European forests: when green sponges make hard wood

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European forests (*1, 2*) are intensively exploited for wood products and yet, they currently sequester carbon at a rate equivalent to roughly 10% of the fossil fuel CO_2 emissions (*3*). To gain insights into the recent history and the underlying causes of the European forest carbon sink, we analyzed data from 16 extensive national forest inventories and timber harvest statistics. Here we show that the standing stocks of carbon in biomass and Net Primary Productivity tailed out linearly between 1950 and today. Despite these growing carbon stocks, the harvest removals of carbon have remained roughly constant, which led to an accumulation of carbon into forests. The causes for the observed two-fold increase in Net Primary Productivity and biomass stocks since 1950 include the relatively young age of forests that are still in a growing phase, forest expansion, nitrogen deposition from the atmosphere, and the effects of rising CO_2 and changing climate. From biogeochemical model results, we estimated that climate and nitrogen can explain up to 80% of the increased NPP, but only 20 to 50% of the increased stock and therefore of the carbon sink. This illustrates the essential role of management in sustaining a large carbon sink in European forests, today and in the near future.

Forests (*1, 2*) supply energy, food and grazing opportunities and have, therefore, been intensively exploited throughout the history of Europe. Until the mid of the 20th century, most European forests were heavily depleted of carbon both in the soil and in the aboveground biomass due to harvesting and litter raking (*4, 5*). Since then, management moved towards multipurpose systems that seek after an optimal wood production in combination with soil and water protection, recreation and conservation. Improved silvicultural practices accompanied by an enhanced fertility resulted in a sharp growth across Europe (*6*).

Forest inventories are a precious source of information to quantify and understand the distribution of terrestrial carbon sinks (*5-8*), the regional processes of the carbon cycle (*9*) and the forest expansion (*10*). We analyzed national forest inventory data and timber harvest statistics from the EU-15 countries excluding Luxembourg, plus Norway and Switzerland, over the period 1950-2000. Data on growing stock, increment, harvest, species composition and forest area were collected through national inventories (Table S1). In their most basic form, inventory surveys measure stand density and tree dimensions (diameter, height) at consecutive dates. These measurements were used to calculate whole tree biomass increments by means of species specific allometric relationships (*7*), Subsequently, tree biomass increments and appropriate turnover rates for leaves and fine roots are used to estimate the litterfall and the Net Primary Productivity (NPP). Finally, NPP can be use to calculate carbon pool changes and the net carbon balance of forests (*3, 8*). We used statistics in which national level averages per species group are provided for growing stock, increment, harvest, and forest area. These data are based on national forest inventories usually carried out through a sample based inventory. Many countries have improved their inventory over these decades, thus causing methodological differences, but with over 400.000 sample plots these data are still the most reliable source of forest information available for these past decades.

During the last 50 years, Europe has on average multiplied the biomass carbon stocks per hectare of forest by 1.75 and NPP by 1.67 (Figure 1). In total, the carbon sequestered in the biomass pools since 1950 sums up to 2.3 PgC, or 10% of the cumulated EU-15 fossil fuel emissions between 1950 and 2007. Not only was there an increase, but everywhere the standing biomass carbon stocks have increased *linearly* with NPP ($R^2_{\text{stock-NPP}} = 0.99$; Figure 1). The linear regression temporal slope of stocks vs. NPP varies by 'only' 40% between countries (Table S2), hence being relatively robust to differences of regional climate, soil conditions, initial stocks and NPP values, and forest management history. The linear relationship between standing biomass carbon stocks and NPP holds for conifers and broadleaved forests (Figure 1A and 1B).

Both total NPP and woody NPP, the latter including stem, branches and coarse woody roots production are shown to increase with increasing standing biomass (Figure 1A and 1B). The difference between total NPP and woody NPP is the production of foliage and fine roots. When derived from allometric relationship the estimation of 'short-lived NPP' is uncertain, because it is then calculated with fixed mortality rates (*13-16*) whereas large spatial variability has been reported (*17-20* and SI*)*. As an example, the short-lived NPP fraction of the total NPP equals 0.35 in the harmonized inventory data, compared to values of 0.50 for conifers and 0.45 for broadleaved forests obtained from a new database of ecological site measurements (ref. *21* and SI). Nevertheless, the important point here is that fine root mortality, albeit being uncertain, has unlikely changed so much over study period that it would affect the close linear relationships found between NPP and stocks (Figure 1).

The build-up of biomass stocks results from NPP constantly exceeding carbon losses by natural disturbances (fire, wind throw), mortality of leaves and roots and -last but not least- timber harvest. Harvest represents today a fraction of 50% of woody NPP for conifers and 34% for broadleaved forests (see Figure 1B and C). In the 1950s, the harvested fraction of woody NPP was 1.5 times higher than today and smoothly decreased since then, indicating a reduced pressure in exploiting forests timber resources. In other words, harvest has increased with growing stocks but *proportionally less* than woody NPP (Figure 1).

The sustained accumulation of carbon in trees results from: 1) harvesting less than the increment for decades because of not adapting harvesting rate to increasing productivity, 2) the juvenile age structure of the European forests, most of which are old coppices (broadleaves in Southern Europe) or post-war plantations (conifers in Central and Northern Europe) that still show increasing increment growth rates, 3) area expansion associated with new conifer plantations in the 1970s and 1980s, 4) the increased fertility of forest soils owing to a reduction of nutrient export by practices like grazing and litter raking, 5) the combined effects of reductions of sulfur emissions and sustained high atmospheric nitrogen deposition, and 6) the favorable effects of increasing atmospheric CO_2 concentration and possibly of regional climate trends. The combined effect of factors 3 to 6 have increased NPP and potential harvest above the expectations of 'optimal' harvest strategies established more than a hundred years ago (*22*). All these processes strongly interact with each other and cannot be disentangled easily. Further, there are large uncertainties on the magnitude of the CO_2 fertilization and nitrogen deposition effects.

Changes in area alone, with a 5% increase for conifer forests and an 8% increase for broadleaved since 1950, cannot explain the observed nearly doubling of NPP and stocks. This is illustrated in Figure 2 where, the slope of biomass stocks vs. NPP changes for each successive decades since 1950 exhibits no significant correlation with coincident changes in area. For instance, the strong increase in both stock and NPP during the period 1970-1990 for conifer forests is not related to any significant increase in area (Figure 2).

The effects on forest NPP of climate trends since 1950 with a drying trend near the Mediterranean and wetter conditions in Northern Europe (*23*), rising CO_2, and high nitrogen deposition, were estimated using a state-of-the-art biogeochemical model called ORCHIDEE (*9*). The model describes the turbulent surface fluxes of CO_2, water and energy, and the dynamics of carbon pools, including phenology, allocation, growth, natural mortality and soil organic matter decomposition (see SI). Only natural mortality is simulated in ORCHIDEE, hence the model does not account for management and logging. The model was integrated at the scale of the European continent on a 50 by 50 km grid between 1901 to 2000 with a constant forest area (*10*) driven by transient climate (*11*) and CO_2. Tree natural mortality was arbitrarily tuned to reproduce exactly the observed initial standing biomass stock in each country by 1950. The simulations assign 70 to 85% of the observed increase in NPP to changes in climate and atmospheric CO_2 concentrations, for conifers and broadleaves, respectively. These simulation runs assumed no nitrogen limitation.

The role of nitrogen deposition in increasing NPP and subsequent carbon sequestration is still the object of debate. Magnani et al. (*27*) concluded that the net carbon sink in European forests was 'overwhelmingly driven by nitrogen deposition'. But the plausibility of this result was recently questioned by de Vries et al. (*28*), who estimated that the N-induced increase in the European carbon sink could be no more than 10%. We used ORCHIDEE to perform two simulations for 12 European temperate and boreal forest sites: one with only CO_2 + climate change and pre-industrial nitrogen deposition and one with observed nitrogen deposition + CO_2 + climate change. The result is that the average increase of NPP due to nitrogen deposition alone is ~20%, so still leaving about ~80% to CO_2 and climate. The higher the nitrogen inputs, the stronger its effect on the total increase in NPP. Hence, owing to the spatial distribution of N-deposition, N-deposition contributed more to the increase in NPP in Central Europe, and was nearly a negligible factor in boreal Europe with total N-inputs below 10 kgN ha^{-1} yr^{-1}. Altogether, the results from these model experiments suggest that climate and CO_2, aided to some extent by nitrogen deposition, can likely explain most of the observed increase in NPP since 1950 (Figure 1A).

Interestingly, even with a realistic simulated NPP increase between 1950 and today, the ORCHIDEE model which has no management description, fails to account for the large increase in biomass stocks, *i.e.* for the observed carbon sink (Figure 1A). From this incapacity of rising NPP to account for the carbon sink in the model, one can deduce that the decreasing harvest pressure since 1950, and changes in age structure, must be a main cause for this sink. These results agree with another recent model study that includes a representation of forest age-classes, forest management and land use changes (*29*). For an almost similar spatial domain as covered here, this study reports that at the continental scale forest NPP increases were mainly due to climate change and CO_2. However, at the site scale changes in NPP were largely driven by changes in forest area and age structure (*29*). Simulated increases in forest carbon stocks that agreed well with inventory estimates were for ~50% related to age structure and management.

Methodological differences between inventories over time (*12*) may produce some spurious carbon stock changes, but these effects are likely to remain limited, since all the data were harmonized to follow common international definition (*31*). In addition, uncertainties in allometric relationships, and uncertainties in fine root and needles tunover rates further increase the uncertainty of woody NPP and NPP estimated from diameter increment measurements, as illustrated above. Despite these limitations, the basic data from countries who consistently used the same methodology between their last and previous inventory all confirm significant increases in tree biomass increment (*8*). In Germany for example, a net annual stem wood volume increment of 12.1 m^3 ha^{-1} y^{-1} was measured for 2001-2002, while in the previous inventory it was 9 m^3 ha^{-1} y^{-1} for 1986-1992 (*13*). In Finland, no major changes in forest area were observed but the total annual stem wood volume increment was 86.7 million m^3 for 1996-2003, while in the previous inventory it was only 77.7 million m^3 for 1986-1994. Thus real increases of biomass increment have occurred and are still occurring. Moreover, the faster growth of European forests detected by inventories is corroborated by numerous dendrochronology studies and repeated measurements on long-term permanent sample plots (*32-36*).

In order to evaluate the sustainability of the observed sink, we compiled biomass carbon stocks from about a hundred old stands in Europe (see methods). We then compared these estimates of potential, maximum, stock under present-day climate conditions (Figure 3), with future projections of the European carbon stocks (*14*). Given that the harvested fraction is further reduced, European forests still have the potential to realize a buildup of stocks by a factor of two, within the next century (Figure 3). Altogether these results suggest that European forests are playing a key role in sinking CO_2 and that this capacity could be maintained in the future over several decades, in accordance with the "buying time" strategy adopted for biogenic sinks.

Under the Kyoto Protocol, only a small fixed amount carbon, typically 15% or less of the carbon sink of European forests, can be accounted for as carbon credit (FCCC/KP/CMP/2005/8/Add.3, 2006 and ref. *38*). However, the potential CO_2 sink is threatened by the proposal of the European Commission to increase the share of renewables to 20% of the total energy consumption by 2020 (*39*). This will almost double the wood demand for bioenergy in EU-15 (*40*) from 55% of harvested wood in 2001 to 100% in 2020 at current harvest trends, or may increase harvest above the levels of 1950 and shorten forest rotation length. In addition, drought, wind thrown, pathogen attacks (*15*) and reduced productivity due to climate change and extreme events (*16*), may totally offset the carbon gains achieved with decades of carbon saving management practices.

Acknowledgements

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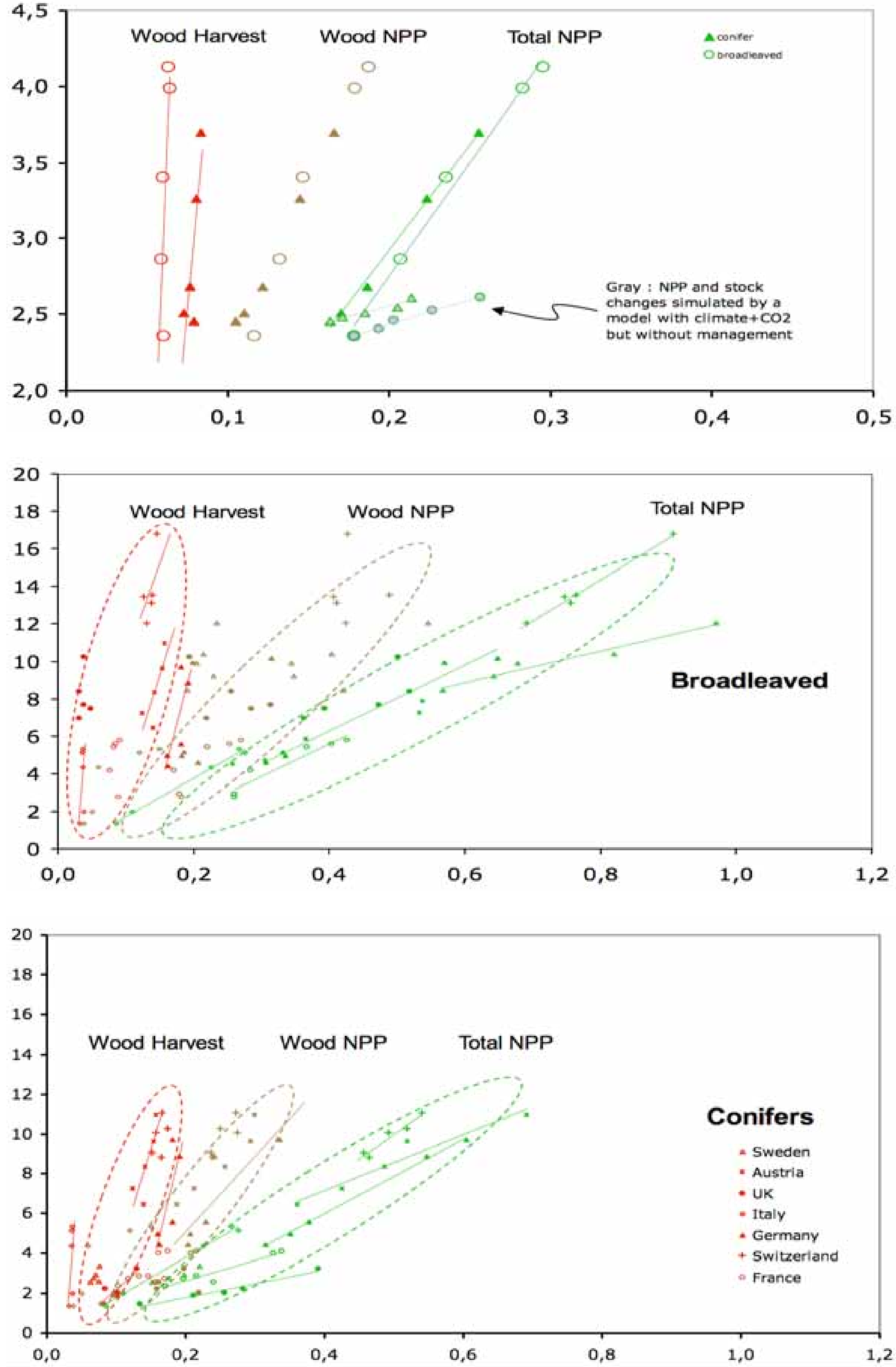
Figure caption

Figure 1. (A) Whole tree carbon stocks for deciduous broadleaved species as a function of total NPP and woody NPP inputs and harvest removals. Data from sample-based inventories for 10-years intervals since 1960 and averaged for the EU-15 plus Norway and Switzerland. The difference between harvest removals and woody NPP gains at a given stock value is the net carbon sink in trees. Remarkable is the linear evolution of stocks vs. NPP showing a positive temporal slope between countries (1-sigma slope difference of 40% between countries), and the small harvest increments compared to the woody NPP increments indicating that harvesting remains well below the biomass annual increment. In gray are the NPP and biomass changes produced by a biogeochemical model forced with increasing CO_2 and changing climate from 1950 until today at a 50 km spatial resolution (see text). (B) Tree biomass vs. NPP, woody NPP and harvest for conifer forests in selected countries with typical Mediterranean, temperate and boreal forests. (C) Same for broadleaved forests. The ellipses have been drawn by hand to guide the eyes.

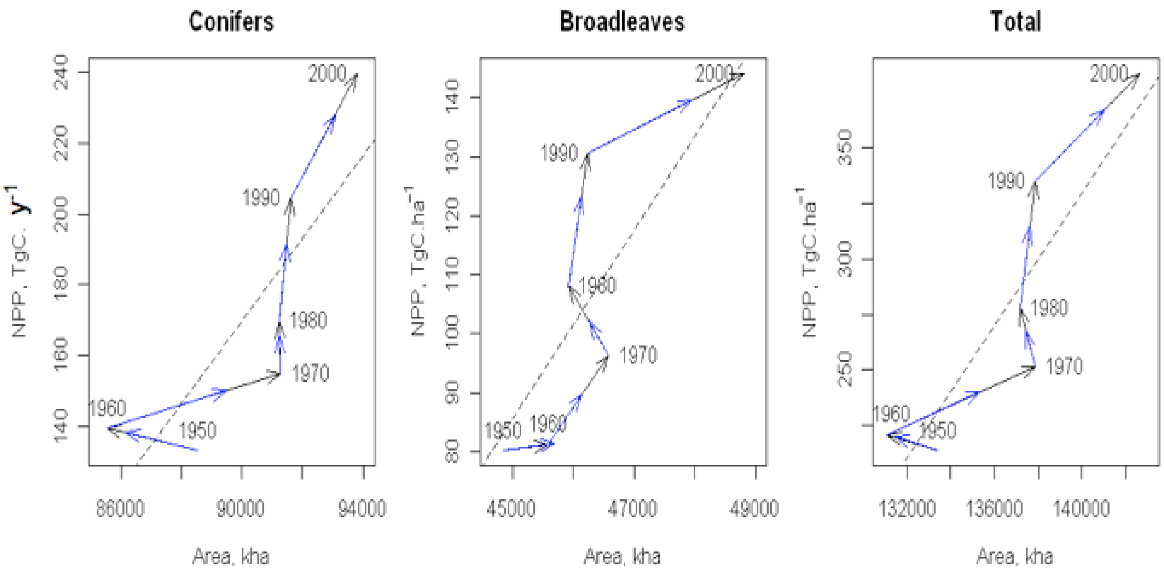
Figure 2. Evolution of NPP as a function of forest area changes from national data averaged over for EU-15 plus Norway and Switzerland. The blue arrows represent the fraction of NPP change that can be attributed to the changes in wood-NPP. The dynamics of the tree carbon stock or NPP show the two active phases of reforestation and afforestation in Europe, namely the post-war period (1960s) concerning the coniferous species particularly, and the last decade (1990's) in which the effort was put on broadleaves probably as a result of the biodiversity concerns and conservation policies. In contrast, the strong increase in both stock and NPP during the period 1970-1990 is not related to any significant change in wooded area.

Figure 3. Observed increase of tree biomass carbon stocks in 16 western European countries since 1950, and future predictions. The lower dash curve is a prediction based upon a forestry model which accounts for forest aging under a moderate harvest scenario IPCC SRES-A2, but without any effects on NPP of rising CO_2, climate change, and nitrogen deposition (*14*). The upper dash-dotted curve is a quadratic curve fitted to the 1950-2000 data and boldly extrapolated to the future. The grey horizontal lines mark the expected maximum biomass value, from a compilation of old forest data. The error bar to the right indicates the uncertainty on this estimate (see Supplementary Information)



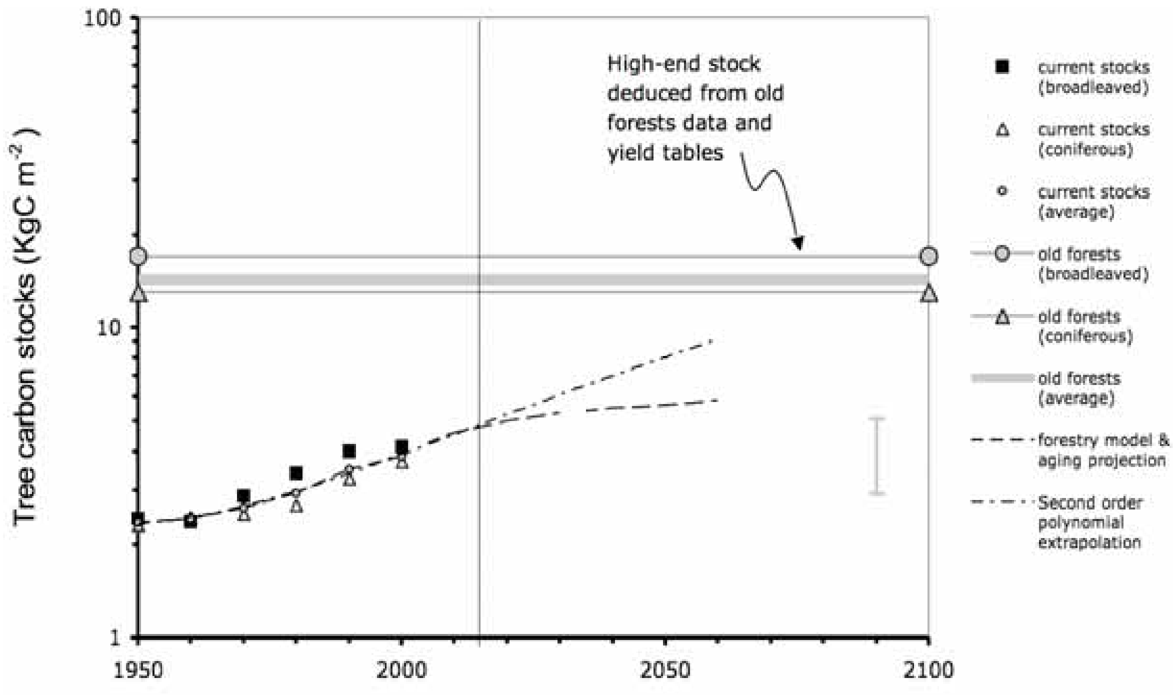
Wood Harvest
Wood NPP
Total NPP
conifer
broadleaved
Gray : NPP and stock changes simulated by a model with climate+CO2 but without management
Broadleaved
Conifers
Sweden
Austria
UK
Italy
Germany
Switzerland
France

Fig2



Conifers
Broadleaves
Total
NPP, TgC. y^-1
NPP, TgC.ha^-1
NPP, TgC.ha^-1
Area, kha
Area, kha
Area, kha
1950
1960
1970
1980
1990
2000

Fig 3



100
10
1
Tree carbon stocks (KgC m^{-2})
1950
2000
2050
2100
High-end stock deduced from old forests data and yield tables
current stocks (broadleaved)
current stocks (coniferous)
current stocks (average)
old forests (broadleaved)
old forests (coniferous)
old forests (average)
forestry model & aging projection
Second order polynomial extrapolation

Supplementary Information

Old forests biomass carbon stocks per hectare of forest

Estimates of old forest carbon biomass per unit area of forest for main western European tree species are summarized in Table S1. The species selected cover more than 70% of European forests. These estimates were obtained by compiling data from individual site measurements or from yield tables. These forests are not truly 'old-growth' pristine stands that have never been managed for centuries, but rather old forests, some of them managed and others not managed since at least two centuries or so. Thus, their biomass is high (range 9.5 to 23.5 KgC m^{-2} in Table S1) but not quite as high as the one measured in pristine old-growth forests e.g. in Russia or in the Pacific North West (range 20 to 30 KgC m^{-2} after Lluyssaert et al. Manuscript Submitted)

Data from stand measurements include managed and unmanaged old stands (see references below). In total, 113 broadleaved and 20 coniferous old stands were included in the analysis. Data from yield tables data come from a European compilation (*17*). Typically, a forest yield table gives information on timber wood volumes as a function of stand age for different site classes and/or management regimes and for a given location. For each table, the volumes at maximum age per site classes and management regimes are extracted and averaged. Timber and small wood volumes per hectares are converted to total tree carbon biomass using a wood density of 400 kgDM m^{-3}, a carbon content of 50 %, a root-shoot ratio of 0.2 and a branches proportion of aboveground biomass of 0.3 for deciduous and 0.15 for coniferous. The values reported in Table S1 are the average of the yield tables.

The two methods we used to estimate old forest biomass suffer from approximations in particular the conversion from volume to carbon biomass, and the spatial representativeness of the data. However, both methods are independent and the fact that their results are comparable within 10% suggests that our estimate of old forest biomass by species is quite robust.

An average biomass value for deciduous and coniferous old forests is calculated by weighting the species biomass density values – stand measurements estimations – by their spatial coverage over Europe (Table S1). Mean carbon biomass estimates obtained for deciduous and coniferous trees are 17 ± 1.4 kgC m^{-2} and 13 ± 1 kgC m^{-2}, respectively. This translates into a European mean of 14.4 ± 1.1 kgC m^{-2} when weighting by the species spatial coverage, as shown in Figure 3.

Species	S	Stand measurements				Yield tables			
	%	*n*	*B*	*stdB*	*Ref*	*n*	*B*	*stdB*	*Ref*
Beech (*Fagus sylvatica*)	7.1	103	19.7	5.7	*(a)*	10	21.1	8.2	*(e)*
Oak (*Quercus robur/petraea)*	5.5	10	23.5	8.2	*(b)*	17	15.4	4.8	*(f)*
Birch (*Betula spp)*	4.7					4	9.5	2.1	*(g)*
Pines (*Pinus sylvestris/pinaster*)	33.5	7	10.1	1.9	*(c)*	10	11.3	4.2	*(h)*
Spruce (*Picea abies*)	21	13	15.7	3.8	*(d)*	6	19.3	6.2	*(i)*

Table S1. Old forest, maximum, standing biomass stocks per hectare of forest (*B*, kgC m^{-2}) and standard deviation (*stdB*, kgC m^{-2}) obtained from stand measurements (e.g. old forests in national reserves) and from yield table compilations in different regions of Europe. *n* gives the number of sites or yield tables and S the percentage of the respective species in the EU-30 forest area. Data references and countries of origin are reported below.

(a) Stand data from Austria, Belgium, Czech Republic, Danemark, France, Germany, Hungary, Netherlands, Poland, Slovakia, Switzerland and Bulgaria *in* Christensen *et al.* (*18*) (compilation), Huet *et al.* (*19*) (compilation), Piovesan *et al.* (*20*) (compilation), Scarascia-Mugnozza *et al.* (*21*), Korpel (*22*) and le Maire pers. comm.

(b) Stand data from France and Germany Korpel (*22*), le Maire pers. comm.

(c) Stand data from France, Germany and Switzerland Scarascia-Mugnozza *et al.* (*21*), le Maire pers. comm.

(d) Stand data from France, Germany and Romania*:* Schulze *et al.* (*23*), Scarascia-Mugnozza *et al.* (*21*), Mund *et al*(*24*)*,* Korpel (*22*), Bouriaud pers. comm.

(e) Yield tables from CH Badoux (*25*)*, DK* Oppermann (*26*)*, GB* Hamilton (*27*)*, CZ* Cerny (*28*),*D* Schober (*29*)*, I* Bianchi (*30*)*,* Gualdi (*31*)*, NL* Jansen (*32*), *S* Carbonnier (*33*)

(f) F Bisch (*34*)*, H* Beky (*35*)*,* Kiss (*36*)*, S* Carbonnier (*37*)*, B* Dagnelie (*38*),*GB* Hamilton (*27*)*, BG* Stanov (*39*)*, HR* Klepac (*40*)*,* Spiranec (*41*)*, CZ* Cerny (*28*), Korsun (*42*),*DK* Svejgard (*43*),*NL* Jansen (*32*)*, PL* Pirogowicz (*44*).

(g) FIN Koivisto (*45*),*D* Schober (*29*), *NL* Jansen (*32*)*, N* Braastad (*46*).

(h) F Décourt (*47*), Lemoine (*48*), *P* Duarte (*49*), *A* Marschall (*50*), *S* Andersson (*51*), *BG* Krastanov (*52*), *FIN* Koivisto (*45*), *D* Wiedemann (*53*), *NL* Jansen (*32*).

(i) A Marschall (*50*), *CZ* Cerny (*28*), *I* Patrone (*54*), *S* Eriksson (*55*), *D* Assmann (*56*), Wiedemann (*53*).

Uncertainties in fine root mortality impacting NPP

Fine root mortality varies between species and across environmental conditions (ref *17-19* in the main text), but this variability is not known enough to be readily accounted for in NPP calculations, which in turn causes a systematic error in the result of total NPP. Including spatial variations in fine root production in the computation would require untested hypothesis for a un-ascertained gain. However, it is worth noting that:

1) The uncertainty of ±0.06 y^{-1} for the fine root mortality, around a mean of of 0.86 y^{-1} in the inventory data (ref *12* in main text) that is used to propagate errors on total NPP, is likely to be too optimistic, compared to the range of fine root turnover values from 0.4 to 2 y^{-1} found in global databases (refs *17-19* in the main text).

2) The mean mean value of 0.86 y^{-1} (ref *12* in main text) yields to a significantly lower fraction of foliage + fine root NPP than the one derived from the new database of ecological site measurements compiled by Luyssaert *et al.*, where all the components of NPP are individually assessed (ref. *21* in main text). In the inventory data, the ratio of foliage + fine root NPP to total NPP is 0.35 only, whereas in the ecological site database, this ratio is 0.5 (95% confidence interval 0.15-0.86) for conifer forests and 0.45 (95% confidence interval 0.15-0.85) for broadleaved forests. The latter uncertainties are from 1000 Monte Carlo simulations using the uncertainty framework of NPP in Luyssaert *et al.*. These data suggest that the fine root turnover rate value used in the inventory data is maybe too fast.

Trends litterfall to NPP ratios

The data reported in Figure 1 clearly show that in Europe, thanks to the increasing fertility and to the application of a an unintended "carbon saving" silviculture through reduced harvest intensity, the fraction of primary productivity that remain sequestered in the forest biomass has substantially increased over time during the past 50 years. These trends are rising concerns about the sustainability of the European forest sinks and the vulnerability of the resulting high carbon stocks. These concerns arise because as forests get older and stock increases, the increasing litterfall and mortality (L) tail off with NPP, and consequently the ratio of heterotrophic respiration over NPP might increase and the sink might be reduced accordingly. To check if this 'saturation' effect is already occurring in European forests, we calculated leaves, fine roots and woody litter for the last 50 years.

The biomass increment is given by the differences between NPP and litter fall (L), including leaves, fine roots and woody litter. L accounts for the carbon respired in the forest and, under the hypothesis of equilibrium in the soil carbon pools, is equal to the heterotrophic respiration. Litter has been deduced from inventory data as:

L = NPP – Net Carbon Accumulation – Harvest

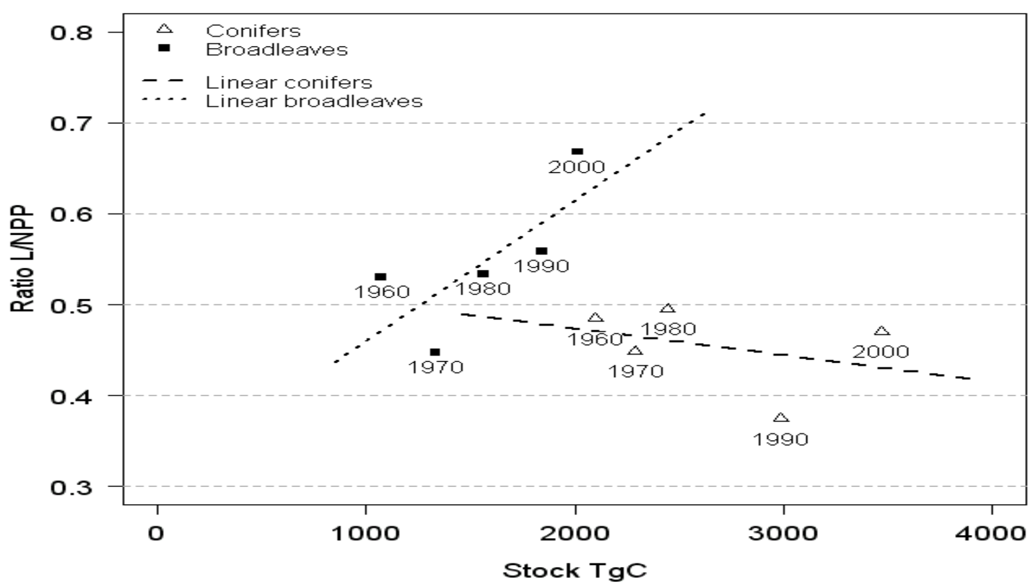


Fig S2. Relationship between the ratio of litter fall (L) losses to NPP gains as a function of increasing tree biomass stocks averaged over the 16 European countries. Each point corresponds to the average value for one decade since 1950.

The figure S2 shows that 40% of conifer NPP and 70 % of broadleaved NPP is currently respired in the forest. Interestingly this fraction is higher for the broadleaves than for the conifer, because only roughly 20% of the needle biomass turns over in evergreen conifers. In addition, L/NPP has increased with increasing biomass since 1950 for broadleaves, as it should be according to classical ecology for a population of aging forests, while no trend is evident for the conifers. This phenomenon may be due to the age structure of the coniferous forests in Europe, most of which are post-War plantations still in a juvenile phase with low L and high NPP. The increase of L/NPP in broadleaved may also be due to the under harvesting of old coppice stands, which leads to an increase of woody litter.

The ratio L/NPP has climbed to a value of 0.7 for the aging broadleaved forests, but has remained remarkably constant for conifer forests, possibly due to the relative young age of European conifer forests. Therefore, for coniferous forests, silvicultural practices seem to have been able to induce a substantial increase in NPP and biomass carbon stock, while maintaining constant the fraction of NPP lost through litter. This result awaits to be further evaluated against site-level litterfall measurements, like those of the ICP Forests network (http://www.icp-forests.org/).

Differences in the temporal slope of biomass carbon stock change of NPP change

Spatial (i.e. between countries) differences in the temporal slope of stock changes (ΔC in TgC) vs. NPP changes (ΔNPP in KgC y^{-1}) have been calculated by two different methods, and the area-weighted average of conifer and broafleaved NPP and stocks. The first method takes the value of ΔC/ΔNPP for each successive decade and then the average of these decadal slopes. The second method takes the linear regression slope of the data during 1950-2000. The results shown in Table S2 below indicate that there are significant differences between countries, with the highest increase of stock relative to NPP being in Switzerland and the lowest in Ireland and Denmark. However, despite significant changes between one decade and the next, the ΔC/ΔNPP slope estimated by both methods is similar. There are some differences in the slopes between broadleaved and conifers in each country, but these differences have no spatial coherence. The standard deviation between countries is on the order of 50% around the mean.

Average of decadal slopes	Average Slope 1950-2000	country
0,09	0,13	Austria
0,24	0,13	Belgium
0,08	0,07	Denmark
0,11	0,11	Finland
0,07	0,15	France
0,10	0,17	Germany
0,12	0,11	Greece
0,06	0,07	Ireland
0,17	0,24	Italy
0,21	0,14	Netherlands
0,16	0,16	Norway
0,14	0,15	Portugal
0,12	0,08	Spain
0,11	0,13	Sweden
0,06	0,21	Switzerland
0,08	0,09	UK
0,12	**0,13**	**mean**
0,05	**0,05**	**std**

Table S2. Temporal slopes of tree biomass stocks vs. NPP changes across the 16 European countries analyzed. Two methods (see text) give same mean and between-countries standard deviation values

Attribution of the effects of climate nitrogen deposition and CO2 on NPP trends and carbon sink in biomass

The dynamic global vegetation model ORCHIDEE ("ORganizing Carbon and Hydrology In Dynamic Ecosystems") described in ref (*9*) was used to separate the contribution of climate trends and variability and the one of rising CO_2 to the increase in European forest NPP and carbon stocks. The ORCHIDEE model describes the turbulent surface fluxes of CO_2, water and energy (transpiration, photosynthesis, respiration), the dynamics of water and carbon pools (soil moisture budget and allocation, growth, mortality, soil carbon decomposition) and longer-term ecosystem dynamics (fire, sapling establishment, light competition). After running the ORCHIDEE model until the carbon pools reach equilibrium based on transient climate (by repeating the 1901-1910 climate of *Mitchell et al.*, (*11*) under constant pre-industrial atmospheric CO_2 of 286.05 ppm), a simulation was made from 1860 to 1900 with the variable climate of the period of 1901-1910 and CO_2 concentration data during 1860-1900. The model was then run from 1901 to 2000, with a constant land cover corresponding to 2000 (*10*) with transient climate forcing (*11*) and historical atmospheric CO_2 concentration data. The biomass mortality parameter was adjusted in such a way that the simulated biomass stocks in 1950 are equal within each country (and separately for broadleaved and conifers) to the forest inventory biomass stocks. This tuning avoids obtaining an unrealistically high 'climax' biomass stock in quasi-equilibrium with climate, which would artificially increase the residence time of an excess carbon (driven by increasing NPP) into the ecosystem, and hence would overestimate the pertaining net carbon sink

Zaehle et al. (*57, 58*) have developed parameterisations of key nitrogen cycle feedbacks on the terrestrial carbon and water cycles have been developed for use in ORCHIDEE. The new approach is built on novel representations of canopy processes (*59*) and plant nitrogen dynamics at a level of detail adequate for global modelling studies (Zaehle, pers. comm.), and explicitly represents organic (*60*) and inorganic (*61*) soil nitrogen turnover to enable calculation of nitrogen losses to leaching and emissions. Simulations were performed for twelve forest sites in Europe, for which site characteristics, including present-day nitrogen deposition, were applied as described in REF6. Pre-industrial nitrogen deposition rates were taken from REF7. The simulation protocol corresponded to that mentioned above, using climatic parameters derived from the nearest grid point of *Mitchell et al.*, (ref *11*) for each site.

Summary table with national European forest inventories characteristics

The TBFRA-2000 report (*1*) describes the national forest inventory systems to some extent. More detailed descriptions on each inventory set-up, and on the harmonisation of these data can be found in ref (*12*) and in the Table

	Forest characteristics				Forest inventory characteristics				References
	Area (1000 ha)	Growing stock (1000 m3)	Type of oforest included in inventory	Increment (1000m3)	Permanent sample plots (n)	Temporary sample plots (n)	Yrs to complete a inventory cycle	Sampling design	
Austria	3924	1107307	total forest	29733	22230		3	one stage	Schieler, K and E Hauk. 2001. Instruktion fur die Feldarbeit Oetsrreichishce Waldinventur 200/2002. Forstliche Bundesversuchsanstalt Wien. 209 p.
Belgium	672	141033	productive forest	5176	10600		10	one stage	Ministerie van de Vlaamse Gemeenschap. 2001. De bosinventarisatie van het Vlaamse Gewest. Resultaten van de eerste inventarisatie 1997-1999. Afdeling I en Groen. Brussel. 486 p.
Denmark	538	60200	forest land	3770	400	200	5	one stage	Miljoministeriet Skov- og Naturstyrelsen. 1994. Skove of plantager 1990. Denm Statistics. Copenhagen. 131 p.
Finland	22768	1963000	productive and poorly productive orest	75974	15566	51181	5	one stage, stratified	METLA, 2005. Finnish Statistical yearbook of Forestry. METLA, Helsinki. 424 p.
France	16989	2977048	forests and forest land	102215		35000	5	two phase	Departement de… Results of third inventory.
Germany	10740	2880000	forests	102736		80000	2	two stage, stratified	Bundesministerium fur Verbraucherschutz, Ernahrung und Landwirtschaft. 2006 Die zweite Bundeswaldinventur, das Wichtigste in Kurze. 87 p.
Greece	6513	154544	forests and forest land *	4193		2744	n/r	two phase, stratified	Ministry Agriculture. General Secretariat of Forest. 1991. First National Forest Inventory. Athens.
Ireland	591	44000	all forests regardless of ownership.	3500		0	2	one stage	Forest Service. 2007 National Forest Inventory - Republic of Ireland - Methodol Covering the 2004-2006 inventory. Dublin . 124 p.
Italy	10842	1518592	natural, semi natural and plnated forest	32526		7000	4	one stage, 3 phase, stratified	MAF-ISAFA. 1988. Inventario Forestale Nazionale 1985. Sintesi metodologica e risultati. Rappresentazioni cartografiche
Netherlands	339	64709	forest according to area stats	3158	3000		4	one stage	Ministry Agriculture, Nature Management and Food Quality. 2006. Meetnet functievervulling bos 2001-2005. Vijfde nederlandse Bosstatistiek Directie Kenn DK065. Ede, 95 p.
Norway	12000	817288	productive forest land	27370	10500		5	one stage	Larson J.Y and G Hylen. 2007. Statistics of Forest Conditions and Forest Resources in Norway 2000-2004. Viten fra Skog og landskap 1/07. As, Norway p.
Portugal	3467	292006	forest	15926		2336	2	two phase	Direccao Geral das Florestas. 2001. Inventario Florestal Nacional Portugal Continental. 3a revisao, 1995-1998. lisbon. 233p.
Spain	25984	594408	closed, open and very open forest	30135	50000		11	one stage, stratified	Ministerio de medio Ambiente. 1998. Segundo inventario forestal nacional 1986 1996. Madrid. 337 p + maps
Sweden	30259	2993640	total forest	103415	4453	3353	5	one stage, stratified	Kempe, G., P Nilsson and H Toet. 2007. Forestry statistics 2007. Swedish Univ Agricultural Sciences. Umea. 102 p.
Switzerland	1234	422453	normal forest without shrub	10107	6000		3	two phase	Brassel, P. and U-B Brandli (eds). 1999. Schweizerisches Landesforstinventar. Ergebnisse der Zweitaufnahme. Bern. Bundesamt fur umwelt, Wald und Landschaft. 442 p.
Uk	2489	353000		15390		40000	5	two stage	Forestry Commission. 2005. National Inventory of Woodlands. Manual. 82 p.
Total	149349	16383228		565324	122749	101814			
source	TBFRA-2000, p. 62	TBFRA-2000, p.181		TBFRA-2000,p.189					

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