

# Carbon Reservoirs in Peatlands and Forests in the Boreal Regions of Finland

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The carbon reservoir of ecosystems was estimated based on field measurements for forests and peatlands on an area in Finland covering 263 000 km<sup>2</sup> and extending about 900 km across the boreal zone from south to north. More than two thirds of the reservoir was in peat, and less than ten per cent in trees. Forest ecosystems growing on mineral soils covering 144 000 km<sup>2</sup> contained 10–11 kg C m<sup>-2</sup> on an average, including both vegetation (3.4 kg C m<sup>-2</sup>) and soil (uppermost 75 cm; 7.2 kg C m<sup>-2</sup>). Mire ecosystems covering 65 000 km<sup>2</sup> contained an average of 72 kg C m<sup>-2</sup> as peat.

For the landscape consisting of peatlands, closed and open forests, and inland water, excluding arable and built-up land, a reservoir of 24.6 kg C m<sup>-2</sup> was observed. This includes the peat, forest soil and tree biomass. This is an underestimate of the true total reservoir, because there are additional unknown reservoirs in deep soil, lake sediments, woody debris, and ground vegetation. Geographic distributions of the reservoirs were described, analysed and discussed. The highest reservoir, 35–40 kg C m<sup>-2</sup>, was observed in sub regions in central western and north western Finland.

Many estimates given for the boreal carbon reservoirs have been higher than those of ours. Either the Finnish environment contains less carbon per unit area than the rest of the boreal zone, or the global boreal reservoir has earlier been overestimated. In order to reduce uncertainties of the global estimates, statistically representative measurements are needed especially on Russian and Canadian peatlands.

**Keywords** carbon reservoirs, carbon pools, global carbon cycle, peat reserves, boreal forests, biomass carbon, global warming, ecological temperature gradient

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## 1 Introduction

The temperature increase in response to increasing amounts of greenhouse gases in the atmosphere is projected to be greatest at high latitudes (Mitchell et al. 1995). The carbon reservoir in the forest soil in the boreal zone has been estimated at 21–48 kg m<sup>-2</sup>, which is 2–4 times greater than the corresponding estimate for mid or low latitudes (Dixon et al. 1994). There is an exceptionally large reservoir of carbon in the part of the globe where a large warming has been projected. In a recent overview, Apps and Price (1996) have discussed the role of forests, particularly the boreal forests, in the global carbon cycle. The global distribution of the boreal biome has been described in many reports, e.g. Mellillo et al. (1993). They estimated the area of boreal forests and boreal woodlands at 12.2 and 6.3 million km<sup>2</sup>, respectively. For the sub regions and timber resources, see Kuusela (1990).

Gorham (1991) has estimated the total reservoir of boreal and subarctic peatlands at 455 Pg (Petagram = 10<sup>15</sup> g = gigaton = billion metric tons). This refers to an area of 3.46 million km<sup>2</sup>, using a mean peat thickness of 2.3 m as a basis of calculation. Post et al. (1982) have estimated the carbon reservoir in the soils of “Boreal forest-wet” and “Boreal forest-moist” at 133.2 and 48.7 Pg, referring to areas of 6.9 and 4.2 million km<sup>2</sup>, respectively. In addition, they have estimated 202.4 Pg on an area of 2.8 million km<sup>2</sup> of global wetlands. Apps et al. (1993) have estimated the boreal C reservoir to be as high as 709 Pg, subdivided in peat (419), forest soil (199), plant detritus (32), and plant biomass (64). They refer to a total area of 12.5 million km<sup>2</sup> and a peatland area of 2.6 million km<sup>2</sup>. The discrepancy between the estimates is partly a result of different definitions (forest vs. forested peatland vs. peatland; temperate zone vs. boreal zone vs. subarctic zone). Assuming a target area of 15 million km<sup>2</sup>, including peatlands and forests, a carbon reservoir of 400–700 Pg has been given for the boreal environment in the most recent estimates. Most of the reservoir is known to exist as peat.

Raich and Schlesinger (1992), Lüdeke et al. (1995), and Kirschbaum (1995) have suggested

that, if the climate turns warmer the carbon reservoir of boreal forests and peatlands would diminish, i.e. there would be a positive feedback from the boreal environment to an eventual climatic warming. However, Townsend et al. (1992) and van Minnen et al. (1995) have suggested just the opposite. In their view, the carbon reservoirs would grow in the boreal zone in response to a warming, thus providing a negative feedback. Whether the feedback would be positive or negative is an unresolved question at present.

The boreal landscape consists of a mosaic of closed forests, open woodlands, peatlands and lakes. Peatlands occur mostly in landscape depressions where edaphic, hydrologic and climatic conditions maintain a high water table and allow organic matter to accumulate as peat at a rate faster than the rate of oxidation.

This study describes the carbon reservoirs of rural, non-cultivated, terrestrial ecosystems in the boreal zone based on a large number of measurements. Our data are from Finland where peatlands, with peat layer  $\geq 30$  cm, cover 24.7 % of the land of the study area. The objective is to estimate the carbon reservoirs of trees, of the soil of closed forests growing on inorganic soils (here referred to as “forest soil”), and of peatlands; to analyse the spatial variation of these reservoirs along the temperature gradient from north to south; and to use this information for assessing the total carbon reservoir of the boreal zone and the eventual feedback mechanisms to a greenhouse warming.

Our data represent the landscape (regional) scale. It is possible by using such data to overcome most of the inaccuracies and biases resulting from extrapolation of measurements taken at a small number of ecosystems. Botkin and Simpson (1990) have demonstrated the importance of landscape level sampling, based on data measured for the vegetation of the boreal forests of North America; see also Brown et al. (1989).

## 2 Methods

The northernmost and the south western regions of Finland fall outside the boreal zone and are not part of the study area. Within the boreal zone

in Finland, an area of 40 000 km<sup>2</sup> of built-up and arable land was also excluded. The focus was on the natural and semi-natural landscape mosaic, an area of 263 000 km<sup>2</sup>, of which inland waters covered 31 000 km<sup>2</sup>. Peatlands cover 65 000 km<sup>2</sup> of the study area, and forests growing on mineral soils an area of 144 000 km<sup>2</sup>.

**Trees.** Stem volume was calculated based on measurements of the eighth national inventory of Finnish forests taken in 1986–1994 from about 490 000 living trees in 69 000 sample plots. Systematic sampling ensures that the measurements represent all living trees taller than 1.35 m (Salminen 1993). About 80 % of the timber growing stock is on mineral soils, the rest on peatlands. The forest inventory has been maintained since the 1920s, with the main objective of monitoring timber resources. The stem volume is defined over bark, including the entire stem from the stump level to the top.

Stem biomass was calculated from volume, assuming a dry weight density of 420, 380, and 480 kg m<sup>-3</sup> for Scots pine, Norway spruce and the deciduous species, respectively (Hakkila 1989). Branch, root and foliage biomass was estimated using conversion coefficients relating other woody biomass to stem biomass (Kauppi et al. 1995). According to these coefficients, stem accounts for 51–71 % of the total tree biomass depending on species and age, variables recorded in the inventory. A carbon concentration of 50 % was used for all woody biomass (Nurmi 1993).

**Forest soil.** Soil samples were taken in 1986–1989 from 377 stands selected as a sub sample of the basic network of 3000 permanent sample plots of the national forest inventory located in clusters at intervals of 16 km × 16 km in southern and 24 km × 32 km in northern Finland. The samples were taken from the humus layer, excluding the litter layer, and from the mineral soil at four depths: 0–5, 5–20, 20–40 and 60–70 cm. For the humus sample, 10 to 30 sub samples, depending on humus thickness, were taken with a cylinder and combined into a single sample for the plot. The mineral soil samples for each layer consisted of a composite of five sub samples, except the 60–70 cm layer, which consisted of a single sample only. Bulk density and C concentration were determined separately for the hu-

mus layer and the mineral soil (Tamminen and Starr 1990). The C reservoir of each stand was determined for the uppermost 75 cm, corrected for bulk density and stone volume (Viro 1952, Tamminen 1991).

**Peat.** The volume of peat was calculated based on ca. 900 000 measurements of peat thickness taken in the field in 1973–1991 in a national peat survey, carried out mainly to estimate peat energy reserves (Lappalainen and Hänninen 1993). Bulk density and C concentration were analysed from about 11 000 laboratory samples taken at 10–20 cm intervals from peat core profiles. For shallow peatlands where the organic layer is less than 30 cm deep, a depth of 20 cm, a (dry) bulk density of 80 kg m<sup>-3</sup>, and C concentration of 50 % in dry matter were used (= 8 kg C m<sup>-2</sup>).

**Gradients.** In order to analyse the geographic variation of the reservoirs, the area was divided into 74 sub regions each covering 1070–12 300 km<sup>2</sup>. The reservoirs in trees, forest soil and peat were calculated for each sub region. Observations were plentiful for trees and peatlands but not for forest soils. Only 1–17 observations were available on forest soils in each sub region, and the arithmetic mean was used.

The spatial variation of the carbon reservoirs was analysed as a function of the mean annual temperature, as observed in 1961–1990. The mean daily temperature observations from 136 Finnish stations and 20 adjacent stations in Sweden and Norway were used. A kriging method was applied to calculate the mean monthly temperature at a spatial resolution of 10 km × 10 km, taking into account the effects of altitude, slope, distance from the Baltic, and occurrence of lakes when filling in gaps between observational stations (Henttonen 1991). From these data the mean annual temperature was calculated for each sub region.

## 3 Results

### 3.1 Carbon Reservoirs

**Trees.** The C reservoir of living trees in the study area was 618 Tg (Teragram = 10<sup>12</sup> g). Stemwood accounted for 374 Tg. Dividing the reservoir by

the area of the landscape, 263 000 km<sup>2</sup>, yields an average of 2.7 kg C m<sup>-2</sup>. This refers to the total area including inland water. As 80 % of the growing stock is on mineral forest soils covering 144 000 km<sup>2</sup>, an average of 3.4 kg C m<sup>-2</sup> can be estimated for such forested land.

In the boreal forests of Russia the vegetation reservoir has been estimated at 19.6 Pg including stems, roots and crowns based on forest inventory covering 5.22 million km<sup>2</sup> of stocked forests (Alexeyev et al. 1995). This would mean an average of 3.75 kg C m<sup>-2</sup>. Assuming 7.6 million km<sup>2</sup> as the boreal land area in Russia, including unstocked land (Apps et al. 1993), the reservoir would correspond to 2.6 kg C m<sup>-2</sup>. This estimate includes both above- and below-ground biomass.

In the North American boreal zone, an above-ground reservoir of 1.9 ± 0.4 kg C m<sup>-2</sup> has been reported for trees and shrubs (Botkin and Simpson 1990). Our Finnish data indicate a reservoir of 2.1 kg C m<sup>-2</sup> in tree biomass, above-ground.

*Forest soil.* The C reservoir of forest soil was estimated at 1040 Tg in the uppermost 75 cm layer, corresponding to 3.9 kg C m<sup>-2</sup> for the landscape (the area of 263 000 km<sup>2</sup> including land and inland water). Mineral forest soils cover 144 000 km<sup>2</sup>. An average forest ecosystem hence contained 7.2 kg C m<sup>-2</sup> in the upper 75 cm of the soil. This is within the range reported earlier for Finnish soils by Liski and Westman (1995).

*Peat.* The total C reservoir in peat was estimated at 4800 Tg, of which only 140 Tg were in shallow peatlands. Peat contributed 18.3 kg C m<sup>-2</sup> to the landscape carbon, referring to the land and water area of 263 000 km<sup>2</sup>. An average mire ecosystem contained 72 kg C m<sup>-2</sup> in peat, referring to the area of 65 000 km<sup>2</sup> where the layer of peat is at least 30 cm thick. The area-weighted average depth of the organic layer in Finnish peatlands is 1.3 m, estimated earlier from these data (Lappalainen and Hänninen 1993).

The sum of the reservoirs measured (trees + soil + peat) was 618 + 1040 + 4800 = 6458 Tg; or 2.7 + 3.9 + 18.3 = 24.6 kg C m<sup>-2</sup>. For the land base of 232 000 km<sup>2</sup>, excluding inland water, the average carbon reservoir was 27.8 kg C m<sup>-2</sup> (Table 1).

**Table 1.** Area, carbon density, carbon reservoir, and the contribution of landscape elements to the total carbon density of the study area.

Landscape element	Area 1000 km <sup>2</sup>	Average carbon density kg m <sup>-2</sup>	Reservoir Tg C	Contribution to landscape carbon kg m <sup>-2</sup>
Closed forests on mineral soil	144	10.7 <sup>1)</sup>	1536 <sup>1)</sup>	5.8 <sup>2)</sup>
Peatlands (depth > 30 cm)	65	73 <sup>1)</sup>	4721 <sup>1)</sup>	17.9 <sup>2)</sup>
Shallow peatlands	18	11.1 <sup>1)</sup>	201 <sup>1)</sup>	0.8 <sup>2)</sup>
Open wooded land	5	n.a.	n.a.	n.a.
Natural and semi-natural land	232	27.8	6458	
Inland water	31	n.a.	n.a.	n.a.
Natural and semi-natural environment	263	24.6 <sup>1)</sup>	6458 <sup>1)</sup>	
Arable & built-up land	40			
Total area	303			

1) Includes both trees and soil

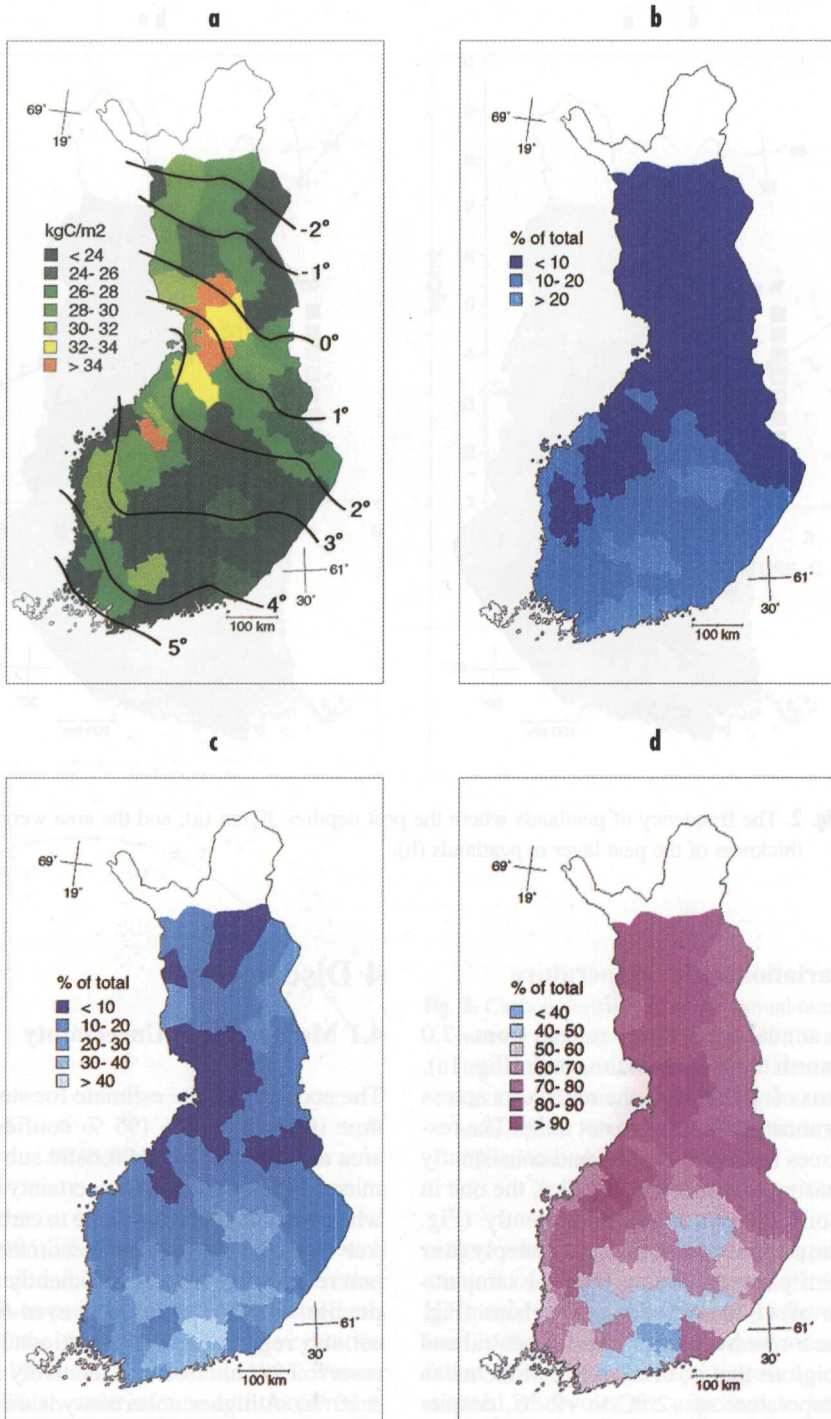
2) Reservoir divided by total area, i.e. by 263 000 km<sup>2</sup>

n.a. = not available

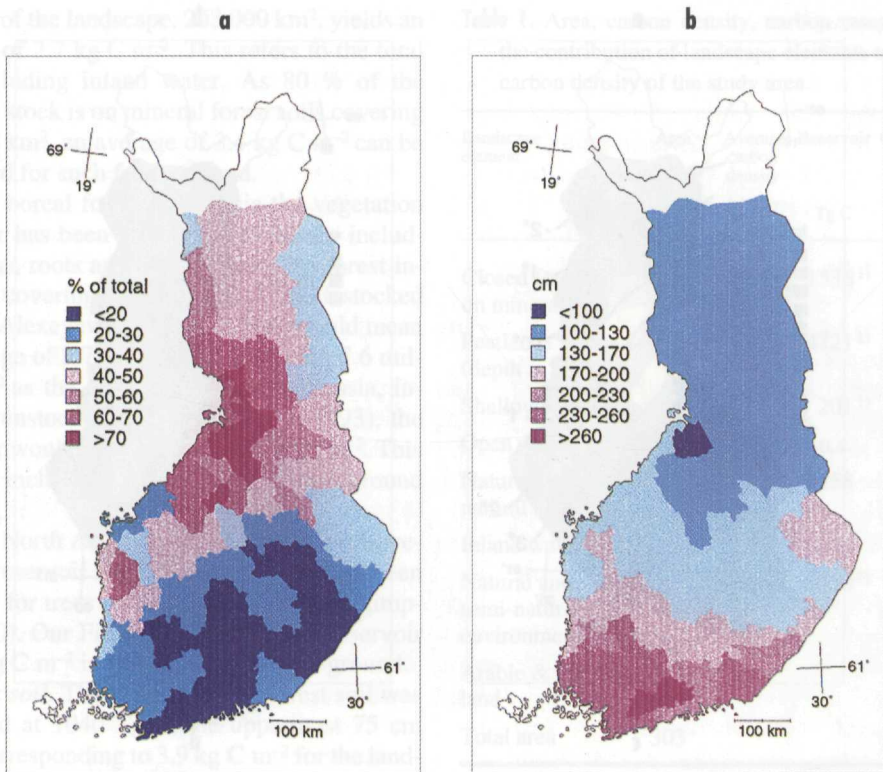
### 3.2 Geographic Gradients

The largest reservoir in the landscape, 35–40 kg C m<sup>-2</sup>, was found in central western and in north western parts of Finland and the smallest reservoir, 20–25 kg C m<sup>-2</sup>, in the lake region of south eastern Finland (Fig. 1a). In some sub regions, more than 90 % of the reservoir was in peat. The relative contribution of trees and forest soil increased southwards (Figs. 1b,c). However, peat made the largest relative contribution also in all southern sub regions except one (Fig. 1d).

The peat storage was relatively small near the Gulf of Bothnia (in the west) where new land keeps emerging from the Baltic because of land uplift (Figs. 1a,d). A land belt up to 50 km from the coast is only 500–1500 years old (Eronen et al. 1995). The peatlands were most common in central and northern Finland, but deepest in southern Finland (Fig. 2).



**Fig. 1.** Carbon reservoir of the landscape, in colours, and mean annual temperature, in isopleths (a); and the contribution to the reservoir by trees (b), forest soil (c), and peat (d).



**Fig. 2.** The frequency of peatlands where the peat depth > 30 cm (a); and the area weighted thickness of the peat layer in peatlands (b).

### 3.3 Co-variation with Temperature

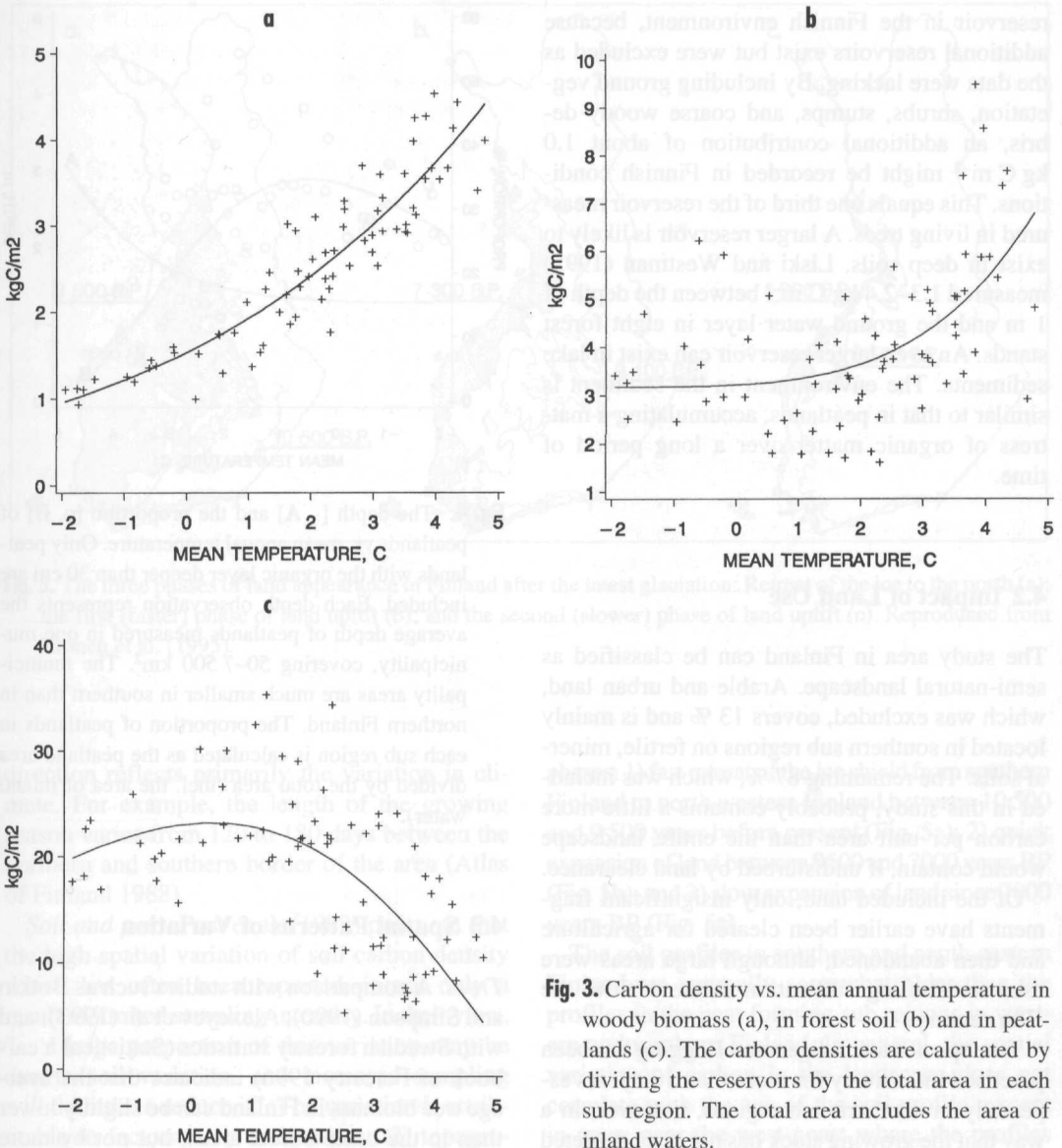
The mean annual temperature ranged from  $-2.0$  °C in the north to  $+4.8$  °C in the south (Fig. 1a). The patterns of variation of the reservoirs across the temperature gradient were not alike. The reservoir in trees increased steeply and consistently with increasing temperature (Fig. 3a), the one in mineral soils increased less consistently (Fig. 3b), and the peat reservoir decreased steeply over the southern part of the area, over the temperature range of  $+1$  to  $+4.5$  degrees Celsius (Fig. 3c). The peat reservoir was largest in central and northern regions that is, in the range of the mean annual temperature of  $-2$  °C to  $+2$  °C, despite the shallow peat depth characteristic to those regions (Fig. 4). In other words, the gradient in peatland frequency overruled the impact of peat depth.

## 4 Discussion

### 4.1 Measurement Uncertainty

The accuracy of the estimate for stemwood volume is about  $\pm 2$  % (95 % confidence) for an area as large as a characteristic sub region (Salminen 1993). Additional uncertainty is introduced when converting stem volume to carbon in whole-tree biomass. However, the estimate for the carbon reservoir in trees is sufficiently accurate and precise, within  $\pm 10$  per cent even for the smallest sub regions. Also the estimate of the peat reservoir is unbiased and relatively accurate (ca.  $\pm 10$  %). A higher uncertainty is associated with forest soils, since the observations are fewer.

Ground vegetation and shrubs, which were excluded, are only 2–5 % of the tree biomass and unimportant quantitatively as a carbon reservoir



**Fig. 3.** Carbon density vs. mean annual temperature in woody biomass (a), in forest soil (b) and in peatlands (c). The carbon densities are calculated by dividing the reservoirs by the total area in each sub region. The total area includes the area of inland waters.

(Mäkipää 1995). Coarse woody debris, which was also excluded, has been reported in other world regions to contain a reservoir which equals 30–40 % of the biomass in living vegetation (Apps et al. 1993, Alexeyev et al. 1993, Turner et al. 1995). This would infer an additional reservoir of 200–250 Tg, or 0.7–1.0 kg C m<sup>-2</sup>, for our study area. However, this is an upper estimate, and an overestimate since most forest stands in Finland have been treated with silvicultural thin-

nings, which has a decreasing impact on the amount of coarse woody debris (Krankina and Harmon 1995). An additional reservoir in Finland is the one in stumps and in coarse roots of felled trees. However, the largest unknown and omitted reservoirs are expected to be found in deep layers of the soil (Liski and Westman 1995) and in lake sediments.

In conclusion, the observed reservoir of 24.6 kg C m<sup>-2</sup> is an underestimate of the true total

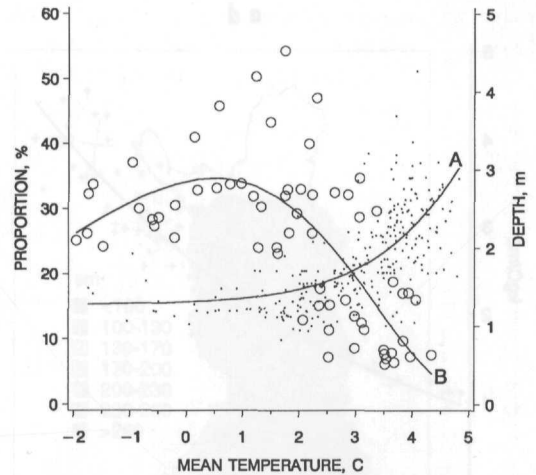
reservoir in the Finnish environment, because additional reservoirs exist but were excluded as the data were lacking. By including ground vegetation, shrubs, stumps, and coarse woody debris, an additional contribution of about  $1.0 \text{ kg C m}^{-2}$  might be recorded in Finnish conditions. This equals one third of the reservoir measured in living trees. A larger reservoir is likely to exist in deep soils. Liski and Westman (1995) measured  $1.3\text{--}2.4 \text{ kg C m}^{-2}$  between the depth of 1 m and the ground water layer in eight forest stands. An even larger reservoir can exist in lake sediments. The environment in the sediment is similar to that in peatlands, accumulating a matress of organic matter over a long period of time.

## 4.2 Impact of Land Use

The study area in Finland can be classified as semi-natural landscape. Arable and urban land, which was excluded, covers 13 % and is mainly located in southern sub regions on fertile, mineral soils. The remaining 87 %, which was included in this study, probably contains a little more carbon per unit area than the entire landscape would contain, if undisturbed by land clearance.

Of the included land, only insignificant fragments have earlier been cleared for agriculture and then abandoned, although large areas were used for shifting cultivation in the 17th to the 19th century.

Tree species are indigenous. Logging has been practised intensively for more than 100 years especially in southern sub regions, however, in a way that the growing stock has not been depleted (Karjalainen and Kellomäki 1996, Pingoud et al. 1996). More than 90 % of the area has been logged, most often treated with partial cuttings but also with regeneration cuttings such as clear felling. Wild fires, which occur frequently in other boreal regions (Stocks at al. 1996), have almost entirely been suppressed in Finland in the 20th century. An area of  $58\,000 \text{ km}^2$  has been drained in Finland for forestry purposes mainly since the 1950s (Tomppo and Henttonen 1996). According to Laine et al. (1995), drainage has not yet affected the carbon reservoir of the peatlands.



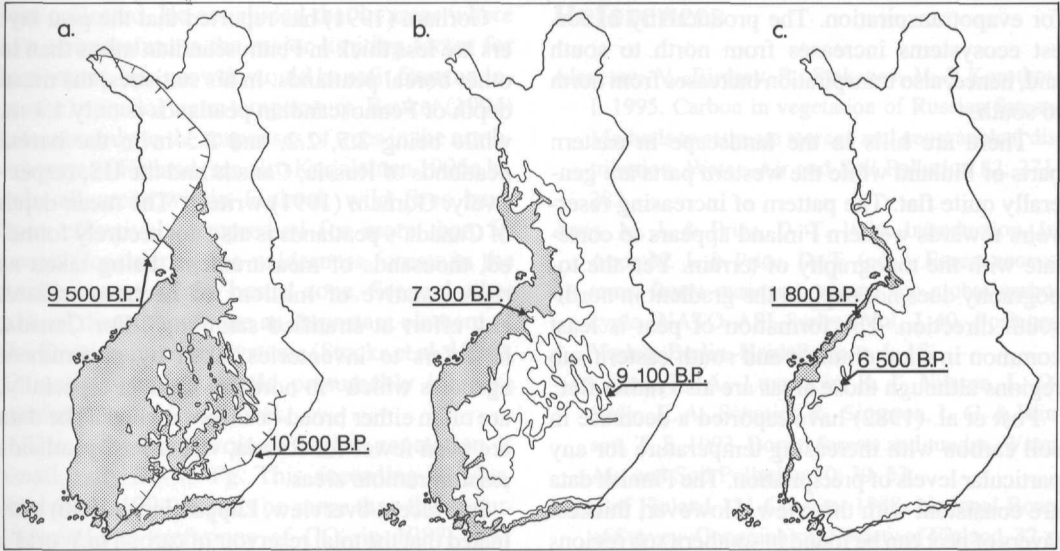
**Fig. 4.** The depth [·, A] and the proportion [o, B] of peatlands vs. mean annual temperature. Only peatlands with the organic layer deeper than 30 cm are included. Each depth observation represents the average depth of peatlands measured in one municipality, covering 50–7 500  $\text{km}^2$ . The municipality areas are much smaller in southern than in northern Finland. The proportion of peatlands in each sub region is calculated as the peatland area divided by the total area (incl. the area of inland water).

## 4.3 Spatial Patterns of Variation

*Trees.* A comparison with studies such as Botkin and Simpson (1990), Alexeyev et al. (1993), and with Swedish forestry statistics (Statistical Yearbook of Forestry 1996) indicates that the average tree biomass in Finland can be slightly lower than in the other boreal areas, but not by more than 10–20 per cent. It is possible that the difference is partly explained by measurement error or differences in concepts, except when comparing with Sweden where the methods of measurement are very similar.

The variation of tree biomass within Finland, from 1 to  $4 \text{ kg C m}^{-2}$  between north and south (Fig. 3a), is much greater than the differences in the average reservoir between the boreal world regions. A similar north-south gradient exists in Sweden (Statistical Yearbook of Forestry 1996). The large variation of vegetation in north-south





**Fig. 5.** The three phases of land appearance in Finland after the latest glaciation: Retreat of the ice to the north (a); the first (faster) phase of land uplift (b); and the second (slower) phase of land uplift (c). Reproduced from Eronen et al. (1995).

direction reflects primarily the variation in climate. For example, the length of the growing season varies from 120 to 180 days between the northern and southern border of the area (Atlas of Finland 1988).

*Soil and peat.* Post et al. (1982) point out that the high spatial variation of soil carbon density which has often been reported, is not only a result of limited sampling intensity. In their view, "... a large proportion of this variation may be due to soil variation, and increased sampling will do little to reduce it". The variation is attributable to factors such as 1) aspect, 2) topography, 3) parent material, 4) age of the soil profile, and 5) vegetation. Regarding mineral soils, Liski and Westman (1996a, b) have analysed this variation in Finnish conditions.

Since the peat reservoir dominates, it is essential to analyse why peatlands are so common in western central Finland, and why the deepest peatlands are to be found in southern Finland. First, there can be impacts of the glacial history which varies globally within the boreal zone (Peltier 1994). In Finland, according to Eronen et al. (1995), the post-glacial changes of the landscape can be divided into three

phases: 1) fast retreat of the ice shield from southern Finland to north western Finland between 10 500 and 9 500 years before present (Fig. 5a); 2) quick expansion of land between 9500 and 7000 years BP (Fig. 5b); and 3) slow expansion of land since 7000 years BP (Fig. 5c).

The soil profiles in southern and south eastern Finland are generally somewhat older than the profiles in the peat forming sub regions in western and northern Finland. In general, the spatial variation of carbon in the landscape does not correlate with the age of the soil profile, except in areas near the west coast where the profiles are younger than 500 to 1500 years. In other words, a period of 2000 to 4000 years has been sufficiently long in western central Finland for the accumulation of the large peat reserves. Beyond that, there is little or no correlation over space between the age of the soil profile and the total reservoir of carbon in peatlands.

Annual precipitation in Finland is 500–700 mm, and rather similar in all sub regions. Evaporation varies more, from 200 mm in the north to 450 mm in the south (Atlas of Finland 1988). The gradient from north to south is even steeper

for evapotranspiration. The productivity of forest ecosystems increases from north to south and, hence, also transpiration increases from north to south.

There are hills in the landscape in eastern parts of Finland while the western parts are generally quite flat. The pattern of increasing reservoirs towards western Finland appears to correlate with the topography of terrain. Yet, the topography does not explain the gradient in north-south direction. The formation of peat is least common in southernmost and south eastern sub regions although those areas are also rather flat.

Post et al. (1982) have reported a decrease in soil carbon with increasing temperature for any particular levels of precipitation. The Finnish data are consistent with this view. However, thickest layers of peat can be found in southern sub regions (Fig. 2 b). A hypothesis can be presented that, firstly, the height increment of peat is fastest in the warmest (southern) peatlands. Secondly, the high temperature also maintains a high rate of evapotranspiration. Therefore, the water table tends to be low in southern Finland, and waterlogged areas are uncommon. A single characteristic in climate – high average temperature compared to the more northern regions – creates the conditions for two different ecological consequences according to this hypothesis: The peat layers are thick, but peatlands are rare (Fig. 4).

#### 4.4 Extrapolation to Other Boreal Areas

Peatlands are the main reservoir of carbon in the boreal zone. Regarding extrapolation beyond Finnish borders, the main issue is whether peatlands are as common in Finland as in other boreal areas, and whether a typical Finnish peatland is representative of all boreal peatlands. The relative cover of peatlands in our data is 28.0 and 24.7 % referring to land area and total area, respectively. Global boreal peatlands have been reported to cover 2.5–3.5 million km<sup>2</sup> (Gorham 1991, Apps et al. 1993). Given the total area of the boreal zone, 12–15 million km<sup>2</sup> depending on definitions, the peatlands would cover 18–28 % of the area. In conclusion, peatlands are as common or slightly more common in Finland than in other boreal areas.

Gorham (1991) has reported that the peat layers are less thick in Fennoscandian mires than in other boreal peatlands. In his statistics, the mean depth of Fennoscandian peatlands is only 1.1 m, while being 2.5, 2.2, and 2.5 m in the boreal peatlands of Russia, Canada and the US, respectively. Gorham (1991) writes: “The mean depth of Canada’s peatlands is also not securely founded, thousands of measurements being taken as representative of millions of hectares without any effort at stratified sampling”. For Canada, he refers to inventories taken by government agencies which “in northern Canada especially, are often either broad-scale or lacking”. The data are even fewer for Russia, where vast peatlands exist in remote areas.

In a recent overview, Lappalainen (1996) estimated that the total reservoir of carbon in World’s peatland would be only 234–252 Pg. This is less than has been estimated for boreal peatlands alone, e.g. by Gorham (1991). Assuming that the bulk density of peat varies in a similar way in all boreal peatlands, the data on peat depth is critical in efforts of improving the accuracy and precision of boreal carbon estimates.

#### 4.5 The Eventual Carbon Feedback

The increment of trees in the boreal region of Finland, both radial and height increment, is higher during warm than during cold periods (Mikola 1950). It is also a fact that forest growth is higher in the southern (mild) than in northern (cold) regions within Finland (e.g. Kauppi and Posch 1985). A hypothesis has been presented that nitrogen mineralization increases with increasing temperature, and supply of nitrogen would be critical in the boreal zone in enhancing Net Primary Productivity in mild areas (e.g. Mäkelä 1993). In addition, the variation from north to south in the length of the growing season has impacts on productivity. Regarding responses to warming, let us first consider forests with continuous tree canopy on mineral soils.

In Beuker’s (1994) data, growth increased relative to the natural rate of growth, when trees were taken from northern Finland and transplanted to southern Finland into an environment 2–5 centigrade warmer than the site from which the seed

was collected. He concluded that in areas where low temperature is the major limiting factor for increment, tree growth would benefit from an increase in annual mean temperature. Beuker (1994) refers mainly to the responses of trees in the northern parts of Finland (see also Karjalainen 1996a,b).

In all areas within Finland, wild fires have been effectively suppressed for more than 50 years. Considering the wilderness forests in the northern parts of the boreal zone, fire and other natural disturbances are an important element of the functioning of ecosystems (Stocks et al. 1996). Climatic warming would presumably increase the frequency of wild fires.

The carbon reservoir of boreal vegetation is small, only 30–45 Pg. This according to Marland et al. (1994) equals no more than the cumulative global emissions of CO<sub>2</sub> in 1987–1991 ( $\approx$  30 Pg C), or in 1984–1991 ( $\approx$  45 Pg C). Changes in vegetation biomass in the boreal zone, whether positive or negative, will have only a small impact on the concentration of CO<sub>2</sub> in the atmosphere. As a potential feedback to climatic warming, it does not matter very much whether the boreal trees would accumulate more biomass, or whether they would burn in flames.

Then, let us consider mire ecosystems, and the eventual positive feedback to greenhouse warming that is, a possible net release of CO<sub>2</sub> from the peat reservoir into the atmosphere. Even if earlier estimates can have been too high, the reservoir in boreal peatlands is at least 200 Pg C, almost one order of magnitude larger than the corresponding reservoir in boreal vegetation. Therefore, the issue of a boreal impact on the future trend of CO<sub>2</sub> in the atmosphere is mainly an issue of a possible decrease of the largest boreal reservoir, peat.

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*Total of 48 references*

## 1 Introduction

Uneven-aged forests constitute about 23 % of the Italian forests (excluding coppices), covering more than 354 400 ha, and irregular forests cover another 391 000 ha, altogether 41 % of the high forests (ISAF A-MAF 1988).

Although forms of uneven-aged management were used in some areas of the Alps for centuries, foresters began to be really interested in them after the Second World War, following the spread of the nature oriented silviculture. The view is that there is a better chance to guarantee the sustainability of cultivated forests, with less expenditures in energy and money, if they are