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Carbon profiles of typical forest types across Europe assessed with CO2FIX

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Abstract

This paper presents for 16 typical forest types across Europe a standard carbon sequestration profile. The study was carried out with the model CO2FIX which was parameterised with local yield table data and additional required parameters. CO2FIX quantifies the carbon of the forest ecosystem–soil–wood products chain at the stand level. To avoid misleading results annual net sequestration rates are not presented here, because these strongly fluctuate in time. Therefore, only its advancing mean is presented as a more reliable indicator. This avoids a great deal of uncertainty for policy makers. The variation between forest types is large, but mean sequestration rates mostly peak after some 38 years (with a net source lasting up to 15 years after afforestation) at an average value of 2.98 Mg C ha^{-1} per year (ranging between forest types from 4.1 to 1.15). After 200 years, the net sequestration rate saturates to a value of 0.8 Mg C ha^{-1} per year (ranging from 1.4 to 0.13). The long-term mean carbon stock in tree biomass and products amounts on average to 114 Mg C ha^{-1} (ranging from 52 to 196).

Keywords: Carbon sequestration; European forests; CO2FIX

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1. Introduction

During the 1990s, the estimated amount of carbon stored in global terrestrial ecosystems increased by about 0.7 Pg C per year. This was based on the residual from fossil fuel emissions, the atmospheric increase, and oceanic uptake. This 0.7 Pg C per year is the difference between a net emission of about 1.6 Pg C per year from land-use changes, primarily in the tropics, and an uptake of about 2.3 Pg C per year (Watson et al., 2000; Ciais et al., 1995; Keeling et al., 1996). It is this latter 2.3 Pg terrestrial carbon uptake that is the subject of ongoing debate concerning its latitudinal distribution, its causes, and persistence (Fan et al., 1998; Houghton et al., 1999; Schimel et al., 2000; Valentini et al., 2000; Schelhaas and Nabuurs, 2001b).

These dynamics of global forests, their potential contribution to curbing the increase of atmospheric carbon dioxide, and the acknowledgement of their role through the adoption of the Kyoto Protocol (UNFCCC, 1997) have initiated many studies into the possibilities of enhancing and maintaining carbon sequestration of global forests. Options for enhancement and maintenance of carbon sequestration are reducing deforestation, expanding forest area, increasing the carbon stock in existing forests (including soils), increasing the use and life span of wood products, and using wood products as biofuels for substituting fossil fuels (Kauppi et al., 2001). This role of forests has not only initiated research studies, but land use

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and forestry projects with the aim to sequester carbon have started in many countries (Brown et al., 2000).

However, quantifying the net carbon sequestration of the above-mentioned options remains a hotly debated, often misunderstood item with seemingly many contradictory results. The confusion often culminates around understanding the difference between stocks and fluxes of carbon or because short- and long-term net carbon balances are often confused (Matthews et al., 1996). Other reasons are that in different studies a varying number of compartments of the forest ecosystem–wood products chain were incorporated. Sometimes differences merely occur because either NPP or NEP figures are presented (Schulze, 2000). Also, study results are difficult to compare because of differences in the methodology used, or because of large interannual variability that may be captured by one method, but not by the other (Valentini et al., 2000).

Furthermore, forest management that focuses on enhancement of carbon in forest biomass has an impact on soils and wood products as well, and there may be a trade-off between a high sustained timber yield and the stock of carbon in the forest ecosystem (Karjalainen, 1996a,b; Thornley and Cannell, 2000). Thus, understanding the whole system with its interactions between compartments is of importance. Part of this ‘whole system’ is also the substitution effect: products derived from woody material require less energy input for processing than aluminium or steel and thus save fossil fuels (Burschel et al., 1993; Marland and Schlamadinger, 1997).

Another complicating matter is that a full greenhouse gas balance (including baseline development with assumptions on continued previous land use), may again reveal another picture of the balance. For example, previous land use may have caused N_2O emissions which ceased after initiation of the forestry project, or draining of peatlands to afforest may cause CH_4 emissions to go down while carbon dioxide emissions from decomposing peat may rise (Cannell et al., 1993).

1.1. AIM

The uncertainty about the role of European forests and forestry-measures in the global carbon cycle, and it spatial distribution, must be resolved to a level acceptable for policy makers. The aim of this paper is to quantify the carbon sequestration potential for a range of forest types across Europe, based on widely accepted input data. These carbon profiles as we call them, can be seen as a frame for carbon sequestration potential in European forest types. They can help in planning activities in forestry, selection of sites, or selection of strategies in forest management.

In order to reduce uncertainty regarding carbon sequestration in forestry, the aim was also to define a reliable indicator for carbon sequestration potential. This indicator had to reduce uncertainty caused by strong temporal fluctuations in net C sequestration and it had to reduce uncertainty concerning maintaining stocks and the persistence of the net sink.

1.2. Methods and data

The CO2FIX model version 1.2 quantifies the carbon budget of a forest–soil–wood products chain at the stand (i.e. hectare) level on an annual basis for multiple rotations (Mohren and Klein-Goldewijk, 1990a,b; Nabuurs and Mohren, 1993; Mohren et al., 1999). CO2FIX is available from the web at http://www.efi.fi/projects/casfor. Since it was made available in June 1999, 861 downloads from 78 countries have been made.

The model comprises the compartments as given in Fig. 1. CO2FIX version 1.2 is a rather simple bookkeeping model that converts volumetric net annual increment data, allocation data, turnover rates, and forest management and wood products data to annual carbon stocks and fluxes. CO2FIX is not a process based model that would work with climate data and calculate photosynthesis and respiration rates.

CO2FIX was calibrated here for 16 forest types across Europe (Fig. 2) based on published data (Table 1). The selection of forest types was made based on a detailed forest resource database for European forests (Nabuurs, 2001). For each tree species and region, average site conditions were chosen. Main driving factor are the current net annual increment curves derived from yield tables. Growth of foliage, branches, and roots is incorporated as an additional allocation of dry matter increment relative to the stem wood. This, together with expected life spans of these tree organs (for stems: natural mortality rate)

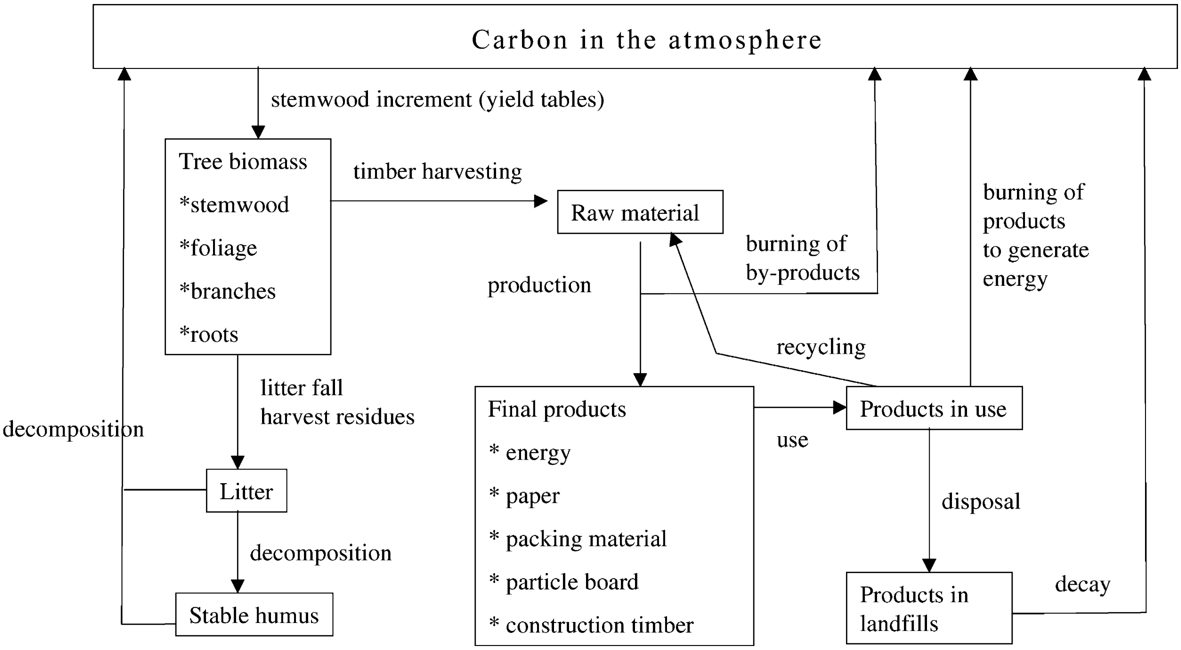

Fig. 1. Carbon fluxes (arrows) and carbon stocks (boxes) in a forest ecosystem and its wood products as distinguished in CO2FIX. In the version that was used here, carbon in products-in-use and in landfills is regarded to occur in one compartment with one estimated life span.

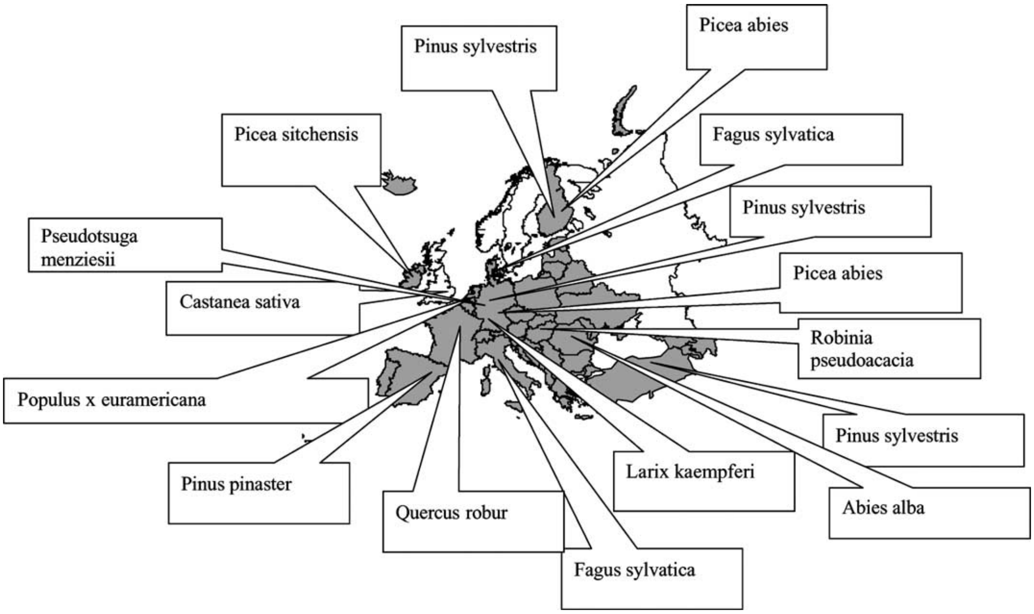

Fig. 2. Location of the forest types.

Table 1
Main characteristics of the forest types

Tree species		Country	Mean annual increment (m^3 ha^{-1} per year)[a]	Initial soil organic matter (Mg dm ha^{-1})	Rotation length (year)	Ages of thinning	Self thinning (1% per year)	Main use of wood from final felling	Reference of yield table
Scientific names	Vernacular names								
Castanea sativa	Sweet chestnut	UK (England)	9.5	140	70	25, 40, 60	No	Construction wood	Everard and Christie, 1995
Picea abies	Norway spruce	Finland (south)	6.3	200	100	25, 35, 45, 55, 65, 75, 85, 95	No	Construction wood	Koivisto, 1959
Picea abies	Norway spruce	Central Europe	14	190	120	25, 30, 35, 40, 45, 50, 55,60, 65, 70, 75, 80, 85, 90, 95, 100, 105, 110	No	Construction wood	Schober, 1975
Picea sitchensis	Sitka spruce	Ireland	16	600	45	25	Yes	Construction wood	Kilpatrick, 1978
Pinus sylvestris	Scots pine	Finland (south)	6.5	230	90	25, 35, 45, 55, 65, 75, 85	No	Construction wood	Koivisto, 1959
Fagus sylvatica	Beech	Denmark	10	170	140	20,25, 30,40,50, 60, 70, 80, 90, 100, 125	No	Construction wood	Jansen et al., 1996; Oppermann, 1914
Pinus sylvestris	Scots pine	Germany (north)	8	170	90	40, 60, 80	Yes	Construction wood	Jansen et al., 1996; Schober, 1975
Pseudotsuga menziesii	Douglas-fir	The Netherlands	14	100	100	30, 40, 60, 80, 90	No	Construction wood	Jansen et al., 1996; Schober, 1975
Populus x *euramericana*	Poplar	Belgium/Flanders	11	90	45	21	No	Packing wood	Jansen et al., 1996
Quercus robur	Sessile oak	France (north)	5.8	170	120	20,25, 30,40,50, 60, 70, 80, 90, 100	Yes	Construction wood and fuel wood	ONF, 1985
Pinus pinaster	Maritime pine	Spain	6	145	95	40, 60, 80	Yes	Construction wood	Garcia Abejon and Loranca, 1989
Fagus sylvatica	Beech	Italy (central Appenines)	7	102	110	40, 75	No	Construction wood and fuel wood	Bianchi, 1981
Larix kaempferi	Japanese larch	Belgium/Ardennes	10	255	80	40, 60	Yes	Construction wood	Jansen et al., 1996
Abies alba	Fir	Romania	14	190	110	25, 40, 60, 80, 90	Yes	Construction wood	Giurgiu et al., 1972
Pinus sylvestris	Scots pine	Turkey (east)	7.5	130	110	50, 75	Yes	Construction wood and packing wood	Batti, 1971
Robinia pseudoacacia	Locust	Hungary	9	90	50	10, 15, 20, 25, 30, 35, 40, 45	No	Construction wood	Redei and Gal, 1985, 1986

[a] Here only the mean value is given, but in fact current annual increment curves through time were used.

Table 2
Additional parameter values of the forest types

Tree species		Country	Basic wood density (Mg dm m^{-3})	Decomposition rate of humus (per year)	Decomposition rate of litter (per year)	Fraction of the decomposing litter that is humifying (per year)
Scientific names	Vernacular names					
Castanea sativa	Sweet chestnut	UK (England)	560	0.00077	0.77	0.08
Picea abies	Norway spruce	Finland (south)	385	0.00182	0.17	0.02
Picea abies	Norway spruce	Central Europe	635	0.00364	0.83	0.08
Picea sitchensis	Sitka spruce	Ireland	450	0.00200	0.50	0.03
Pinus sylvestris	Scots pine	Finland (south)	390	0.00182	0.17	0.02
Fagus sylvatica	Beech	Denmark	560	0.00364	0.83	0.08
Pinus sylvestris	Scots pine	Germany (north)	490	0.00364	0.20	0.02
Pseudotsuga menziesii	Douglas-fir	The Netherlands	450	0.00400	0.50	0.06
Populus x *euramericana*	Poplar	Belgium/Flanders	340	0.00444	1.00	0.10
Quercus robur	Sessile oak	France (north)	635	0.00364	0.83	0.08
Pinus pinaster	Maritime pine	Spain	490	0.00364	0.20	0.02
Fagus sylvatica	Beech	Italy (central Appenines)	560	0.00364	0.83	0.08
Larix kaempferi	Japanese larch	Belgium/Ardennes	490	0.00364	0.50	0.04
Abies alba	Fir	Romania	450	0.00313	0.50	0.03
Pinus sylvestris	Scots pine	Turkey (east)	490	0.00267	0.20	0.01
Robinia pseudoacacia	Locust	Hungary	630	0.00400	1.00	0.10

determines the biomass of the organs in the stand and determines the rate of litterfall (Cannell, 1982; Reichle, 1981; Schelhaas and Nabuurs, 2001a).

The dynamics of the forest soil compartment are characterised by decomposition rates for litter and stable humus and a humification rate for litter alone (Table 2). These, and initial values for dead wood, litter, and soil stable humus were based on current knowledge in literature (Liski and Westman, 1997a,b; Liski et al., 1998; Fraters et al., 1993; Gardenas, 1998; USDA, 1999; Johnson, 1992; Polglase et al., 2000; Buford and Stokes, 2000; Tolbert et al., 2000). Litter, dead wood, and humus in the mineral soil are considered to form the soil organic matter compartment. The carbon content in the humus was assumed to be 58%. All forest types are assumed to be afforestations on former agricultural sites. Thus, the initial values for soil stable humus represent agricultural arable sites, except the deep peat site in Ireland.

The forest product compartment is incorporated in the model as a bookkeeping model following the raw material from the harvesting regime (Karjalainen, 1996a,b). The harvested wood (in case of thinnings as a percentage of the standing volume) is allocated to five product groups according to assortments, types of use of the tree species, and by taking into account the use of processing losses to other product groups. Products are assumed to decay with a certain fraction per year depending on the life span estimates. These are estimated for energy wood, paper, packing wood, particle board, and construction wood at, respectively 1, 2, 3, 20 and 35 years (Karjalainen and Apps, 1995; Karjalainen, 1996a,b; Nabuurs and Sikkema, 2001; Schlamadinger and Marland, 1996). There is no separate landfill compartment distinguished in the present version of CO2FIX.

With basic wood density (dry matter weight per fresh volume, Table 2) and carbon content (50% of dry matter), the volumes are converted to carbon (Laming, 1978; USDA Forest Service, 1987; IPCC, 1996). The model produces an annual output of stocks and fluxes of carbon for each compartment of the forest biomass, the wood product compartment, and the soil organic matter compartment. The main characterisation of each forest type is given in Table 1, and important additional parameter values are given in Table 2. Not all parameter values can be given here. For a more detailed representation of parameter values, we refer to (Nabuurs and Mohren, 1993; Schelhaas and Nabuurs, 2001a).

2. Results

2.1. Defining indicators

A stand level net annual carbon cycle can be characterised by a negative net balance (=source) the first decade or so (Fig. 3). During that time the litterfall of the recently established forest is often not sufficient to balance the decomposition of the soil carbon stock. During that time the net decrease of soil carbon can be larger than the growth in the living trees, and thus a negative net ecosystem exchange (NEE) may occur. Then forests display a period of rapid growth; a strong net annual sink is visible in Fig. 3, in the period up to 40 years. As forests accumulate biomass towards maximum biomass, the net growth diminishes, and thus the net sink declines gradually towards the end of the rotation. In case of thinnings and final felling, a large net source is visible for a couple of years. Carbon is then released through slash oxidation on-site and product oxidation off-site. Including these disturbances we talk of the net biome production (NBP). The balance between new products being produced and old products decomposing, may provide a net sink in products-in-use as well.

In the long run, forests will (in theory) reach an equilibrium (NEE $= 0$). When including disturbances, a balance in NBP may only occur at the landscape level that is composed of a number of stands in an aggrading stage and a few stands in a declining (or recently disturbed stage). This landscape equilibrium can in principle sustain under stable levels of disturbances by fire, insects, or sustainable harvesting even though these single events cause large effluxes. Only when the rate of disturbances changes, this equilibrium in NBP is lost (Apps, 2000).

These strong temporal fluctuations in both stocks and fluxes in the forest ecosystem–soil–wood products chain have caused great uncertainty about persistence of the net sink, maintenance of stocks and how these temporary sinks should be accounted under the Kyoto Protocol. To cope with the strong temporal fluctuations, we introduce here the ‘advancing mean of the net annual sink’, as a more reliable and stable indicator (see dashed line in Fig. 3). This advancing mean at a certain point in time (n years) is calculated as the sum of all net annual values from 0 to n years, divided by n. The fluctuations in net annual values are dampened by this advancing mean.

2.2. Advancing mean of the net sink

Fig. 4 shows that the carbon profiles of the advancing mean of the net annual sink vary a lot between sites, locations and tree species across Europe. This reflects the great variation in management regimes, tree species potential and site conditions. Largest carbon sequestration potential was found for the Atlantic sites and the central European/middle mountain sites (peaks of the advancing mean in the range of 3–4 Mg C ha^{-1} per year). Smallest potential was found for the boreal and Mediterranean sites (peaks of the advancing mean around 1 Mg C ha^{-1} per year). Naturally, in all cases the net sink saturates, causing the advancing mean to diminish to values of around 0.8 Mg C ha^{-1} per year (ranging from 1.4 to 0.13) after 200 years. The rate at which this saturation occurs differs very much per forest types. Generally this happens more gradual in the long rotation forest types as fir in Romania, and beech in Denmark, in which regular management of thinnings and final fellings produces more wood products with long life spans. This saturation occurs rather soon in poplar in the Atlantic zone.

2.3. Long-term average stocks

The persistence of a net annual sink for centuries in all forest types results in build-up of large stocks in tree biomass and products. Due to human induced disturbances these stocks can change significantly from year to year. Fig. 5 displays the long term average stock in soils, and in the sum of products and tree biomass. Even though the Sitka spruce plantation on drained peatland, losses carbon from the soil (Fig. 6), it still maintains the largest soil carbon stock after 300 years. Largest carbon stock in biomass and products is achieved in the long rotation forest types as beech in the Atlantic zone of Europe (196 Mg C ha^{-1}). The soil compartment usually displays a slow increase in stock from on average some 100 Mg C ha^{-1} in

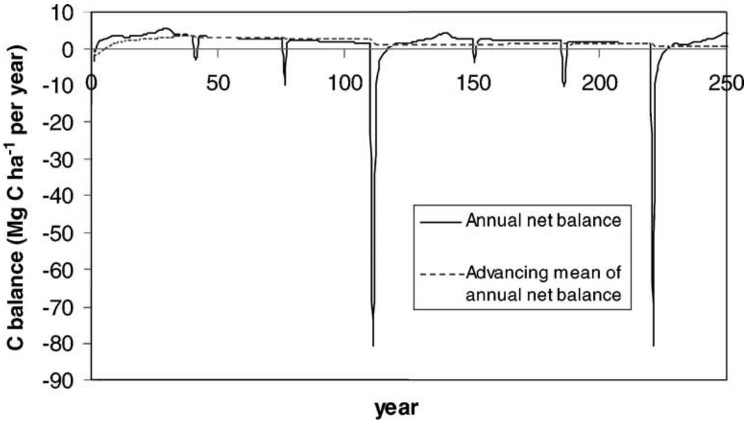

Fig. 3. Example of the temporal variation in the carbon cycle of a tree–soil–wood products chain. The continuous line represents the net carbon balance in each year; the dashed line is the advancing mean of the blue one. Positive values represent a sink.

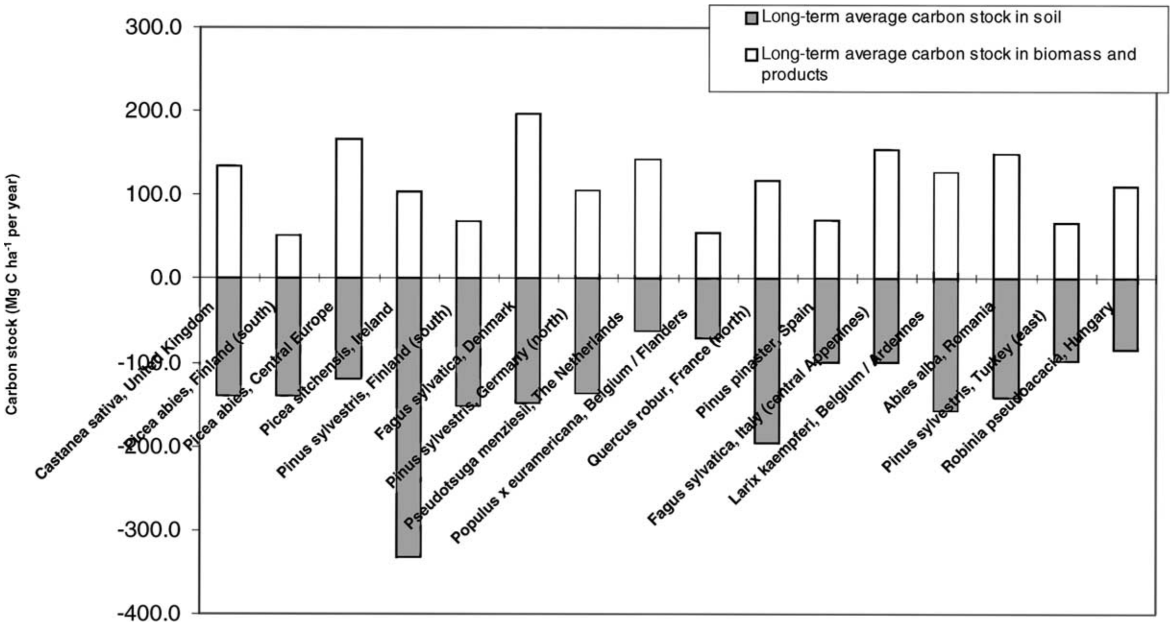

Fig. 5. The long term average carbon stock in soil (below *x*-axis) and biomass and products (above *x*-axis) of the 16 forest types. The negative sign for the stocks in soil was only used to display the soil stock below the *x*-axis.

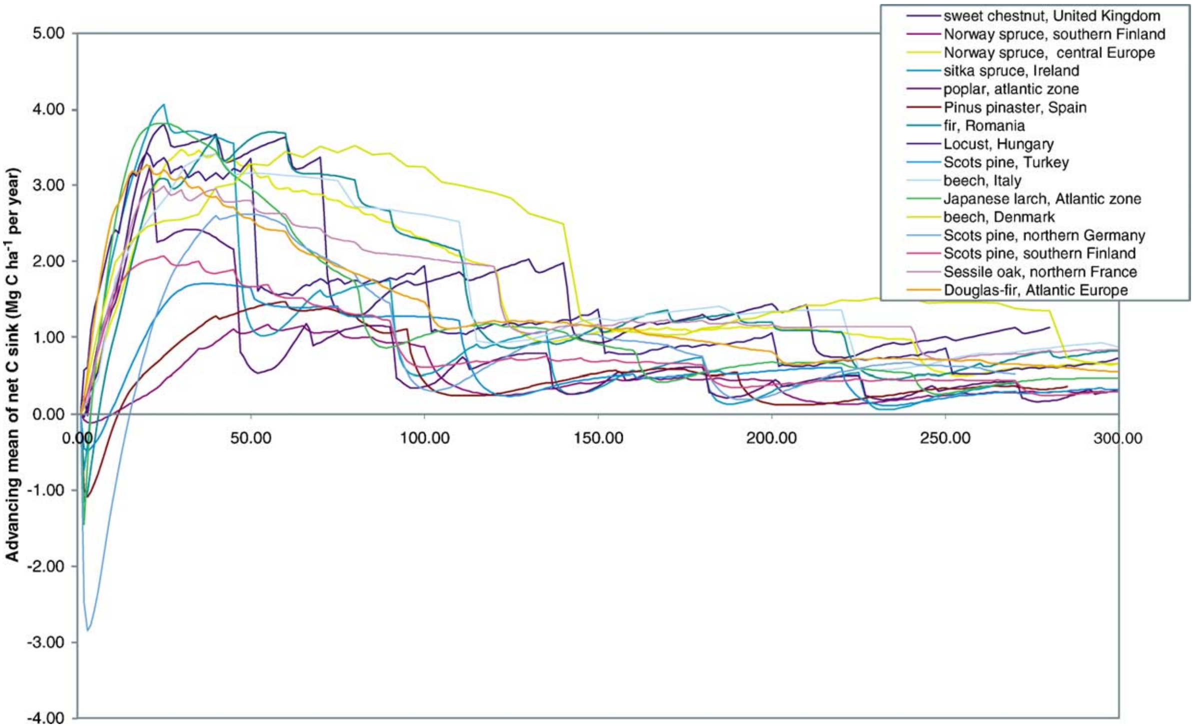

Fig. 4. Advancing means of the net carbon balance of the 16 forest types.

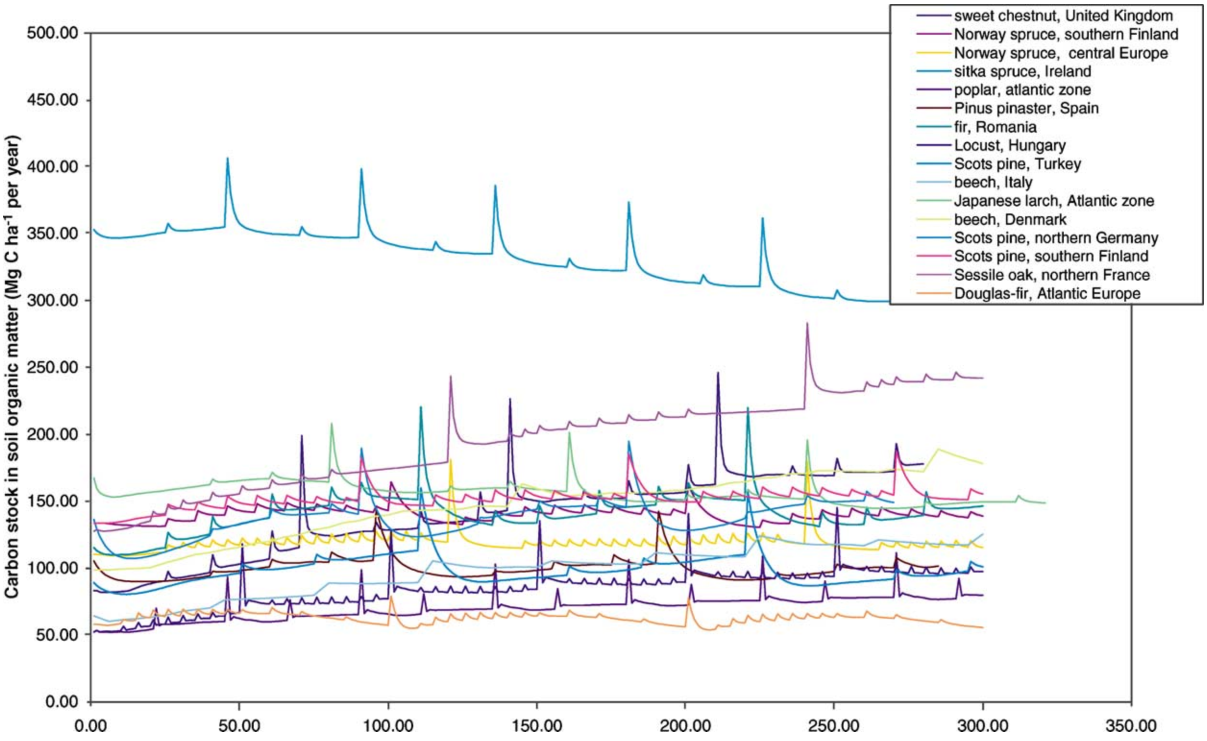

Fig. 6. Temporal development of the carbon stock in the soil compartment of the 16 forest types.

the initial year to 135 after 300 years (a net sink of 0.11 Mg C ha^{-1} per year).

3. Discussion

Annex I countries to the Kyoto Protocol show large interest in land use and forestry carbon sequestration projects in central and eastern European countries. This, in order to achieve their emission reduction commitment. However, before investing in afforestation, the maintenance of the forest, and the monitoring and reporting of the credited share of the sink, they want to have insight in what the biological potential sequestration may be. For this reason the carbon profiles as presented in this paper were quantified. These standard profiles with emphasis on long term indicators may set a frame for carbon sequestration in forestry projects across Europe. They will assist in planning activities in forestry, selection of sites, or selection of strategies in forest management.

Although the available land may be limited and the costs rather high in Europe, we found that the hectare scale potential is large. Mean advancing sequestration rates are high and persist for a long time resulting in large stocks being achieved, especially in Atlantic regions and in the central European middle mountain forest sites. Net sequestration (although small) often occurred in the soil compartment as well, because it was assumed that mostly (degraded) arable land will be chosen for afforestation projects.

Van der Voet (Nabuurs and Mohren, 1993) carried out an uncertainty analysis of the model CO2FIX for the Norway spruce forest type in central Europe. For the 32 independent inputs to the model, he found that for the total carbon stock, the average amounted to 316 Mg C ha^{-1}, whereas the 95% confidence interval ranged from 254 to 403 Mg C ha^{-1} which was found to be reasonable. The main uncertainty was caused by uncertainty over the soil organic matter dynamics and the carbon content of dry matter. The present study for all 16 forest types would probably give a comparable span in results, because for all forest types the main input was based on widely accepted growth and yield tables. On the one hand the use of growth and yield tables may have underestimated the carbon sequestration potential because these tables are known to be based on rather old monitoring data, that do not represent current (better) site conditions anymore (Spiecker et al., 1996). On the other hand, yield tables represent fully stocked forests which do not occur very often in practice.

Still, the results of the present study are not conclusive. Reduced use of fossil fuels because of the use of wood products instead of more energy demanding materials, was not taken into account here. This aspect of forest-wood products chains can especially become important in the long-term. In contrast to CO2FIX, this aspect is mainly captured in the GORCAM model which puts emphasis on these technological sides of forestry and wood processing (Marland and Schlamadinger, 1997).

Furthermore, the present study does not capture the continuation of a baseline land-use activity as it might have occurred if the afforestation had not been carried out. This aspect can be very important as well to determine the net greenhouse forcing (taking into account the global warming potential of N_2O and CH_4) of the forestry project. These aspects and side effects of large land-use change projects aimed at carbon sequestration must all be taken into account when decisions are taken over either reducing emissions or sequestering carbon in the biosphere in order to achieve the Kyoto targets. The pure quantitative matters as presented here, are then only part of the discussion.

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