THE IMPACT OF NITROGEN DEPOSITION ON CARBON SEQUESTRATION BY EUROPEAN FORESTS

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ABSTRACT

An estimate of net carbon pool changes was made at more than 600 Intensively Monitoring plots. Carbon pool changes in trees were based on repeated forest growth surveys. Carbon pool changes in the soil were based on calculated nitrogen retention (N deposition minus N leaching) rates in soils minus N uptake and multiplied by the C/N ratio of the forest soils. Results were scale up to Europe based on data for more than 6000 plots in a systematic 16km x 16 km grid. The carbon pool changes in the tree are generally 5-10 times as high as the estimated carbon pool changes in the soil. The changes in the carbon pool in tree due to forest growth increased from Northern to Central Europe, whereas the changes in the carbon pool in soil are high in Central Europe and low in Northern and Southern Europe. Net increases in the carbon pool by forests in Europe (both trees and soil) are in the range of 0.1-0.15 Gton.yr^{-1}, being an important part (about 50%) of the terrestrial carbon sink in Europe, derived from atmospheric inversion models. The contribution of N deposition to the increase in carbon in standing biomass is approximately estimated to be less than 10%.

INTRODUCTION

It is of importance to arrive at reliable estimates of carbon sequestration in forests since this may delay the rise in the atmospheric CO_2 concentration with implications for the speed of climate change. An overview of various estimates of the carbon sequestration in Europe, focusing on different ecosystem compartments and using different methods is given in Table 1. Apart from a distinction in the type of flux and the forest compartment, a differentiation has been made in the quality of the upscaling methods, going from individual sites to the European scale.

A direct comparison of these studies on carbon sequestration in forests (in Europe), is hampered because of the measurement of different carbon sink terms. First of all, there is a difference in the assessment of the so-called net ecosystem production (NEP) or net ecosystem exchange (NEE), and the net biome production (NBP). The NEP or NEE stands for the total uptake of CO_2 by photosynthesis, corrected for plant and soil respiration, whereas the NBP equals the NEP corrected for CO_2 emissions due to harvest and forest fires. The latter term is critical with respect to long-term carbon storage, since an aggrading forest may temporarily sequester large carbon amounts, but most of it is re-emitted to the atmosphere after logging. Secondly, a distinction can be made in sequestration in the trees and in the soil. Over the long term, the soil is the ultimate sink or source of CO_2 for these ecosystems. A systematic discussion related to the various approaches and results is given in De Vries et al. (2003) [1].

Table 1 Overview of different estimates of carbon sequestration on a European wide scale.

Type of C flux	Compartment	Method	Estimated sink Gton. yr^{-1}	Upscaling method	Reference
NBP landscape					
NBP	Landscape	Inversion modelling	0.30	Good	[2]
NEE/NEP Whole forest/trees					
NEE	Whole forest	CO_2 net flux measurements	0.47	Neural networks	[3]
			0.25	Forest maps	[4]
NEP	Total above-ground biomass	Tree growth measurements	0.39-0.53[1]	Multiply with forested area	[5]
NBP whole forest/trees					
NBP	Trees (stem wood)	Repeated forest Inventories	0.10	Country inventory data	[6] [7]
NBP	Trees (stem wood)	Modelling forest growth	0.08-0.12[2]	Country inventory data	[8]
NEP contribution	Trees (above-ground biomass)	N retention	0.025[3]	World average values	[9]
NBP forest soil					
NBP	Forest soil (below-ground biomass)	Carbon soil input minus carbon mineralisation	0.13	Multiply with forested area	[5]
NBP	Forest soil (below-ground biomass)	Modelling forest growth and decomposition	0.038-0.061[2]	Country inventory data	[8]
NBP	Forest soil (below-ground biomass)	N retention	0.022[3]	World average values	[9]

[1] The first estimates was derived by [5] based on a forested area in Europe of approximately 150 million ha, whereas the second estimate is based on an area of 200 million ha, used in this study

[2] These estimates were originally limited to the EU + Norway and Switzerland (approximately 138 million ha) but results were scaled to the European forested area, excluding most of Russia (approximately 200 million ha)

[3] These estimates were originally global but were scaled to the European N deposition and forest area. Actually, [9] also estimated a NEP of 0.0.25 for carbon sequestration in trees but this was presented as the contribution of N deposition to NEP in trees and not the total growth

Important questions with respect to carbon sequestration are related to its cause and the time-period in which the terrestrial sink will be saturated. Apart from changes in standing growing stock (influenced by forest management), changes in net primary productivity may also play a role due to increases in atmospheric CO_2 concentrations, nitrogen deposition and temperature. In this context, N deposition is claimed to be most important [10]. Nitrogen is often the limiting nutrient in terrestrial ecosystems. The increase in nitrogen deposition on forests may thus cause a significant interaction increase in carbon sequestration by increased wood production and accumulation of soil organic matter. Insight in the latter effect is crucial since the soil is the ultimate sink or source of CO_2 for forest ecosystems over the long term. Current hypotheses suggest that increased N deposition causes an increased rate of soil organic matter accumulation at least in two ways due to an increased leaf/needle biomass and litter production [e.g. 5] and a reduced decomposition of organic matter [11]. Earlier estimates suggested that this mechanism could take up one third of the global CO_2 emission from fossil fuel (or 2 x 10^{15} $g.yr^{-1}$) if most of the deposition nitrogen was taken up by trees and used to form new woody biomass [12]. Recent data on the distribution of deposition nitrogen between trees and soil [9], however, suggest that a large part of the nitrogen is accumulated in the soil at low carbon to nitrogen ratio (10-40) and not in the trees at carbon to nitrogen ratio (200-500). Nadelhoffer et al. (1999) [9] calculated additional C sequestration on a global scale from additional N uptake by trees and N immobilisation in soils in response to N deposition. From their estimate, the authors conclude that C sequestration in forest trees and forest soils over the world is of equal magnitude. The upscaling of the results to a European scale by these authors was very simple, thus hampering an adequate estimate on this large scale.

This paper presents an estimate of carbon sequestration in trees and soil in Europe and the likely impact of N deposition on the sequestration rates in the period 1960-2000. Use is made of measured and estimated data on N retention (input minus output), N uptake and soil C/N ratios at approximately 120 so-called Intensive Monitoring Plots with data on atmospheric N deposition and forest ecosystems responses and of approximately 6000 so-called Level 1 plots with data on forest vitality and soil chemistry.

METHODS

Calculation of carbon pool changes in trees at Intensive Monitoring plots

Information on carbon pool changes at Intensive Monitoring plots was based on a first re-measurement of the trees, five years after installation. The repeated data on tree diameter (at breast height) and tree height were used to calculate standing wood volume and changes therein. By multiplying single tree volume with estimated wood densities and tree carbon contents, an estimate for the carbon pool stored in the stem was derived and extrapolated to carbon pools per hectare. Most countries submitted results of their volume calculations. If not, stem wood volume of each individual tree (V in m^3) was calculated as a function of the diameter at breast height (dbh in cm) and tree height (TH or h in m). The calculations were done for (clusters of) major tree species, while distinguishing between coppice forests and high forests.

The volume equations that were used to calculate the volume of each individual tree as a function of diameter and height: were either direct relationships, according to some type of polynomial relationship, or an indirect relationship between making use of individual tree form factor equations [1]. In situations where height data are missing, they were calculated from species and plot specific height curves. The form factor f was calculated according to Schieler, 1988 [13]. Carbon pools in trees in stem wood were calculated by multiplying stem wood volumes ($m^3.ha^{-1}$) with stem wood density ($kg.m^{-3}$), based on literature data [14], and an assumed C content of 50% in stem wood.

Calculation of carbon sequestration in soils at Intensive Monitoring plots

An estimate of net C sequestration in Intensive Monitoring plots was based on the calculated nitrogen immobilisation (sequestration) in the soils, multiplied by the C/N ratio of the forest soils, distinguishing between the organic layer (forest floor) and mineral soil. The basic assumption is that CO_2 sequestration can be calculated from nitrogen retention in the soils since carbon and nitrogen accumulation in organic matter occurs through the same mechanisms. N immobilisation (sequestration) was calculated as:

$$\text{N immobilisation} = \text{N deposition} - \text{N leaching} - \text{N uptake} \tag{1}$$

This approach is based on the assumption that denitrification can be neglected in the organic layer and the mineral topsoil, where both N and C sequestration is assumed to occur. Figure 1 shows the calculated N retention (N deposition minus N leaching) and N uptake for the Intensive Monitoring plots for which carbon pool changes in trees and soil were calculated (Fig 1). This included the plots with information on: (i) both bulk deposition and throughfall of N, thus allowing the calculation of total N deposition, and (ii) soil solution chemistry, thus allowing the calculation N leaching. Such budgets were only available for 124 plots, due to the limited availability of soil solution chemistry data. The actual N uptake was derived by multiplying changes in standing biomass in terms of stem wood, from repeated growth surveys in the period 1995-2000 with deposition dependent N contents in biomass. The results (Fig. 1) show that N uptake systematically increases going from Northern to Southern Europe while the N retention generally follows this pattern. In nearly all cases total retention (equal to uptake, denitrification and soil immobilisation) is larger than uptake implying that N is immobilised in the soil.

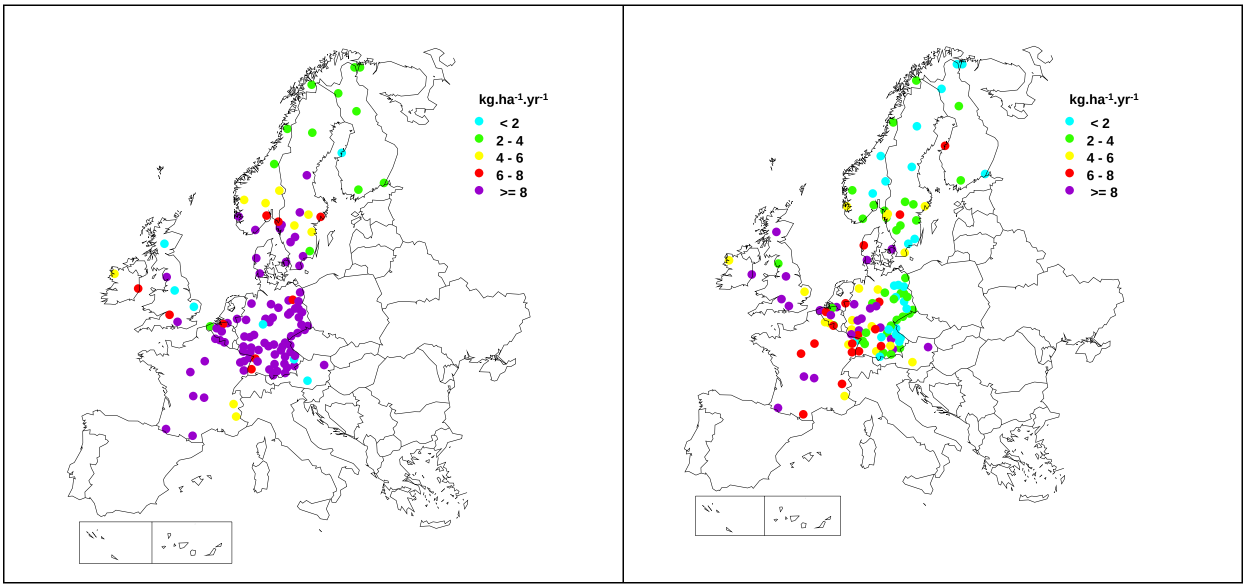

Figure 1 *Nitrogen retention (N deposition minus N leaching; left) and N uptake (right) at the 121 Intensive Monitoring plots ($kgN.ha^{-1}.yr^{-1}$) that were used for the calculation of carbon sequestration in soils.*

In multiplying the net N immobilisation with the C/N ratio, the variation of the C/N ratio with the depth of the soil profile was accounted for, as there is often a large difference between C/N ratio in the organic layer (forest floor) and in the mineral soil. This was done according to:

$$\mathrm{C\ sequestration} = \mathrm{N\ immobilisation} \cdot (\mathrm{fret}_{\mathrm{ff}} \cdot \mathrm{C/N}_{\mathrm{ff}} + (1 - \mathrm{fret}_{\mathrm{ff}}) \cdot \mathrm{C/N}_{\mathrm{ms}}) \qquad (2)$$

Where C/N_{ff} and C/N_{ms} are the C/N ratios of the forest floor and the mineral soil (up to a depth of 20 cm), and $fret_{ff}$ is the N retention fraction in the forest floor, being the ratio of the N retention in the forest floor and the N retention in the complete soil profile (forest floor and mineral soil). The fate of deposition N in forest soils has been studied by nitrogen tracer (15N) technique [9, 15] Based on the results of these experiments we modelled the N retention fraction in the forest floor as a function of the NH_4-fraction in the N input and the C/N ratio of the forest floor, as given in [1]. A comparison of calculated N retention fractions in the forest floor for sites and treatments included in [15] and the observed partitioning from the tracer experiments showed a reasonable comparison [1].

Extrapolation of carbon sequestration to the European forested area

In order to scale up results to Europe, an estimate of net carbon sequestration was calculated for the more than 6000 level I plots located in a systematic grid of 16 km x 16 km, being representative for approximately 2,0 million km^2 for Forests in Europe. As with the Intensive Monitoring plots, the calculation was based on calculated nitrogen retention in the soils, multiplied by the C/N ratio of the forest soil considered. N immobilisation (sequestration) was now calculated as a fraction of the N deposition corrected for N uptake, according to:

$$\text{N immobilisation} = \text{frN}_{\text{im}} \cdot (\text{N deposition - net N uptake}) \tag{3}$$

The fraction frN_{im} was calculated as a function of the C/N ratio of the forest soil using presently available results on this relationship [16] and results from the Intensive monitoring plots as shown in Figure 2.

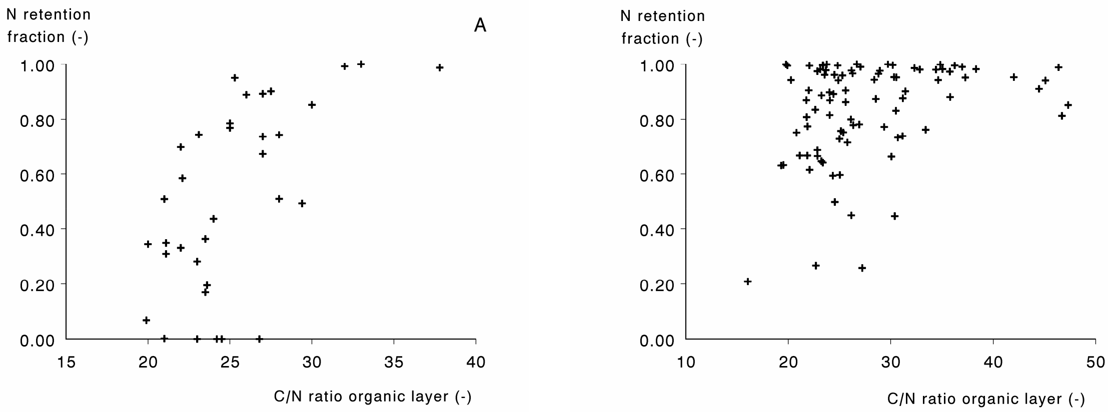

Figure 2 *Relationship between N retention fraction and C/N ratios in the organic layer. The left graph refers to 34 forest plots of mainly conifers using ECOFEE-data from [16] with N input being (throughfall of N and N output referring to nitrate only (A). The right graph refers to 121 Intensive Monitoring plots with available data on total N deposition and N leaching (B).*

The results show that N retention is nearly complete (above 90%) at C/N ratios above 30-35 and very low at low C/N ratios (below 20) but in between it is highly variable. Using these data, the N immobilisation fraction was calculated as a function of C/N ratio according to:

$$frN_{im} = \frac{1}{1+\alpha^{(\beta \cdot (CN-25))^{\gamma-1}}} \tag{4}$$

where α = 0.95, β = 0.4 and γ = -0.95. In the calculation use was made of site specific estimates for the more than 6000 forest soils in a systematic grid of 16 km x 16 km (level I) of

- N (NH_4, NO_3) deposition: EDACS model estimates from 1960-2000
- Net N uptake: yield estimates as a function of stand age and site quality as described in [17] multiplied by deposition dependent N contents in biomass.
- frNret: related to measured C/N ratios forest soil and modelled fraction NH_4 in deposition
- C/N ratios for forest soils: measurements, partly extrapolations

The EMEP deposition data for 2000 were used to calculate the carbon sequestration in the soil for that year. The data for the whole period 1960-2000 (data at 5 year intervals that were linearly interpolated) were used to assess the contribution of elevated N deposition in that period on the increase in carbon pools in standing biomass in that period. The methodology is described in detail below.

An estimate of C sequestration in stem wood of European forests (NEP) was derived from stand age and available site quality characteristics, using forest yield tables to estimate the actual forest growth [17], using a C content of 50%. This estimate was assumed to equal the baseline growth without impact of elevated N deposition. This estimate was increased with additional growth due to elevated N deposition as described in the following section. The net C sink (NBP) in stem wood was calculated by assuming that NBP equals 33% of the NEP. This percentage is based on an estimated average NBP/NEP ratio for Europe, implying a net increase in standing forest biomass of 33% of the growth since 67 % is removed by harvesting or forest fires [18].

Assessing nitrogen deposition effects on carbon sequestration by European forests

The methodology used to calculate the impact of elevated nitrogen deposition on carbon sequestration by European forests is inspired by the approach of [9]. These authors assessed additional C sequestration on a global scale from additional N uptake by trees and N immobilisation in soils in response to N deposition. The estimate by [9], which suggest that C sequestration in forest trees and forest soils over the world is of equal magnitude is based on the following assumptions:

- Present total world N deposition estimate.
- Constant N retention fractions in trees (uptake; a fraction of 0.05) and soil (immobilisation; a fraction of 0.70), based on short-term fate (1-3 year) of ^{15}N labelled tracer experiments in nine temperate forests
- Averages values for the C/N ratio in stem wood (500) and forest soils (30).

Apart from the rough generalisation, the confusing aspect in this approach is that the present total world N deposition is used, whereas the paper discusses the possible impact of elevated N deposition. The 'unaffected' growth figures should be related to a certain N deposition as well. This implies that one should discuss the impact with reference to the increase in carbon pool in trees in the last decades, as presented by [6] and [7]. Those authors estimated a net increase in the C pool in trees in Europe of approximately 0.1 Gton C.yr^{-1} in the period 1970-1990. This implies that one has to estimate what the impact of increased N deposition in that period is on the C sequestration. In this study we used this approach but we extended the period to 1960-2000, assuming that the net C pool change in trees in that period is also 0.1 Gton C.yr^{-1}.

An overview of al differences used in this approach and those used by [9] is presented in Table 3. First of all, we used 1960 as the reference for N deposition (this leads to 'normal' growth) and calculated what the additional N deposition was in the period 1960-2000 compared to that reference year. [9] implicitly assumed that the reference N deposition is negligible. Unlike those authors we included the spatial differences in N deposition on the plots (EMEP estimates). Furthermore, we assumed that the additional N uptake due to N deposition is (uptake fraction) is a function of the N deposition, with values being higher in low deposition areas, because of N deficiencies, and lower in high deposition areas. Similarly, the N immobilisation fraction was assumed to be a function of the C/N ratio of the organic layer and the NH_4/NO_3 in deposition, as described before, and not a constant of 70%.

Similar to the uptake fraction, the C/N ratios in trees were assumed to vary with the N deposition, values being higher in low deposition areas and lower in high deposition areas. This was based on the idea that luxury consumption takes place at a high N availability, meaning that the additional N uptake is only partly leading to additional growth (C pool change) since part is just leading to higher N contents (lower C/N ratios) in stem wood. For the C/N ratio in the organic layer and mineral layer, we used the measured values at all Level I plots, instead of using a constant value of 30. In [1] the above described methodological approach is presented in detail including the mathematical descriptions.

Table 3 Overview of differences between the approach used by [9] and in this study to calculate the impacts of N deposition on carbon sequestration.

Nadelhoffer et al. [9]	Our approach
Reference N deposition is negligible	Reference N deposition is 1960
Constant average N deposition	Spatially distributed and time dependent N deposition[1)]
N uptake fraction is constant	N uptake fraction is f(N deposition)
N immobilisation is constant	N immobilisation fraction is f(C/N ratio humus layer/soil, NH_4/NO_3 in deposition)
C/N ratio tree is constant	C/N ratio tree varies in space and time as f(N $\text{deposition}_{x,t}$)[1)]
C/N ratio soil is constant in space and time	C/N ratio organic and mineral layer varies in space[2)]

[1)] Based on calculated EMEP N deposition

[2)] Based on the measured C/N ratio data at approximately 6000 forested plots

RESULTS

Carbon pool changes in trees and soils at Intensive Monitoring plots

The result of the calculated annual carbon sequestration in soils at the 121 Intensive Monitoring plots, together with the estimated sequestration due to forest growth in the last five years at the same plots, is shown in Figure 3. The results show that the carbon pool changes in the tree are generally 5-10 times as high as the estimated carbon pool changes in the soil. As expected, the changes in the carbon pool in tree due to forest growth increase going from Northern to Central Europe and decrease again in Southern Europe. In line with the calculation procedure, the calculated changes in the carbon pool in soil do follow the N deposition pattern being high in Central Europe and low in Northern and Southern Europe (Fig. 3). Interestingly, however, the same kind of pattern is found by [3], presenting spatial (1 x 1km) estimates of carbon fluxes of European forests based on the net CO_2 exchange flux collected at sixteen of sites in the EUROFLUX network, using neural networks for the spatial extrapolation.

Carbon sequestration in soils and trees on the European scale

The estimated actual carbon sequestration in the tree wood (NEP) during the period 1960-2000 is given in Table 4. The calculated carbon sequestration in stem wood due to forest growth equals approximately 0.28 Gton.yr^{-1}. Using a forested area of 200 million ha, the mean carbon sequestration rate in tree stem wood based on uptake is approximately 1400

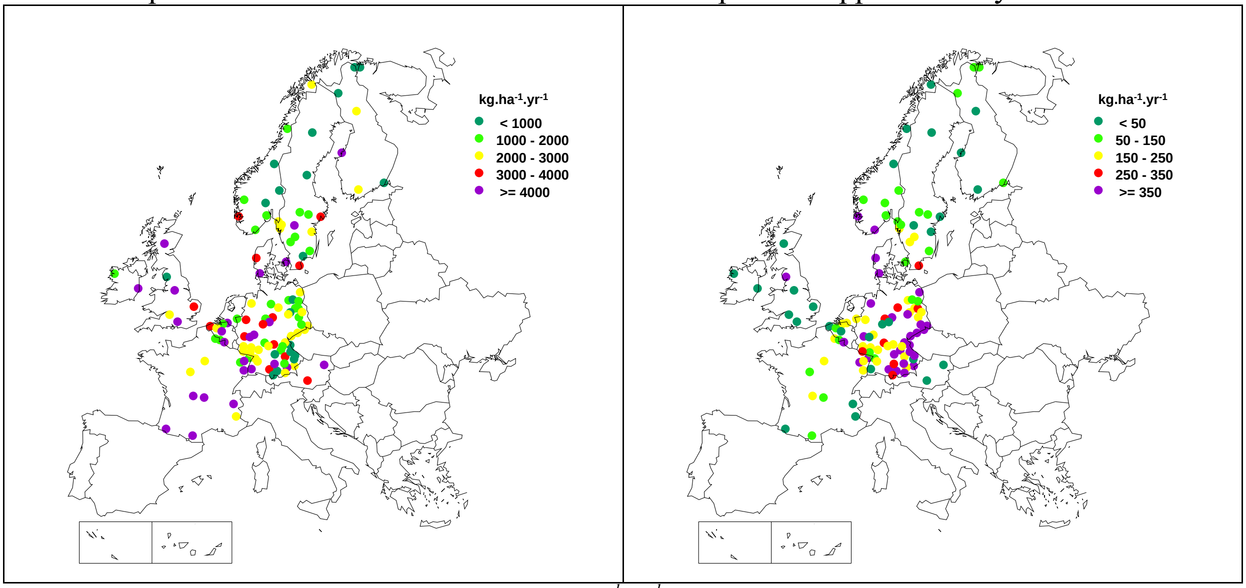

Figure 3 Calculated carbon pool changes (kgC.ha^{-1}.yr^{-1}) in trees (left) and soils (right) at the 121 Intensive Monitoring plots for the year 2000

Table 4 Estimated total and net carbon sink for European forests due to tree growth (NEP) and increase in standing biomass (NBP, being 33% of the NEP) for the year 1960 and 2000.

Region	Carbon sequestration in wood (Gton.yr^{-1})			
	NEP 1960 -2000		NBP1960 -2000	
	No N impact	With N impact	No N impact	With N impact
EU	0.184	0.194	0.061	0.064
Candidate member states	0.036	0.038	0.012	0.013
Other European countries	0.059	0.063	0.020	0.021
Total	0.279	0.295	0.093	0.098

kg.ha^{-1}.yr^{-1}. Assuming that NBP is 33% of the NEP, gives results close to 0.1Gton.yr^{-1}, being equal to a mean net sequestration rate of approximately 450 kg.ha^{-1}.yr^{-1}.

Estimated net carbon sequestration by accumulation in forest soils is given in Table 5. A distinction was made in the standard calculation with respect to N uptake and N accumulation and an alternative in which all the net incoming N was assumed to accumulate (total immobilisation, no leaching). The results using the standard run were lower than those derived by [9] (0.0138 vs. 0.022 Gton.yr^{-1}; compare Table 1 and 5). This is to be expected since these authors assumed a constant low net uptake (5%) and a constant high soil accumulation of 70% in the forest soil. Using the assumption that all the net incoming N is retained gives an estimate that is comparable to the estimate by Nadelhoffer et al. (1999) [9], while the upper limit in this study appeared to be nearly twice as high [9].

Table5 Estimated net carbon sink by accumulation in European forest soils, for two different calculation scenarios for the year 2000.

Region	Net carbon sequestration in soil (Gton.yr^{-1})	
	Standard run	Total immobilisation
EU	0.0104	0.0183
Candidate member states	0.0013	0.0036
Other European countries	0.0020	0.0016
Total	0.0138	0.0235

The geographic variation in carbon sequestration in trees and soils is illustrated in Fig. 4. Comparable to Fig. 1, C sequestration is small in Northern Europe, where the N input is low and nearly all incoming N is retained by the vegetation, and higher in Central and Eastern Europe where the N input is larger. The finding that C sequestration is negligible in northern boreal forest is in line with results from [4] based on flux measurements for CO_2.

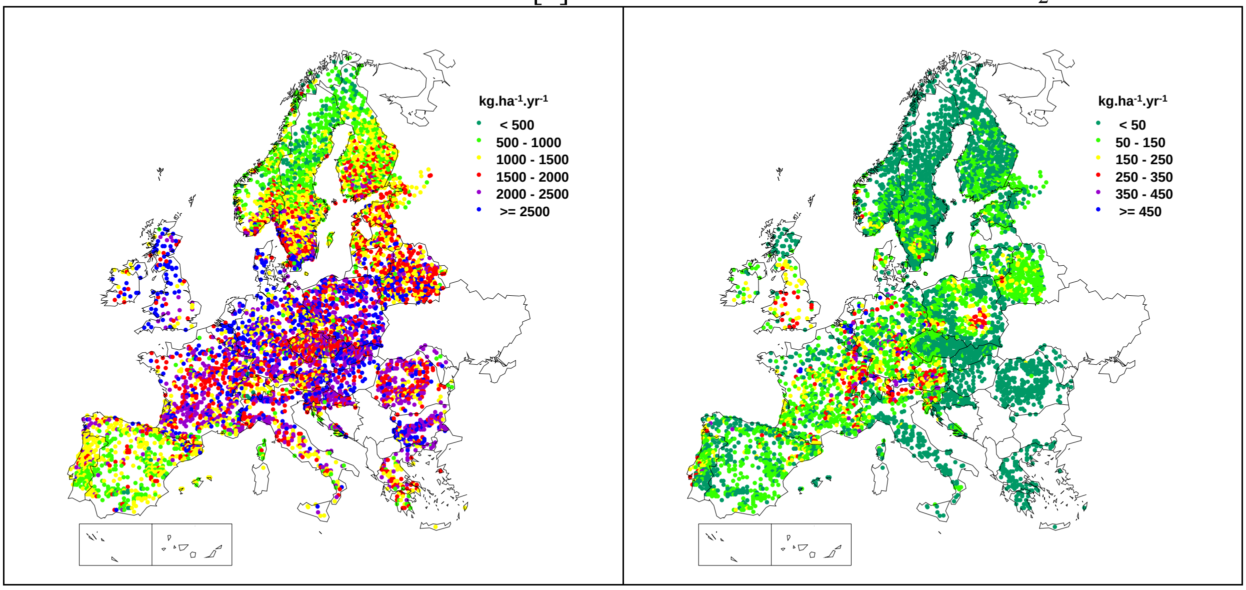

Figure 4 Geographic variation of the calculated carbon sequestration in trees and soil over Europe, using the standard run.

DISCUSSION AND CONCLUSIONS

From this study, it can be concluded that:

- Carbon pool changes in the tree are generally 5-10 times as high as the estimated carbon pool changes in the soil. Changes in the carbon pool in tree due to forest growth increase going from Northern to Southern Europe. The calculated changes in the carbon pool in soil do follow the N deposition pattern being high in Central Europe and low in Northern and Southern Europe.
- Net increases in the carbon pool by forests in Europe (both trees and soil) are in the range of 0.1-0.15 Gton.yr^{-1}, being about 50% of the terrestrial carbon sink in Europe. Carbon sequestration by forest is mainly due to a net increase in forest growth, since carbon immobilisation in the soil is limited.
- The estimated contribution of N deposition to the increase in carbon in standing biomass is approximately 10 and 20 Mton.yr^{-1}. This is 3.5 –7% of the carbon pool increase by forest growth

The result of this study implies that the impact of forest management is most important in explaining the carbon pool changes in forest in Europe due to the fact that forests in Europe are aggrading because the removal by harvesting and forest fires is less than the net growth. A further contribution to C sequestration on the forest area may come from earlier and recent afforestations on fields or grasslands. Effects of such land use change are not included in the calculations. On these areas the build up of C stock in trees may be substantial but still a transitory phenomenon lasting a forest generation.

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