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Original article

Carbon accumulation in Finland's forests 1922–2004 – an estimate obtained by combination of forest inventory data with modelling of biomass, litter and soil

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Abstract – Comparable regional scale estimates for the carbon balance of forests are needed for scientific and political purposes. We developed a method for deriving these estimates from readily available forest inventory data by using statistical biomass models and dynamic modelling of litter and soil. Here, we demonstrate this method and apply it to Finland's forests between 1922 and 2004. The method was reliable, since the results obtained were comparable to independent data. The amount of carbon stored in the forests increased by 29%, 79% of which was found in the biomass and 21% in the litter and soil. The carbon balance varied annually, depending on the climate and level of harvesting, with each of these factors having effects on the biomass differing from those on the litter and soil. Our results demonstrate the importance of accounting for all forest carbon pools to avoid misleading pictures of short- and long-term forest carbon balance.

carbon inventory / forest biomass / greenhouse gas inventory / litter / soil modelling

Résumé – Accumulation de carbone dans les forêts finlandaises entre 1922 et 2004, une estimation obtenue en combinant les données de l'inventaire forestier avec une modélisation de la biomasse de la litière et du sol. Une estimation comparable à l'échelle régionale du bilan de carbone des forêts était nécessaire pour des objectifs scientifiques et politiques. Nous avons développé une méthode pour déduire ces estimations de données facilement disponibles de l'inventaire forestier en utilisant des modèles statistique de la biomasse et une modélisation dynamique de la litière et du sol. Ici nous présentons cette méthode et l'appliquons aux forêts de Finlande entre 1922 et 2004. La méthode a été fiable, puisque les résultats obtenus ont été comparables à des données indépendantes. La quantité de carbone accumulée dans les forêts s'est accrue de 29 %,79 % de ce qui a été trouvé dans la biomasse et 21 % dans la litière et le sol. Le bilan de carbone varie annuellement, selon le climat et l'importance de la récolte, chacun de ces facteurs ayant des effets sur la biomasse différents de ceux qui agissent sur la litière et sur le sol. Nos résultats démontrent l'importance de comptabiliser tous les réservoirs de carbone en forêt pour éviter des images trompeuses du bilan de carbone des forêts à court et moyen terme.

inventaire du carbone / biomasse forestière / inventaire des gaz à effet de serre / litière / sol

1. INTRODUCTION

Forests may act both as important sinks and as sources of atmospheric carbon dioxide (CO_2) [18]. Therefore, to understand the development of the atmospheric CO_2 concentration and, consequently, changes in the world's climate, it is necessary to know the carbon balance of forests and the processes and factors controlling it.

This importance of forests has been recognized in the United Nations Framework Convention on Climate Change (UNFCCC) [71], which enjoins countries to include changes in forest carbon stocks in their annual greenhouse gas (GHG) inventories. In addition, the Kyoto Protocol states that some of these changes will be accounted for in the GHG emissions of countries during the first commitment period of limiting these emissions between 2008 and 2012 [72].

Acknowledging that it is the entire forest carbon balance that is crucially linked to the atmosphere, not only the balance of some parts of it, the 7th Conference of Parties (COP) to the UNFCCC agreed that countries must account for all forest carbon pools in their annual GHG inventories and under the Kyoto Protocol [19]. The COP named these pools as above- and belowground biomass, deadwood, litter and soil organic carbon. Thus, in addition to the scientific need, there is also an urgent political need for reliable accounting of all forest carbon pools.

In many industrialized countries, the national estimates for the carbon balance of tree biomass are calculated based on data from national forest inventories (NFI) [41]. The NFIs in general provide statistically sound estimates of forest resources, and these estimates are characterized by a small sampling

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error because the measurements are taken at thousands of forest sites [28, 70]. In addition, it is a fairly straightforward matter to estimate the carbon balance of tree biomass based on the inventory data on stem volume, using conversion factors available for many tree species and geographical regions [21, 30, 32, 62, 65, 74, 75, 78].

In contrast, readily available methods for estimating the carbon balances of the nonliving organic matter pools are still lacking. Measuring the carbon balances of litter and soil organic matter is particularly difficult because the expected changes [37, 60] are one or two orders of magnitude smaller than the spatial variability inside forest sites [33]. For this reason, various modelling approaches were applied to obtain these estimates [14, 25, 37, 58]. The diversity of these methods makes, however, comparison of the results difficult [9].

We developed a method for estimating the total carbon balance of forests based on NFI data. Here, we demonstrate this method and test its applicability and reliability by applying it to Finland's forests between the 1920s and 2000s. In addition, we explore the variability in the carbon balance of these forests and factors that caused it. Based on these results, we analyse the importance of natural and human-induced factors for the carbon balance of these managed forests and discuss the rationality for the reporting requirements of the UNFCCC.

2. MATERIAL AND METHODS

2.1. Calculation method

The calculation method is based on forest inventory measurements of forest area and stem volume. The pools and fluxes of carbon in forests are estimated from the inventory data with the aid of modelling. The biomasses of the various components of trees are calculated using biomass expansion factors, and the biomass of ground vegetation is obtained using other statistical models. The litter production of vegetation is calculated by multiplying these biomass estimates by compartment-specific turnover rates. The carbon pools of litter (including deadwood) and soil organic matter as well as the cycling of carbon in these pools are simulated using a dynamic model. The basic concepts of this calculation method were presented earlier [37], but here we demonstrate a more advanced version of the method consisting of new models shown to be appropriate for regional and national scale inventories.

2.2. Application to Finland's forests

We applied this calculation method to Finland's forests from 1922 to 2004. The calculations were conducted for the main tree species, i.e. Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* (L.) Karsten) and broadleaved trees (mainly silver birch *Betula pendula* Roth and downy birch *B. pubescens* Ehrh.), and separately for the southern and northern parts of the country. The pine forests covered 49–66% of the total forested area during the period studied, the spruce forests 23–36% and the broadleaved forests 7–15%. Our results for trees cover all forest land including both upland forests and peatlands, whereas our results for soil, litter and ground vegetation are for upland forests only because we had no appropriate models for these components on peatlands. Moreover, in Finland's reports for the UNFCCC, GHG accounting of peatland soils is based on measurements of GHG fluxes for different ecosystem types and corresponding areal estimates, not on estimates of changes in the carbon stock of these soils [19]. The upland forests represented 74–79% of the total forested area during the period studied.

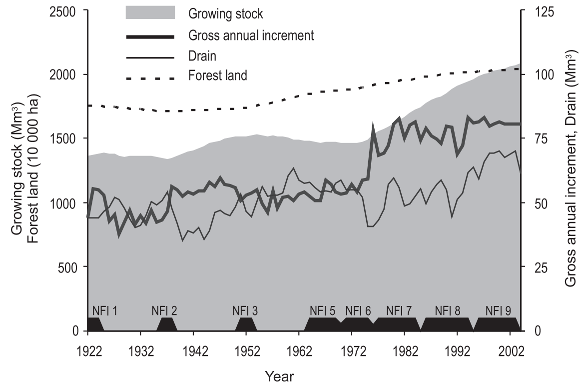

Figure 1. Growing stock, gross annual increment, drain (fellings plus natural losses) and area of Finland's forests between 1922 and 2004.

2.2.1. Forest inventory data

The NFI has been conducted in Finland nine times so far (Fig. 1), each time requiring three to nine years to inventory the entire country. The first NFI in 1921–1924 was a line transect survey, with the length of the surveyed line totalling more than 13 000 km and the distance between the survey lines being 26 km [17], whereas the last NFI applied systematic cluster sampling and obtained measurements at about 70 000 sites [67].

The volume of the growing stock of trees (GS, m^3) was given by age-class in the two latest NFIs, while the earlier NFIs provided it in total and only the forested areas by age-class. To estimate the GS distribution between the age-classes in these earlier NFIs, we assumed that the shape of the distribution of the mean volume (m^3/ha) between the age-classes had remained the same as in the eighth NFI and, consequently, divided the total volume into age-classes using the age-class-specific data on forested areas.

To obtain the annual values for the GS volume, we first estimated annual gross increment (GAI, m^3). GAI at year T between two consecutive NFIs, N and $N+1$, having the volume weighted midyears T_N and T_{N+1}, was calculated by scaling the average growth during the period with growth indices, $g_{i,T}$

$$GAI_i(T) = g_{i,T}\,\frac{GS_{i,T_{N+1}} - GS_{i,T_N} + d_i D_{(T_N,T_{N+1})}}{T_{N+1} - T_N}.$$

In this equation, i is specific for tree species and age-class and $D_{(TN,TN+1)}$ (m^3) is the sum of drain between the midyears of the inventories; D includes commercial fellings, domestic wood use and natural mortality (mortality of trees from causes other than cutting by man). The drain estimates were reported by Forest Statistics Information Service at the Finnish Forest Research Institute; information on the commercial fellings was based on reports by the major industrial wood users [45]. Variable d_i represents division of drain between tree species and age-classes i. The fellings were allocated to age-classes by estimating the age distribution of cuttings and thinning at the permanent sample plots of the NFI. The g_i reflect the climate-induced

Table I. Biomass turnover rates (year^{-1}) used to estimate the litter production of trees and ground vegetation.

	Trees					
	Spruce forests		Pine forests		Broadleaved forests	
	S[1]	N[2]	S	N	S	N
Foliage	0.10[3]	0.05[3]	0.22[4]	0.10[4]	0.78[5]	
Branches and roots	0.0125[3]		f(t)[6]		0.0135[7]	
Stump bark	0.0[8]		0.0030[9]		0.0001[10]	
Reproductive origins and stem bark	0.0027[8]		0.0052[9]		0.0029[10]	
Fine roots	0.811[11]		0.868[12]		1.0[13]	
	Ground vegetation					
Bryophytes	0.33[14]					
Lichens	0.1[15]					
Dwarf shrubs, aboveground	0.25[16]					
Herbs and grasses, aboveground	1.0[17]					
Dwarf shrubs, belowground	0.33[18]					
Herbs and grasses, belowground	0.33[16]					

[1] Southern Finland. [2] Northern Finland. [3] [51]. [4] [50]. [5] Leaves of broadleaved trees became 22% lighter during yellowing process in autumn [77]. [6] As a function of age [31]. [7] Estimated from the repeatedly measured permanent sample plots of the Finnish National Forest Inventory. [8] Derived from the results of Viro [77]. [9] Derived from the results of Viro [77] and Mälkönen [54]. [10] Derived from the results of Viro [77] and Mälkönen [55]. [11] [42]. [12] [26]. [13] We assumed that broadleaved trees replace all their fine roots each year. [14] Rough estimation that the litter fall equals the annual biomass production [12, 23, 57, 64]. [15] Rough estimation that the litter fall equals the annual biomass production [24, 39]. [16] Rough estimation that the litter fall equals the annual biomass production [12, 49, 54]. [17] Aboveground parts of herbs and grasses change completely into litter at the end of the growing season. [18] Rough estimation that the life expectancy for roots is about 2–3 years [13].

annual variability in tree growth with no trend like changes, and was based on field measurements of several hundreds of trees as part of the NFI [16, 46, 66]. The last g_i values were available for year 2000 for pine in southern Finland and 1993 for all the other tree species and regions. For this reason, only limited variation occurred in our growth estimates after 1993 and none after 2000. For all deciduous forests, we applied the mean g value of pine and spruce because there were no specific values for the broadleaved species. Finally, we calculated the annual values for the *GS* volume between the inventory midyears by adding *GAI* to and subtracting *D* from the previous year's estimate of *GS*.

2.2.2. Biomass

The estimates for the *GS* volume were converted to biomass using biomass expansion factors specific for tree species, stand age and biomass component (foliage, branches, stem wood, bark, stump and transportation roots) [30].

Suitable factors were available for neither the fine roots of any forests nor for the stumps, transportation roots or foliage of broadleaved forests. To estimate the biomasses of these components, we assumed that the fine root biomass of conifers was proportional to foliage biomass and estimated these proportions from studies of both foliage and fine root biomasses [5, 15, 76]. For pine forests, this proportion was 50% and for spruce forests 30%, while for broadleaved forests, we assumed that the ratio between fine root and stem biomass was the same as in pine forests of the same age. The compounded biomass of the stumps and transportation roots was assumed to be 53% of the stem biomass in broadleaved forests [27] and we divided this biomass equally between these components. We assumed that the leaf biomass of broadleaved forests was proportional to branch biomass and that this proportion decreased from 80% to 20% with increasing stand age of from 10 to 150 years.

The biomass of ground vegetation was estimated using regression models that give the biomass of various species groups based on stand age and dominant tree species [52, 60]. There were separate models for pine and spruce forests; for broadleaved forests, we applied the latter. All biomass estimates were converted to carbon by multiplying by 0.5 [19].

2.2.3. Litter production

The calculation method distinguishes three carbon fluxes from forest biomass to litter and soil: (1) the litter production of living vegetation resulting from biomass turnover, (2) the mortality of tree individuals due to natural causes and (3) the harvest residues. We calculated the first of these fluxes by multiplying the biomass estimates by biomass turnover rates (Tab. I). The second flux was taken to be equal to the biomass of dying trees, and this biomass was added to the litter and soil pools as soon as the trees were dead. The third flux was assumed to be equal to the biomass of trees felled, excluding 91% of the stem biomass that was removed from the forests.

2.2.4. Litter and soil

The carbon pools of litter and soil organic matter, the annual changes in these pools and heterotrophic respiration (*Rh*) resulting from decomposition were calculated using the Yasso dynamic soil carbon model [36]. This model simulates cycling of carbon in upland forest soils to a depth of 1 m in mineral soil.

Yasso consists of five decomposition compartments and two woody litter compartments (Fig. 2). The dynamics of carbon in these

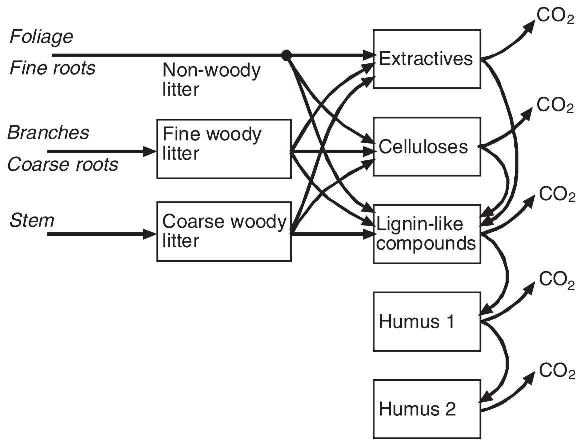

Figure 2. Flow chart of the Yasso litter and soil carbon model. The boxes represent carbon compartments and the arrows carbon fluxes. Reprinted from [36], with permission from Elsevier.

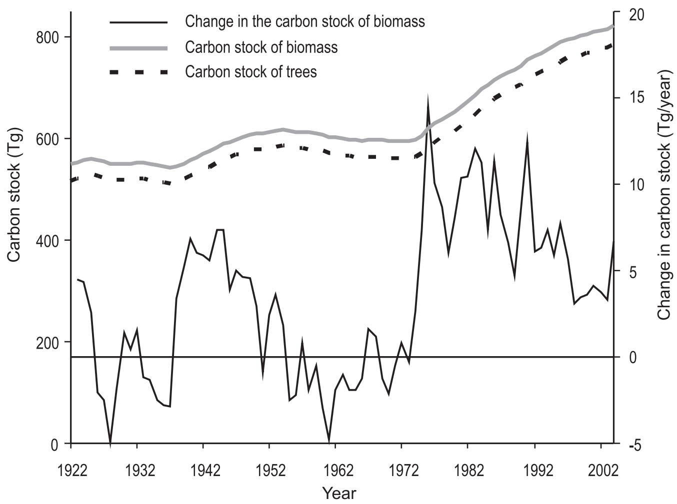

Figure 3. Carbon stock of biomass (trees plus ground vegetation), carbon stock of trees alone and annual changes in the carbon stock of biomass in Finland's forests between 1922 and 2004.

compartments is controlled by the physical and chemical characteristics of litter and climate. The chemical characteristics of litter are accounted for by dividing litter between three decomposition compartments having different decomposition rates. One of these compartments is for the most easily decomposable compounds, while the others are for cellulose and lignin; division is done according to the actual concentrations of these compounds in the litter. The remaining two decomposition compartments are for humus formed in the decomposition process. The physical characteristics of litter are accounted for by dividing woody litter between the compartments of fine (branches and transportation roots) and coarse woody litter (stem and stump) and releasing it for actual decomposition at higher rates from the compartment of fine woody litter. The climatic controls of decomposition in the Yasso model are temperature and summer drought. In the present study, we excluded the effects of summer drought because temperature alone explains more than 85% of the climatic effects on decomposition on an annual basis in Finland [35,47]. We calculated the values for the effective temperature sum based on CRU TS 1.2 data set (Mitchell et al., unpublished manuscript).

The soil and litter carbon pools at the beginning of the study period were calculated by assuming a steady state with mean litter input between 1922 and 1936 and mean temperature between 1901 and 1930. Starting from this steady state in 1922, the model was run using annually varying values of litter input and temperature.

In addition to litter production of forest vegetation and removals of carbon as a result of *Rh*, the soil and litter carbon balance in Finland's forests was affected by changes in land use. Conversion of other types of land to forest introduced carbon to the soil and litter of the forests, whereas conversion of forest to some other land type removed carbon. We did not know the carbon contents of afforested or deforested land and therefore assumed that all this land had the same carbon content (6.1 kg/m^2), which was the mean value for soil and litter at the beginning of our calculations. To estimate the amounts of carbon transferred between forests and other land uses, we multiplied the annual net changes in forested area by this figure. To follow the effects of this carbon on the carbon balance of forest soils, we divided it into the compartments of the Yasso model according to the division of the steady-state stock in 1922 and used this model to simulate its dynamics in the forests.

2.3. Ecological concepts

To enable comparison of our results with those of other ecological studies, we calculated values for the ecological concepts of the forest carbon cycle (e.g. [18]) from our inventory-based estimates. In the equations that follow, the terms used in forest inventories are marked between quotes and are represented as converted to carbon in whole-tree biomass; the international definitions of these terms are given in [70].

The estimate for net primary production (*NPP*) was calculated by summing the change in the growing stock of trees ΔGS, change in the biomass of ground vegetation ΔB, litter production of trees and understorey L, natural losses (mortality) of trees M and fellings (harvesting) of trees by humans F

$$NPP = \text{“}\Delta GS\text{”} + \Delta B + L + \text{“}M\text{”} + \text{“}F\text{”}.$$

The estimate for net ecosystem production (*NEP*) was obtained by subtracting *Rh* from *NPP* which was simulated using the Yasso soil model

$$NEP = NPP - Rh.$$

The net biome production (*NBP*) was calculated by subtracting from *NEP* removals (*RE*) that represented felled roundwood removed from the forests

$$NBP = NEP - \text{“}RE\text{”}.$$

3. RESULTS

3.1. Carbon balance of biomass

The biomass carbon stock increased by 50%, from 550 to 823 Tg, in Finland's forests between 1922 and 2004 (Fig. 3). This increase, equal to an average of 3.3 Tg/year, was due to both a higher mean amount of carbon per forested area in forests remaining as forests and an expanded forested area (see Fig. 1). Carbon accumulated mainly in the biomass of trees,

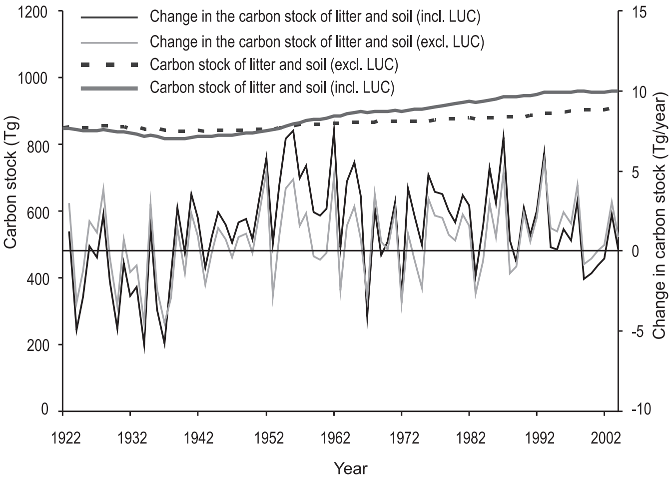

Figure 4. Carbon stock of litter and soil and its annual changes in Finland's forests between 1922 and 2004. The black lines show these variables when the transfers of carbon in litter and soil between forests and other land uses were accounted for (incl. LUC) and the grey lines show these variables when these transfers were ignored (excl. LUC).

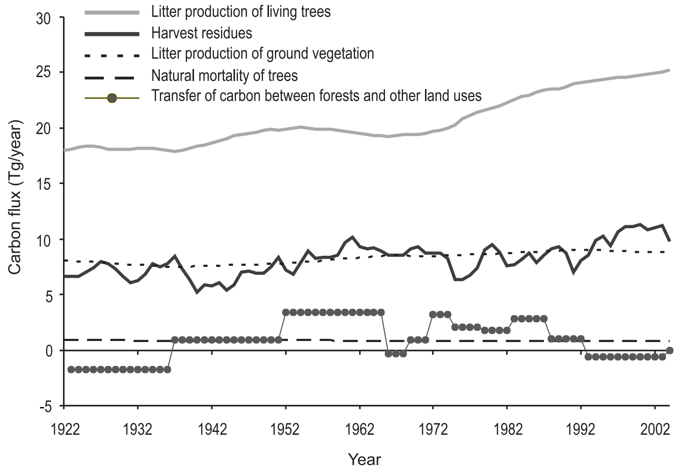

Figure 5. Input of carbon to the carbon stock of litter and soil by origin, and the transfers of carbon in litter and soil between forests and other land uses in Finland's forests between 1922 and 2004.

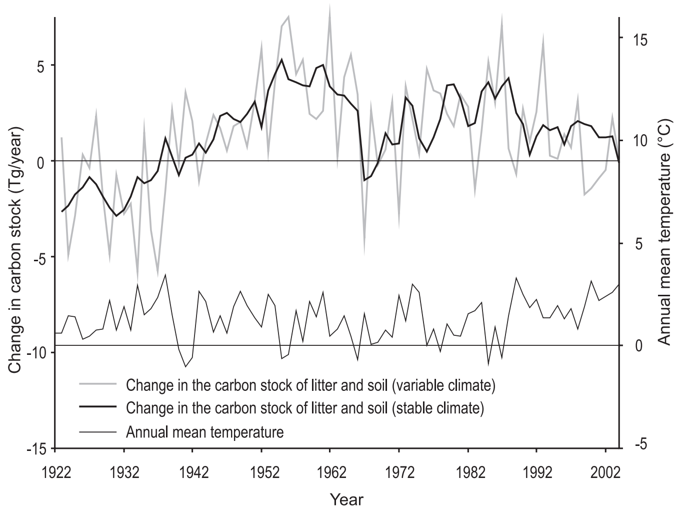

Figure 6. Annual changes in the carbon stock of litter and soil in Finland's forests between 1922 and 2004 when the transfers of carbon in litter and soil between forests and other land uses were accounted for (incl. LUC), simulated using the actual variable climatic conditions or stable average climate. The annual mean temperature of Finland is also shown.

whereas our estimate for the biomass of ground vegetation remained relatively stable (Fig. 3). The mean biomass carbon stock was 3.1 kg/m^2 in 1922 and 4.0 kg/m^2 in 2004.

Despite this trend towards increase, the annual changes in the biomass carbon stock were highly variable (Fig. 3). The biomass gained 14.5 Tg of carbon in an extreme year in the 1970s and lost 5.0 Tg in another year in the 1920s.

This high annual variability was caused by changes in tree growth and harvesting. In the 1920s, 1930s, 1950s and 1960s harvesting exceeded tree growth, thus decreasing the carbon stock of trees, whereas in the 1940s during and after World War II large amounts of carbon accumulated in tree biomass since the level of harvesting was low (Figs. 1 and 3). The tree carbon stock also rapidly increased since the 1970s despite the greater harvests as a result of increased tree growth.

3.2. Carbon balance of litter and soil

The carbon stock of litter and soil increased by 13%, from 848 to 959 Tg, during the 82-year period studied, when the transfers of carbon between the forests and other land uses were accounted for (Fig. 4). When these transfers were ignored, the carbon stock increased by 7%, from 848 to 905 Tg. In the former case, the mean accumulation rate of carbon was 1.4 Tg/year and, in the latter case, 0.7 Tg/year. The mean carbon content of the soils was 6.1 kg/m^2 in 1922 and increased to 6.3 kg/m^2 in 2004 when the transfers of carbon between the forests and other land uses were accounted for.

The interannual changes in the litter and soil carbon stock also varied widely (Fig. 4). Our highest estimates for the annual increases and decreases were 7.5 and 5.8 Tg/year, respectively, when the transfers of litter and soil carbon between the forests and other land uses were accounted for and 5.3 and 2.9 Tg/year when these transfers were ignored.

There were three causes for this increase and the annual variation in the litter and soil carbon stock: (1) transfers of litter and soil carbon between the forests and other land uses, (2) litter input to the soils and (3) temperatures that affected the rates of decomposition. Among these factors, litter input from living trees and the transfers of soil carbon from other land uses appeared as the major causes for the increase (Fig. 5). The annual changes, on the other hand, were caused mainly by the variability in temperature (Fig. 6) and harvest residues (Fig. 5). Among these two factors, the harvest residues were slightly more important because more than half of the variability still

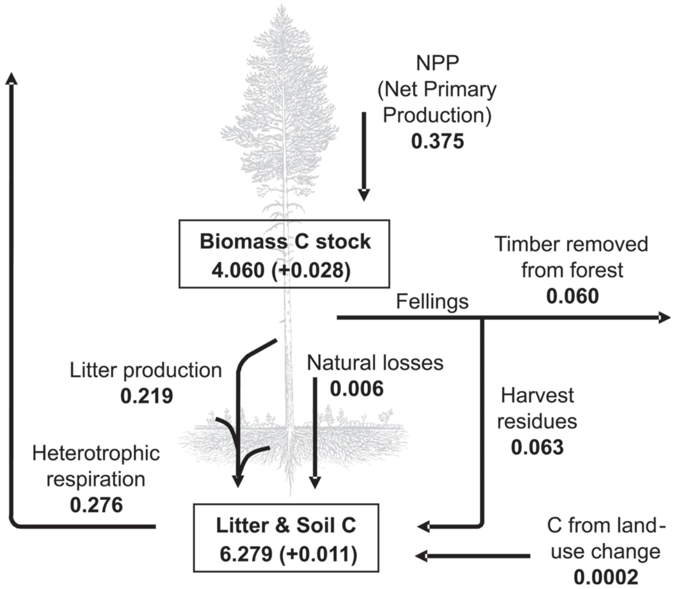

Figure 7. Average carbon budget of Finland's forests in the 1990s (carbon fluxes and annual changes in the carbon stocks (in parentheses) in kg/m^2/year, carbon stocks in kg/m^2).

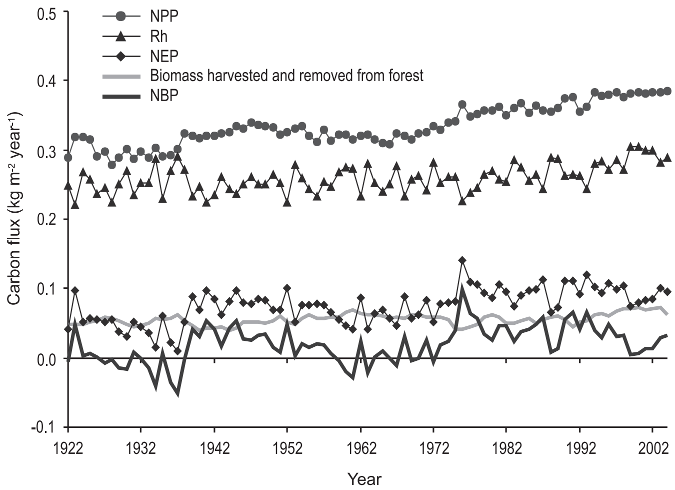

Figure 8. Carbon fluxes in Finland's forests between 1922 and 2004.

remained in the results of an additional simulation that applied stable average temperatures over the entire period studied; the amplitude of the variability was decreased by only about one third (Fig. 6) and the standard deviation by only about one fourth.

3.3. Carbon fluxes

The mean estimated *NPP* of Finland's forests was 0.38 kg C/m^2/year in the 1990s, about 70% of which (0.28 kg C/m^2/year) was decomposed and released from the litter and soil as *Rh* (Fig. 7). The difference between these values for *NPP* and *Rh*, equal to 0.099 kg C/m^2/year, is our estimate for the mean *NEP* of these forests during this decade. More than half of the *NEP* (0.060 kg/m^2/year) was removed from the forests as harvested timber, while the rest (0.039 kg/m^2/year) that accumulated in the forests represented our estimate for the *NBP*. Nearly 72% (0.028 kg/m^2/year) of this *NBP* accumulated in the biomass of the forests, while the rest (0.011 kg/m^2/year) accumulated in the litter and soil. The transfers of carbon from other land uses had a negligible effect on the litter and soil carbon content during the 1990s because the changes in forested areas were small (Fig. 1).

Over the entire 82-year period studied, the *NPP* of Finland's forests increased by 0.09 kg/m^2/year, from 0.29 to 0.39 kg/m^2/year (Fig. 8). At the same time, the *Rh* increased by only 0.04 kg/m^2/year, i.e. from 0.25 to 0.29 kg/m^2/year. This development more than doubled the *NEP* of these forests, which increased from 0.04 to 0.10 kg/m^2/year. The *NBP* did not increase quite this much because some of the increased *NEP* was removed from the forests with the larger harvests. Nevertheless, some of the increased *NEP* was left in the forests to accumulate in biomass, litter and soil; consequently, our estimate for the *NBP* of these forests increased from a level fluctuating around zero in the 1920s and 1930s to a mean equal to 0.04 kg/m^2/year in the 1970s, 1980s and 1990s.

4. DISCUSSION

4.1. Method for calculating forest carbon balance based on forest inventory data

We calculated the balance of all forest carbon pools based on forest inventory data, which was complemented using statistical modelling to estimate the biomass carbon balance and dynamic modeling to estimate the litter and soil carbon balance. The data these calculations required are readily available for temperate and boreal forests. The inventory data can be found in national reports or international compilation works (e.g. [44, 68–70]). The statistical models needed to estimate the tree biomass and its litter production are also available (e.g. [21,43,61,65,78]). Models of ground vegetation are less available however, and more research is needed to develop them for different forests. The climate data required by the Yasso litter and soil carbon model can be found in local or global databases (e.g. Intergovernmental Panel on Climate Change (IPCC) Data Distribution Centre) and the data on chemical characteristics of litter in ecological databases such as the Long-Term Intersite Decomposition Experiment (LIDET) or Canadian Intersite Decomposition Experiment (CIDET) or publications (e.g. [11]).

Our method is useful because it can be applied throughout the temperate and boreal zones to calculate comparable estimates for forest carbon balance. It was difficult to compare the field-data-based estimates for different regions because they were obtained using different methods [9]. The explicit equivalencies between the concepts used in forest inventories and ecology that we presented are another methodological step forward because they aid in combining the methods of these two disciplines. These equivalencies correct those presented earlier by the IPCC [18].

4.2. Reliability of the results

The NFIs provide statistically sound and in most cases also reliable information on forest resources throughout the temperate and boreal zones [70]. For example, the likely range for the estimates of stem volume is less than 5% of the mean in most countries; this range includes error due to measurement, sampling and adjustment to common international definitions. When inventory data are this reliable, the reliability of the estimates for carbon balance is dependent mainly on the other components of the calculation method.

The factors we used to convert the inventory data on stem volume to the tree biomass were developed specifically for use in Finland's forests [30]. These factors were somewhat higher than those used earlier in Finland, and consequently our national estimate for tree carbon stock is about 8% higher [67]. The method for developing these conversion factors is generally applicable to other regions [30] and it results in factors that give reliable regional biomass estimates [20, 29].

We estimated the biomass of ground vegetation based only on stand age and the main tree species although there are many other factors that affect biomass. Despite our inaccurate method of estimation, we included ground vegetation in our calculations because it may and did contribute remarkably to the *NPP* and total litter production in these forests [6, 54]. We estimated that ground vegetation represented 16% of the *NPP* and 28% of the litter production of living vegetation in Finland's forests during the 1990s. This suggests that studies ignoring ground vegetation (e.g. [25, 56]) may result in underestimation not only of these parameters but also the soil carbon stock and sink that are dependent on total litter production.

The turnover rates of needles and branches that we applied to the coniferous forests to estimate litter production were developed specifically for these forests and, when combined with the biomass estimates, resulted in estimates for litter production that were similar to those obtained in litterfall measurements [31, 50, 51]. For the turnover rates of the other biomass components, we had to use published values whose validity we could not test. Another short-cut we had to take was to apply the same turnover rates for all years and forest sites of the same tree species, although these rates may vary widely between years and sites [1, 8]. Despite these simplifications, our estimate for the *NPP* of Finland's forests, equal to 0.40 kg/m^2/year in the 1990s, is well within the range of measurements (0.22–0.46 kg/m^2/year) taken at six forest sites in the Nordic countries [10]. Provided that our biomass estimates were correct, the similarity of these estimates suggests that our turnover rates were feasible because our *NPP* estimates are dependent on these two factors.

The Yasso litter and soil model we used was calibrated with data from forests in Finland and neighbouring countries [36]. However, this model also includes equations that describe the effects of climate on decomposition and therefore may be used in other environments [34, 59]. In a test carried out, these equations explained the majority of climatic effects on the decomposition rates of various litter types from arctic tundra to tropical rainforests (Liski et al., [35]). Provided that litter input is estimated correctly, Yasso gives estimates for the amount of soil carbon and its development similar to measurements obtained at different forest sites in southern Finland [60], suggesting that Yasso may provide correct estimates for the carbon dynamics in these soils. In the present study, our model-calculated nationwide estimate for the mean amount of soil carbon in the 1990s was 6.3 kg/m^2, which is within the range of earlier measurement-based estimates varying from 6.2 to 7.2 kg/m^2 [22, 38].

Finally, to test the feasibility of our method as a whole, we compared our estimate for the *NEP* of Finland's forests with measurements taken at comparable forest sites using the eddy covariance method. Our estimate for the mean *NEP* in the 1990s (0.10 kg/m^2/year) is in the midrange of *NEP* measurements taken at six forest sites in the Nordic countries, varying from a carbon source equal to 0.09 kg/m^2/year to a carbon sink equal to 0.25 kg/m^2/year [73]. On the other hand, our estimate is lower than measurements taken at a 40-year-old Scots pine stand in southern Finland, where they ranged from 0.23 to 0.31 kg/m^2/year between 1997 and 2000 [63]. The measurements were high for this site probably because the tree stand was still young and growing vigorously in the most productive part of the country.

In summation, our estimates for the various components of forest carbon balance were similar to independent measurements, suggesting that this method can be used to calculate appropriate estimates for forest carbon balance based on forest inventory data.

Uncertainty in the estimates obtained using this method can be assessed by means of Monte Carlo simulations that account for uncertainty of input data and parameter values [48]. Such simulation-based methods are also recommended by the IPCC [19] for uncertainty analyses of nationally significant key categories of GHG inventories. This kind of an analysis has already been carried out for our method in Finland [48]. In addition to the uncertainty estimates, these analyses are useful as they help to prioritize research to improve the overall reliability of forest carbon estimates.

4.3. Accumulation of carbon in the forests

Carbon accumulated in the biomass, litter and soil of Finland's forests during the 82-year period studied. Similar trends toward increase in forest carbon stocks have been observed everywhere across the temperate and boreal zones during recent decades [9, 34]. The reasons behind these trends are still not entirely clear but are known to differ among regions [3, 25, 34, 56, 58].

In Finland, carbon accumulated in forests because the forested areas expanded and the mean amount of carbon per forested area increased. Both these changes were important for the biomass carbon stock which increased by 50%, while the carbon density increased by 29% and the forest area expanded by 16%. For the litter and soil carbon stock, the expansion of forested areas by 16% accounted for most of the 13% increase, while the carbon density did not increase by more than 4%. The carbon density remained stable because the litter and soil carbon stock responded slowly to the increased litter production. On the other hand, for this same reason, carbon would still accumulate in the litter and soil with no further expansion of the forested area if the production of litter is only maintained at the level of 2004 and, centuries later, these carbon stocks would stabilize at a 38% higher level than in 1922.

Both the expansion of forested areas and the increased carbon density in Finland's forests were the results of forest management that aimed at increasing the potential of sustainable timber harvests by increasing the *GS* of trees. The striking increase in the level of tree growth since the 1970's (Fig. 1) was caused essentially by active programs established during the preceding decades involving well-planned harvesting operations, effective regeneration of forest stands, fertilization and peatland drainage. In the mid-1970s, tree growth peaked additionally as a consequence of the dropped level of harvesting during the oil crisis. These changes favourably affected the carbon balance of the forests: the larger *GS* implied a larger tree carbon stock (Fig. 3), increased uptake of carbon from the atmosphere (Fig. 8), enhanced litter production (Fig. 5) and, consequently, accumulation of carbon in litter and soil (Fig. 4). Clearly, nonhuman-induced factors such as natural disturbances have been less crucial to the carbon of balance of forests in Finland than in the remote forests of Canada or Russia [3, 25, 58] because Finland's forests have been intensively managed and efficiently protected from natural disturbances.

The history of Finland's forests shows that timber production can actually be beneficial for the carbon balance of forests. This may come as a surprise to some, since it is known that the carbon stock of trees must be decreased considerably from the maximum to maximize sustainable timber harvests at the stand level [4]. In addition, regions exposed to timber harvesting carry less tree biomass than undisturbed natural forests [7], although it is difficult to protect natural forests from long-term disturbances because trees age and become increasingly susceptible to natural disturbances. Our results show that the effects of timber production on forest carbon balance are not trivial but are dependent on the forest management activities taken to promote timber production and on the status of forests before these activities.

Of all the additional carbon that accumulated in Finland's forests during the 82-year period (385 Tg), 79% was found in the biomass and 21% in litter or soil. However, only half of the additional litter and soil carbon was taken up and brought there from the atmosphere by forest vegetation during the period studied, while the remaining half was transported there from other land uses when the forested area expanded. Ignoring this carbon, after defining carbon sink as a process that removes carbon from the atmosphere [18], decreases the total carbon sink of these forests to 331 Tg and the contribution of the litter and soil to 17%. This is somewhat less than in the forests of Western Europe (32%) in 1990 according to Liski et al. [37] or in Europe's forests (32–56% depending on the year) according to Nabuurs et al. [56]. Nevertheless, all these model-calculated estimates suggest that soil has been a sink for atmospheric carbon in Europe's forests during recent decades but that this sink has been smaller than the biomass sink.

4.4. Annual variability in forest carbon balance

In addition to the trends towards increase, the annual changes in the biomass, litter and soil carbon balance were highly variable. Such inter annual variability is important on a site scale based on measurements of carbon fluxes [63] and on a global scale based on ecosystem modelling [40], inverse modelling [2] or satellite observations [53]. This variability has not, however, been accounted for in earlier regional scale studies based on field inventories because it has not been possible to derive the annual estimates from these inventories [9].

In Finland's forests, both changes in climate and the level of harvesting have contributed significantly to this interannual variability. Interestingly, a change in each of these factors led to contrasting effects on biomass, litter and soil. For example, favourably warm climatic conditions promoted not only the growth of biomass and thus the carbon uptake in the forests but also the decomposition of soil organic matter and litter and consequently the release of carbon from these pools to the atmosphere. Large harvests, on the other hand, showed a decreasing effect on tree carbon stock but a temporary increasing effect on litter and soil carbon stock because the residues of the harvests were an important source of litter and soil carbon. As a result of these contrasting effects, the compounded carbon balance of the biomass and the litter plus soil was less variable than that of any of these components alone. Nabuurs et al. [56] emphasized the importance of natural disturbances for the annual variability in the carbon balance of Europe's forests, but in Finland's forests these disturbances have shown only a minor effect during the past 82 years. Although these results emphasize the importance of accounting for the interannual variability in inventory-based studies to obtain realistic estimates of forest carbon balance, they also demonstrate how crucial forestry operations are for this variability in managed forests.

4.5. Forest carbon balance in the UNFCCC and Kyoto Protocol

Our results support the recommendations by the 7th COP to the UNFCCC requesting countries to account for the balance of all forest carbon pools in their annual GHG inventories and under the Kyoto Protocol. Firstly, the biomass, soil and litter contributed significantly to the trend towards increase in carbon stored in the forests. Secondly, all these stocks were important for the interannual variability in the carbon balance and, even more importantly, tended to shift in opposite directions between years despite the similar trends in the long-term. Consequently, a partial accounting of the carbon balance may easily lead to biased results and misleading conclusions. The possibility of contrasting changes in the carbon stocks of biomass and soils as a consequence of natural disturbances was demonstrated earlier by Kurz and Apps [25]. In the present study, we demonstrated in addition that even the annual responses of these carbon stocks to changes in climatic conditions and the level of harvesting tend to shift in the opposite directions.

Land use changes and the associated carbon transfers were important for the carbon balance of litter and soil (Fig 4). Although these transfers do not represent a direct sink or source of atmospheric carbon, they must be included in national GHG inventories of forests in addition to carbon directly bound to or released from litter or soil in forests. This requirement calls for coordination between different sectors to avoid double accounting or disappearance of carbon nationally; when land use changes, carbon added to or removed from forests must be respectively removed from or added to the other land use category. In the present study, we had only limited information to estimate the quantities of these carbon transfers which makes our estimates uncertain. However, we think that our estimate are accurate enough to illustrate that the transfers of litter and soil carbon between forests and other land uses may be significant even in a highly forested country where the annual changes in forested area are relatively small. Further research is needed to improve the estimates.

The UNFCCC requests countries to report GHG emissions and removals for their forests on an annual basis. In most of the countries, however, inventory data does not support calculation of the annual estimates and the values reported represent longer-term averages. In the present study, we calculated the annual estimates using growth indices and modelling of litter and soil. We found high annual variation in the carbon balance of both biomass and litter and soil. This indicates that between year variation in the carbon balance of forests is more remarkable than currently reported to the UNFCCC by countries. The estimates are also sensitive to the reporting period. Longer reporting periods of five to ten years may thus be more reasonable than annual estimates for monitoring the mitigation potential of climate change in the forest sector.

According to the IPCC [19], countries should apply more reliable higher-tier estimation methods for those categories of their GHG reporting that have the greatest contribution to the overall uncertainty of the inventory. Forest vegetation, litter and soil are often such key categories of the GHG inventory in a forested country like Finland [48]. The calculation method we developed uses national forest inventory data and is supplemented by statistical biomass models and a dynamic litter and soil carbon model. Such methods belong to the highest tier three categories in the IPCC classification [19].

Our study demonstrates that it is possible to calculate appropriate estimates for total forest carbon balance based on forest inventory data by complementing these data with statistical and dynamic modelling. Therefore, we argue that it is more reasonable to use these methods to estimate the total forest carbon balance than to exclude some parts of the balance due to the high costs and methodological difficulties involved in quantifying these parts by pure measurements.

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