands and agricultural fields in Finland. Land area of these soils may be quite large, since, for instance, the total land area of the peatlands, 104 000 $km^2$, is scattered over a total of about 49 000 individual mires (Lappalainen & Hänninen 1993). This gives a mean size of 2.12 $km^2$, and assuming all these peatlands to take a circular shape, a 50 m wide strip around all the individual mires makes up about 13000 $km^2$ of land area. Assuming twice the C density we used in our analysis for the strip, i.e. on the average 3.72 kg $m^{-2}$ in the organic layer and 9.08 kg $m^{-2}$ in the 0–1 m mineral soil layer, would increase the estimates of the amount of C both in the organic and 0–1 m mineral soil layers by about 6% for the whole country (Table 3).

Assuming the different error percentages are additive, the C storage of the organic layer is overestimated by 13% and that of the 0–1 m mineral soil layer by 29% in the initial estimates ignoring the potential error sources (Table 3). The actual storages are probably between our initial estimates and estimates corrected for the errors, because the errors were estimated to be as large as appropriately possible. Among the considered error sources, the largest error in the mineral soil C storage is associated with the volume of stones in the soil and in the organic layer C storage with the effects of forest harvesting (Table 3). A better knowledge of these factors in particular would thus help to improve the accuracy of the soil C storage estimates.

The only independent data available to test the models are the C densities for the *Calluna* type (CT) and *Myrtillus* type (MT) sites in southern Finland in our earlier study (Liski & Westman 1995). There the mean C density of the organic layer at the CT sites was 1.6 kg $m^{-2}$ compared to 1.2 kg $m^{-2}$ used for the calculations in this study and at the MT sites 2.0 kg $m^{-2}$ compared to 1.9 kg $m^{-2}$ used in this study. For the 0–1 m mineral soil layer the model predicts (the effective temperature sum 1190 degree-days) 3.4 kg $m^{-2}$ at the CT sites and 5.9 kg $m^{-2}$ at the MT sites, while we measured 4.2 kg $m^{-2}$ and 6.0 kg $m^{-2}$ respectively at the CT and MT sites. The method of interpolating linearly between separate samples in the soil profiles, used in the former study, tends to overestimate the amount of C in the parent material of the poorest sites, where the C concentration decreases very sharply from the soil horizons to the coarse-textured parent material. At more fertile sites, the interpolation method is appropriate. To illustrate the difference, we calculated the C densities of C in the 0–1 m mineral soil layer at the CT and MT sites of our earlier study again. We multiplied the volumetric C density in the soil horizons and parent material by the thickness of the layer. The mean C density for the MT sites was not altered, but the mean C density for the CT sites was 3.6 kg $m^{-2}$, thus very close to the model predictions. For properly testing the C density models and possibly further developing them, it would be very useful to have more field data on the soil C density in different parts of the country.

Despite its limitations and involved uncertainties, we found the approach of relating the soil C density to more easily measurable factors in order to estimate the amount of soil C and illustrate the regional patterns of the C storage applicable in Finland. We think that a similar kind of approach could be used to improve the accuracy of the estimates of the soil C reserves in other parts of the boreal zone as well.

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