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Are Swedish forest soils sinks or sources for CO_2—model analyses based on forest inventory data

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Abstract Forests soils should be neither sinks nor sources of carbon in a long-term perspective. From a Swedish perspective the time since the last glaciation has probably not been long enough to reach a steady state, although changes are currently very slow. In a shorter perspective, climatic and management changes over the past 100 years have probably created imbalances between litter input to soils and organic carbon mineralisation. Using extant data on forest inventories, we applied models to analyse possible changes in the carbon stocks of Swedish forest soils. The models use tree stocks to provide estimates of tree litter production, which are fed to models of litter decomposition and from which carbon stocks are calculated. National soil carbon stocks were estimated to have increased by 3 Tg yr^{-1} or 12–13 g m^{-2} yr^{-1} in the period 1926–2000 and this increase will continue because soil stocks are far from equilibrium with current litter inputs. The figure obtained is likely to be an underestimation because wet sites store more carbon than predicted here and the inhibitory effect of nitrogen deposition on soil carbon mineralisation was neglected. Knowledge about site history prior to the calculation period determines the accuracy of current soil carbon stocks estimates, although changes can be more accurately estimated.

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Introduction

Accounting for carbon stocks is important from both a scientific and social perspective. Changes in soil stocks are particularly important because of the large quantities of carbon in soils and the potential of rapid responses to climatic and management changes. A recent paper (Bellamy et al. 2005) indicates that soil carbon stocks decreased in England and Wales between 1978 and 2003. In Sweden, we expect both standing biomass and soil carbon stocks to have increased in the same period, as a result of large-scale afforestation since the late 19th century. This paper investigates the possibilities of predicting long-term changes in soil carbon and also considers the permanence of such stocks (e.g. Smith 2005).

An important concept when analysing changes in dynamic systems such as soils is steady state, because it provides a convenient reference point. The question is how relevant steady state is with regard to soil carbon. Model analyses show that the build-up of a soil carbon stock is initially quite rapid, but once approximately half the steady state stock has been reached the progress becomes very slow, and changes over even thousands of years are hardly perceptible (Fig. 1). With forest litter typical of coniferous needles and Swedish climatic conditions, calculations using the Q model (Ågren and Bosatta 1998) show that 50% of the steady state value is reached after ca. 200 years but 15,000 years are required to reach 80%. A similar situation applies when carbon is lost from a steady state situation. Half the carbon is lost over 250 years, but 10,000 years are required to lose an additional 50%. The reason is that the soil carbon consists of carbon compounds of varying qualities and the last fraction to be built up consists of highly refractory carbon compounds produced only in small quantities. The reverse applies when carbon stocks are degraded. This very slowly decaying, almost inert, carbon may explain why the Rothamsted model requires an inert pool to explain the ^{14}C content in the soil (Coleman and Jenkinson 1996).

Model

We used official forestry statistics (http://www.svo.se, see also relevant years of Swedish Statistical Yearbook of Forestry) on actual standing tree volumes and harvests to estimate the standing stock of tree components for every year between 1926 and 2000. These statistics provided us with data on forest areas and standing stocks in each of 23 Swedish counties varying in size from 1,200 to 36,000 km^2. Inventories of stocks are always reported for intervals of years and we refer these to the median year. Only the intervals 1923–1929, 1938–1952, 1968–1972, 1983–1987 and 1988–1992 were available in the earliest period. Thereafter statistics exist for all 4-year periods but we only used 1993–1997 and 1998–2002. For years between observations, we used linear interpolation estimates. For simplicity we only considered Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*), as they contribute 41.9 and 38.7%, respectively, to the standing stock, the remainder being mostly birch species. For each county, the forest land was partitioned between spruce and pine according to the statistics for that county. The standing stock was distributed into three diameter classes: 0–14 cm, 15–24 cm, and >25 cm. Trees in the diameter class 0–14 cm were assigned an average diameter of 7 cm, those in the 15–24 cm class a diameter of 20 cm, and those in the >25 cm class a diameter of 30 cm. Combining tree diameters with the Marklund (1988) allometric functions for stem biomass and a wood density of 420 kg (dw) m^{-3} (http://www.svo.se), we were able to calculate the number of trees for each year, county, species and diameter class. Other allometric functions (Marklund 1988) were then used to calculate the standing stocks of the

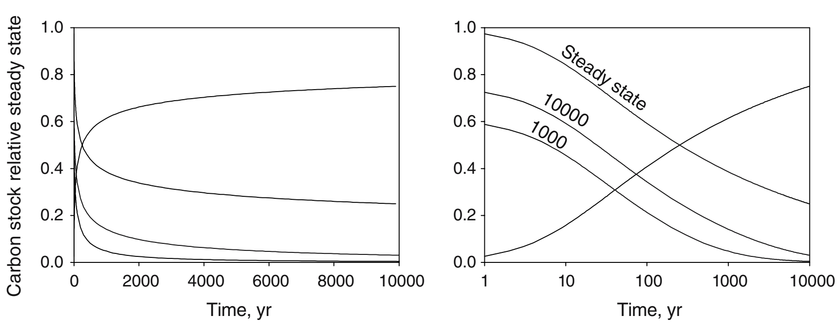

Fig. 1 Build-up of soil carbon stocks towards steady state and decay of carbon stocks, when input is stopped, from steady state and from soils that have received constant litter input during 1,000 and 10,000 years, respectively. Note the logarithmic time scale in the right-hand figures

other tree components: needles, branches, and coarse roots plus stumps. For conversion to carbon we used 206 kg (C) m^{-3} for stemwood and 0.5 kg (C) kg^{-1} (dw) for other tree components.

The area distributions of pine and spruce were taken from the year 2000. There have been changes in the extent of forest area but mostly in regions with small forest areas, as from 1951 (the earliest year for which we have information) to 2000, the forest area for the entire country decreased by only 1%. Because of official changes in the partition of the country into counties, we were also obliged to re-partition forest stocks in one county (Västra Götaland) during the last years, based on relative distributions in earlier years.

For each tree component, we estimated the annual litter production. Needle and branch litter production were calculated by multiplying the standing stock estimated from forest statistics by a turnover rate. The turnover rate (yr^{-1}) of needles is correlated to latitude (Eq. 1; Fig. 2):

$$\text{Pine}: \quad \text{Turnover rate} = 1.656 - 0.0231 * \text{Latitude} \tag{1a}$$

$$\text{Spruce}: \quad \text{Turnover rate} = 0.489 - 0.0063 * \text{Latitude} \tag{1b}$$

These turnover rates were calculated from data in Berg et al. (1993, 1999a), and Albrektson (1988) for pine and Berg et al. (1999b) and LUSTRA (Berggren et al. 2004) for spruce. Branches were assumed to have a turnover rate of 10% of the needles and fine roots were assumed to produce litter at a rate 1.51 times that of needles (based on data from Berggren Kleja et al. (2007) for spruce but also used for pine). Litter from stems in the form of tops is only produced as harvest residues and similarly, stumps and coarse roots also become litter only at harvest (see Table 1). Needles, branches and fine roots were also added as litter in proportion to their contribution to the harvested biomass; no harvest apart from stems was assumed. We only had harvesting statistics for the whole country and for each year. To partition the harvest over regions, we assumed that the fraction of the standing volume of trees in the largest diameter class (>25 cm) reflected the fraction of harvest from that region, as clear-cutting is the dominant form of harvest and leads to harvest of the largest trees. For simplicity, we used an average of the fractions from the years for which we had statistics on tree volume (1926, 1945, 1970, 1985, 1990, 1995, and 2000) rather than interpolating for the missing years. Since current forest statistics only permit us to consider tree biomass, litter production from other vegetation components was not included. We return to this point in the Discussion.

The decomposition of the different litter fractions was calculated using the Q model in the form where invasion rates of litter types are taken into account (Hyvönen and Ågren 2001; Eq. 2).

$$
\begin{aligned}
G_{\mathrm{n}}(t) &= (1+\alpha t)^{-z} \\
G_{\mathrm{w}}(t,t_{\max}) &= \frac{2}{t_{\max}}\frac{1}{\alpha(1-z)}\left[(1+\alpha t)^{1-z} - \left(1-\frac{t}{t_{\max}}\right)\right] \\
&\quad + \frac{2}{t_{\max}^2}\frac{1}{\alpha^2(1-z)(2-z)}\left[1-(1+\alpha t)^{2-z}\right] \\
&\quad + \left(1-\frac{t}{t_{\max}}\right)^2 \quad t<t_{\max} \\
G_{\mathrm{w}}(t,t_{\max}) &= \frac{2}{t_{\max}}\frac{1}{\alpha(1-z)}(1+\alpha t)^{1-z} \\
&\quad + \frac{2}{t_{\max}^2}\frac{1}{\alpha^2(1-z)(2-z)} \\
&\quad \times\left[(1+\alpha(t-t_{\max}))^{2-z} - (1+\alpha t)^{2-z}\right] \\
&\qquad t>t_{\max} \\
\alpha &= f_{\mathrm{C}}\beta\eta_{11}u_0q_0^{\beta} \\
z &= \frac{1-e_0}{\beta\eta_{11}e_0}
\end{aligned} \tag{2}
$$

where $G_{\mathrm{n}}(t)$ is the fraction of initial carbon remaining in a needle or fine root cohort after time t and G_{w} $(t,t_{\max})$ is the same function for the woody components with $t_{\max}$ the time taken for decomposers to completely invade these litter components. The other parameters were $f_{\mathrm{C}} = 0.5$ (carbon concentration in decomposer biomass), $\beta = 7$ (a shape parameter determining how steeply decomposer growth rate changes with substrate quality), $\eta_{11} = 0.36$ (a parameter determining how rapidly substrate quality decreases as substrates is

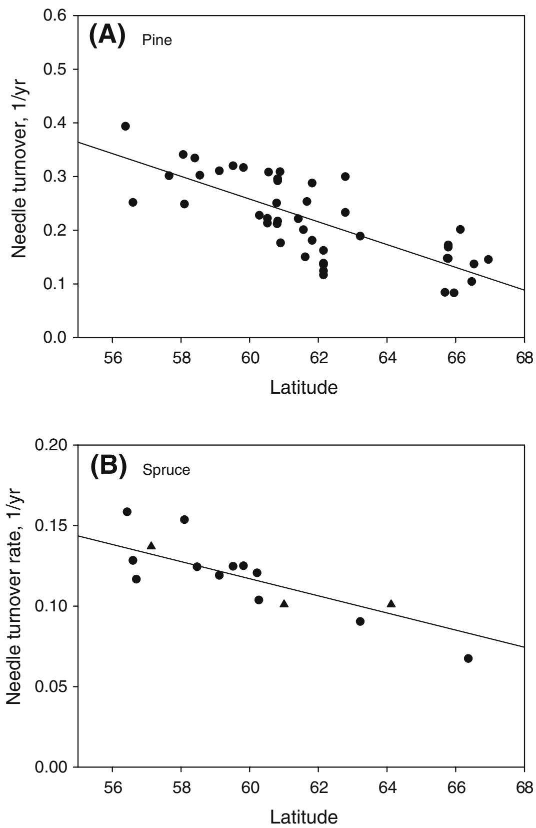

Fig. 2 Turnover rate of needle biomass as a function of latitude. (**A**) Pine. Data from Berg et al. (1993, 1999a) and Albrektson (1988). (**B**) Spruce. • Berg et al. (1999b). ▲ Lustra CFS Berggren et al. 2004)

used by decomposers), $e_0 = 0.25$ (decomposer growth efficiency or production-to-assimilation ratio) are fixed (see Ågren and Bosatta 1998). The initial quality of litter cohorts (q_0) measures the chemical accessibility to litters for the decomposers and was assigned a value based on previous analyses (Hyvönen and Ågren 2001). The parameter u_0 is coupled to decomposer growth rate and depends on climate, which is correlated with latitude such that:

$$u_0 = 0.0855 + 0.0157(50.6 - 0.768 \text{ Latitude}) \quad (3)$$

The calculations of remaining carbon were made by year for each litter component and each litter cohort separately such that the total soil carbon consisted of the sum of remaining litter cohorts of different ages and from different tree components. There is no vertical partitioning of soil carbon in our model and all soil carbon should therefore be included. This assumes that we can neglect climatic variability with depth, as well as differences in the interaction between soil carbon and the mineral soil matrix. The carbon in the soil from litter produced before 1926 was estimated from the assumptions that litter production in 1926 was representative for that earlier period and that soil carbon in 1926 was in steady state with respect to that litter production. We refer to this carbon as ''old'' carbon and carbon remaining from litter produced after 1926 as ''new'' carbon.

Soil data

We used two sources of data for evaluating the performance of the model. The LUSTRA common field sites (Berggren et al. 2004)

Table 1 Methods and parameters for calculations of litter production and decomposition

Litter component	Production of litter	q_0	t_{max}
Needles	Fraction of standing crop, depends on latitude (see Fig. 2) Harvest residues	1.10 pine 1.01 spruce	0
Branches	Fraction of standing crop, depends on latitude. Assumed to be 10 times longer than for needles Average diameter 3–4 cm Harvest residues	1.06 pine 1.00 spruce	13 yr[a]
Tops	10% of the stem at harvest. Average diameter 3–4 cm	1.06 pine 1.00 spruce	13 yr[a]
Coarse roots plus stumps	Fraction of harvest residues. Average diameter 50 cm	1.06 pine 1.00 spruce	60 yr[a]
Fine roots	1.51 times needle litter production Harvest residues	1.10 pine 1.01 spruce	0

[a] See Hyvönen and Ågren (2001)

provided detailed soil information from Norway spruce sites situated in three widely separated geographical regions of Sweden (Asa 57°08′N, 14°45′E; Knottåsen 61°00′N, 16°13′E; Flakaliden 64°07′N, 19°27′E). The other data source was a database at the Department of Forest Soils, Swedish University of Agricultural Sciences, consisting of 78 soil profiles from 55 sites with stands of Norway spruce or Scots pine. These soil profiles were thoroughly investigated and sampled in different projects during 1985–2003 and the sites are well distributed over most parts of Sweden (latitude 56°22′N–67°45′N). Soil material <2 mm was analysed for total organic carbon and bulk density. The soil carbon stocks for all sites are given to 1 m depth or down to the bedrock and are corrected for rock fragments (>2 mm).

Results and discussion

We first tested the model of the build-up of soil carbon against observed soil carbon observations for specific stands; additional tests of the Q model under various conditions can be found in Ågren and Bosatta (1998). For this, we generated stand volume development with growth functions as described by Ågren and Hyvönen (2003) and then followed the procedure outlined above, although a given stand consisted of only one diameter class. Stands were characterised by their site index (height in metres at age 100 years, which is a standard parameter used in growth functions to generate stands of different productivities) and latitude. There is considerable variation in soil carbon during the rotation period (e.g. Covington 1981), although this is not always observed (e.g. Martin et al. 2005). Figure 3 illustrates one simulation with a typical management with respect to harvests, and our calculations agree closely with those of Peltoniemi et al. (2004). It should be observed (Fig. 3) that harvest residues (tops, branches, needles, and roots) make a considerable contribution to the variability in the soil carbon stock during a rotation period; clear-cutting produces considerably more harvest residues than thinning operations.

The predicted effects of site index and latitude on soil carbon stocks are shown in Fig. 4 for pine and spruce stands. The stocks were estimated as the average carbon stock between year 20 (when most of the harvest residues from the previous stands have decayed) and the year of the next clear-cut. In principle, there could be a substantial effect from productivity (site index) and latitude (temperature climate) for the spruce stands and a smaller effect for the pine stands. In practice, the variations are likely to be much smaller because latitude and productivity are negatively correlated such that high productivities occur only at the lowest latitudes and the lowest productivities are associated with the highest latitudes. Observations of soil carbon stocks should therefore not vary too much within the country, see further below.

The predicted soil carbon stocks are compared to observed carbon stocks in Fig. 5. Both measurements and predictions show increasing stocks with increasing site index as well as with decreasing latitude and with our predictions following the lower part of the observations. One important reason for the lack of high values in the predictions is that we have not included any effects of soil water. When we consider the wet LUSTRA sites, it is clear that the model underestimates soil carbon stocks on wet sites. We do not think that our lower estimates of soil carbon relative to observed ones are a result of an underestimation of litter production. A regression of needle litter production (excluding harvests) in pine stands versus latitude gives

$$\text{Needle litter production (kg DW ha}^{-1}\text{ a}^{-1}) = 10592 - 156.3\text{ latitude } (r^2 = 0.84)$$

which can be compared with the regression 9544–131.9 latitude by Berg et al. (1999a). Our regression is consistently somewhat lower than that of Berg et al. but that their observations are based on sample plots with higher site indices, and thus production, than the average for the latitude.

The changes in tree stocks over the period investigated were not distributed uniformly across Sweden but concentrated to southern parts. This is reflected in the changes in litter production predicted from the statistics on standing volumes (Fig. 6). There was a steady increase in litter

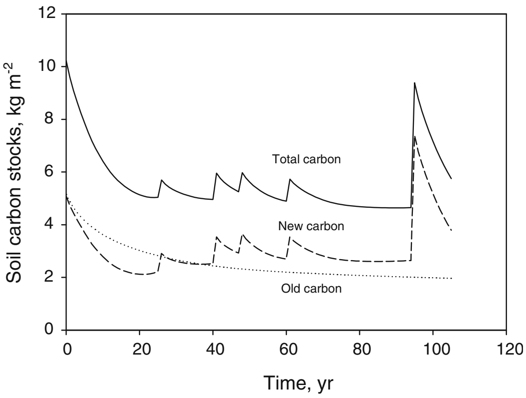

Fig. 3 Simulated variation in soil carbon stocks during a rotation period, which starts with a clear-cut and ends in year 95. The stand is a pine stand (site index 26) at latitude 57.38. The dotted line is carbon from older stands assumed to have been in steady state when the clear-cut occurred. The broken line is carbon from the current stand, including harvest residues from the previous stand. The solid line is total soil carbon. The peaks in curves occur when harvest residues are added to the soil stock

production when averaged over the entire country. This rate of increase was closely followed by the increases in the counties where the LUSTRA sites Knottåsen and Flakaliden are situated. However, the increase in litter production in the county where the southernmost site (Asa) is situated greatly exceeded the national average.

The development of carbon stocks in Swedish forests is shown in Fig. 7. In the live vegetation, stem biomass dominated the carbon stock, whereas in the soil, it was residues from decomposing stumps (pine) and fine roots (spruce) that provided most carbon (Fig. 7). Spruce forests contained somewhat more carbon than pine forests, and between 1926 and 2000 there were no major changes in the relative contribution from the two species to forest carbon stocks. In the old carbon pool, the carbon in remaining stumps and coarse roots decreased more rapidly than any other tree component. The reason is that at the point when input is stopped, stumps and coarse roots contain a large fraction of still uninvaded material (cf. $t_{max} =$ 60 years, Table 1), which is of high quality. Once all this material has been colonised, the decay rate of stumps and coarse roots becomes more similar to that of other tree components.

There was a steady increase in carbon stocks in Swedish forests in the period 1926–2000. We estimated that forest ecosystems in 2000 contained 526 Tg or 35% more carbon than in 1926. Tree biomass was mostly responsible (71%) for this increase in carbon stocks (Table 2). The increase in carbon stocks in spruce forests seemed to have begun to level off around 1980, whereas stocks continued to increase even in 2000 in pine forests. The average rate of carbon accumulation in Swedish forests between 1926 and 2000 was estimated at 7.1 Tg yr^{-1}, which can be compared to 16 Tg yr^{-1} of Swedish carbon emissions from fossil fuel burning.

However, the increases in soil carbon stocks were not evenly distributed over the country but showed a clear trend from almost no changes in the north to up to 1 kg m^{-2} or around 0.01 kg m^{-2} yr^{-1} in the south (Fig. 8). The dominant factor driving the increases in carbon stocks was the increasing standing stock of trees; there was little variation in the relative contributions of trees and soil to the change over the country.

We estimated forest carbon stocks by a combination of empirical data and modelling. The empirical data (survey data) for tree stocks had been collected over many years with standardised methods and should be reliable. Similarly, the model used to predict decomposition of litter and turnover of soil organic matter has been tested extensively for many types of system (Ågren and Bosatta 1998) and can also be considered reliable. The major problem in the present study was obtaining sufficient information to apply the model. The estimate of the soil carbon stock (1,047 Tg) is almost identical to the estimate of 1,050 Tg produced by Ågren and Hyvönen (2003), although the latter refers to a steady state situation. The model used in the present paper led to higher values because we had better and higher estimates of the fine root production relative to needle litter production. The introduction of variability in needle turnover with latitude in this paper changed the regional distribution of carbon accumulation, but this should more or less average out over the entire country compared to the constant value used by Ågren and Hyvönen (2003). In contrast, Lilliesköld and Nilsson (1997) estimate a total soil carbon stock of

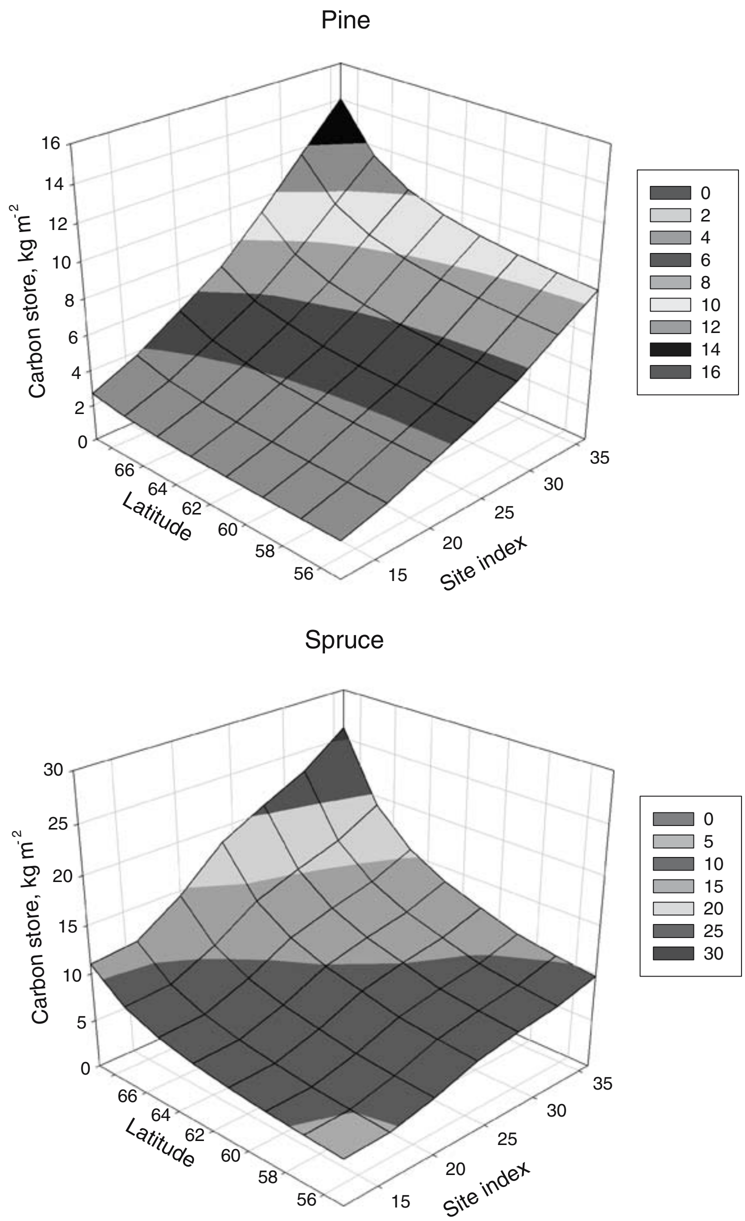

Fig. 4 Variation in soil carbon stocks with latitude and site index for spruce and pine forests

1,700 Tg in Swedish forest soils. There are several reasons why our estimate was lower. First, we neglected forest areas dominated by tree species other than coniferous types, which would have underestimated the carbon stock by about 10%. Second, we neglected the considerable litter contribution from all other vegetation than pine and spruce. Data used by Peltoniemi et al. (2004) suggest that between the ages 28 and 47 years, ground vegetation in Scots pine forest contributes 23–33% of the aboveground litter production. The data from the LUSTRA project (Berggren Kleja, 2007) show ground vegetation litter production in the range 15–65% of tree litter production, but a lower value is expected in these spruce forests. Third, the parameters used to describe decomposition are based on data from mostly dry to mesic sites and, as can be seen in

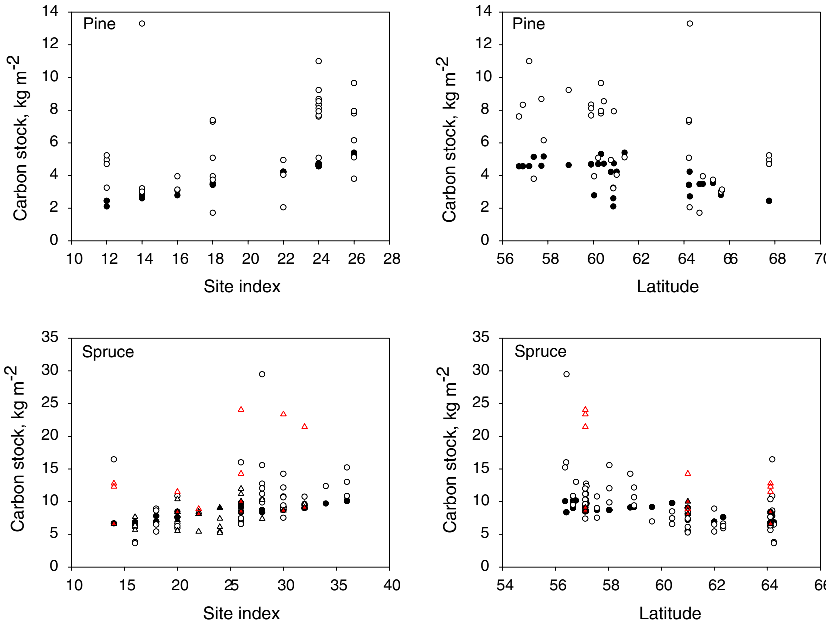

Fig. 5 Comparison between predicted (solid symbols) and observed (down to 1 m) (open symbols) soil carbon stocks. Circles are soil carbon stocks from 78 different soil profiles at 55 sites distributed over Sweden. These sites were investigated in different projects during 1985–2003. Triangles are LUSTRA CFS and red triangles are the wet plots

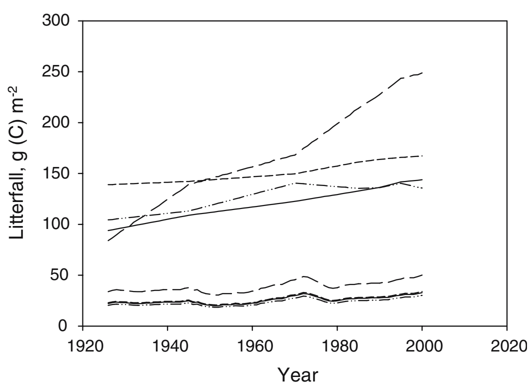

Fig. 6 Development of litter production for Sweden (solid line), for the county where Asa is located (long dashes), for the county where Knottåsen is located (short dashes), and for the county where Flakaliden is located (dash-dots). The upper set of curves is litter production from stands and the lower set of curves is litter in the form of harvest residues

Fig. 5, we overestimated decomposition rates on wet sites. At the same time, we overestimated the contribution from ‘‘old soil’’ by assuming that it was decaying from a steady state in 1926; this overestimate should be in the order of 200 Tg (see Fig. 1). However, this might not apply at lower latitudes, where tree production increased most. At these latitudes, land use before 1926 was different in that vegetation components other than pine and spruce trees (e.g. heathland shrubs in certain areas) dominated litter production. This could to a large extent explain the decline in the 1926 baseline soil carbon stocks in Fig. 8 at the lower latitudes. However, this last factor would not have had any major effect on the temporal development of the soil carbon because it represents the oldest and most recalcitrant carbon; it more or less just subtracts a constant amount over the time scale of interest, but it represents a considerable obstacle when initialising models over large areas.

Our estimate of the current rate of soil carbon accumulation of 1.7 Tg yr^{-1} or 7.5 g m^{-2} yr^{-1} is comparable to the 9 g m^{-2} yr^{-1} estimated by Liski et al. (2002) for Sweden with a different model and the 8 g m^{-2} yr^{-1} estimated for forests in south-east Norway by de Wit et al. (2006). In a long time perspective, our estimates are likely to diverge from the estimates produced by the other two approaches because their models will approach steady state more rapidly. We also predicted larger accumulation of soil carbon with decreasing latitude in the northern part of the country, in agreement with Olsson et al. (2007). A possible reason for the discrepancy between our estimate and that of Olsson et al. in the south is that we ignored a potentially important reduction in car-

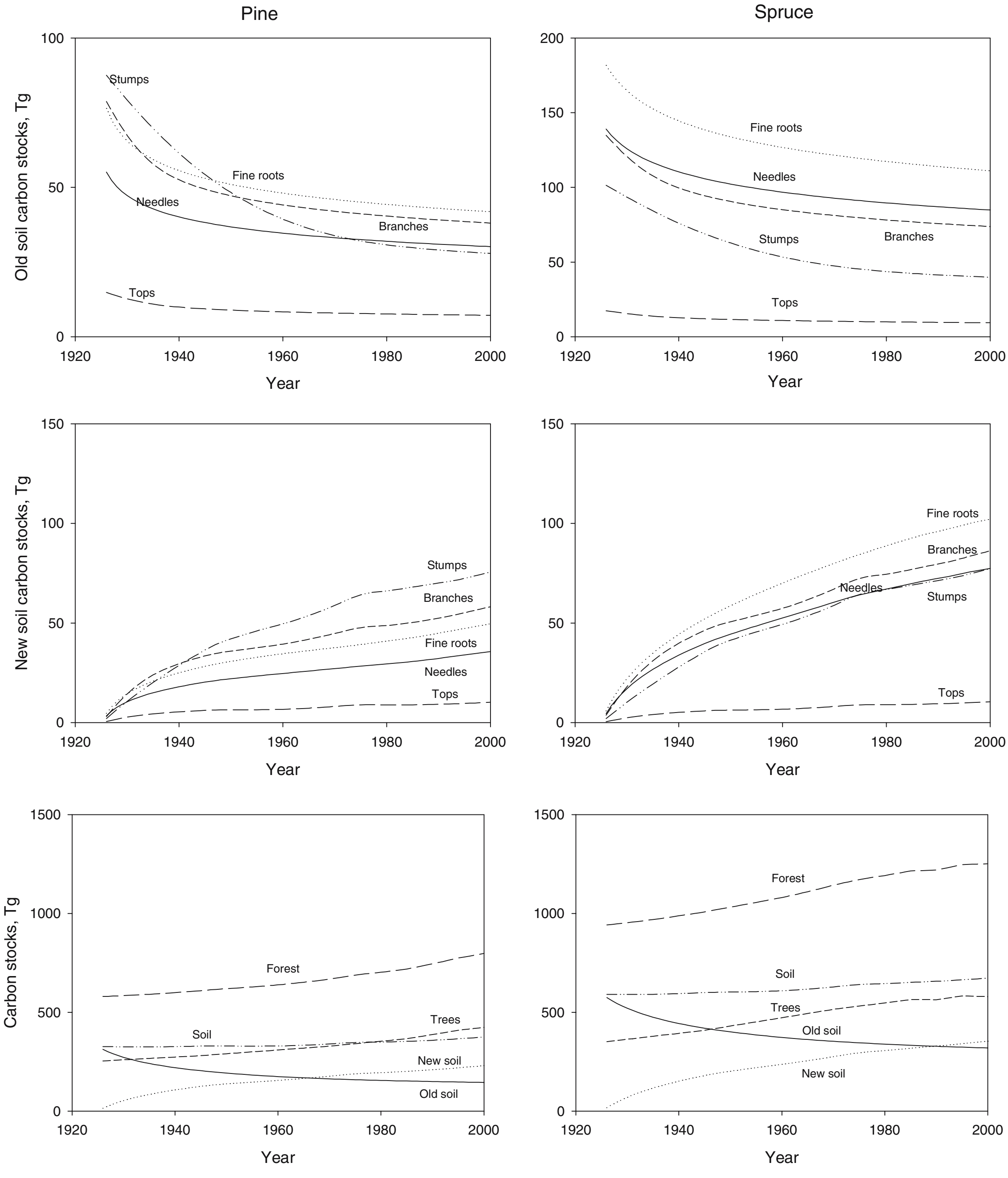

Fig. 7 Development of carbon stocks in various compartments in Swedish forest ecosystems. Left column = pine, right column = spruce

bon mineralisation as a result of nitrogen deposition (Ågren et al. 2001 and references therein). However, we do not know whether we underestimated recent litter production or the stock in 1926.

One of most critical factors for improving our estimates of forest carbon stocks would appear to be better parameterisation of the model with respect to moisture. However we would have to rely on forest statistics that classify forest areas into moisture categories, and that classification

Table 2 Comparison of carbon stocks (Tg) in Swedish pine and spruce forest ecosystems and in all forests for the years 1926 and 2000

Year	Pine			Spruce			All forests		
	Trees	Soil	Ecosystem	Trees	Soil	Ecosystem	Trees	Soil	Ecosystem
1926	254	327	581	351	591	942	605	918	1,523
2000	423	374	797	579	673	1,252	1,002	1,047	2,049
Change	169 (67%)	47 (14%)	216 (37%)	228 (65%)	82 (14%)	310 (33%)	397 (66%)	129 (14%)	526 (35%)
Rate of change, 1926–2000 Tg yr^{-1}	2.28	0.64	2.92	3.08	1.11	4.19	5.36	1.74	7.11

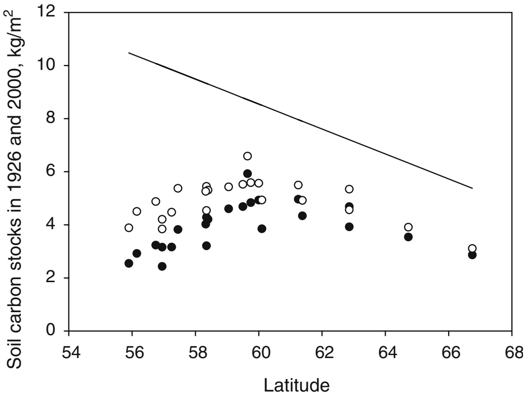

Fig. 8 Soil carbon stocks in 1926 (solid circles) and 2000 (open circles) as a function of latitude (county). The line is the regression of soil carbon stock as a function of latitude from Olsson et al. (2007)

would have to be compatible with the way the model is parameterised with respect to moisture. We also need better information on the contribution of vegetation other than trees (rates of litter fall, decomposition rates).

The current soil carbon stock is not in equilibrium with the current rate of litter production. The increase in soil carbon stocks since 1926 is only 33% of what would be required to be in equilibrium with current tree biomass. The further south in Sweden, the further the situation was from equilibrium because of the larger change in litter production in the south. If tree biomasses are maintained at current levels, or even allowed to increase as still seems to be the case for pine, soil carbon stocks will also increase but this increase will soon become slow because the last stage before steady state is reached is extremely slow (see Fig. 1). At the same time, we should be aware that reducing the litter input by harvesting more forest biomass would lead to a rather rapid decline in soil carbon stocks, which would be particularly apparent if large-scale extraction of stumps becomes common practice. However, that loss should be compared to the fossil fuel it replaces, or as Janzen (2006) phrases it "The soil carbon dilemma: Should we hoard it or use it?".

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