Carbon accumulation in European forests

European forests are intensively exploited for wood products, yet they also form a sink for carbon. European forest inventories, available for the past 50 years, can be combined with timber harvest statistics to assess changes in this carbon sink. Analysis of these data sets between 1950 and 2000 from the EU-15 countries excluding Luxembourg, plus Norway and Switzerland, reveals that there is a tight relationship between increases in forest biomass and forest ecosystem productivity but timber harvests grew more slowly. Encouragingly, the environmental conditions in combination with the type of silviculture that has been developed over the past 50 years can efficiently sequester carbon on timescales of decades, while maintaining forests that meet the demand for wood. However, a return to using wood as biofuel and hence shorter rotations in forestry could cancel out the benefits of carbon storage over the past five decades.

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Forests[1,2] supply energy, food and grazing opportunities and have therefore been intensively exploited throughout the history of Europe. Until the mid twentieth century, most European forests were heavily depleted of carbon both in the soil and in the aboveground biomass owing to harvesting and litter raking[3–5]. Since then, management has moved towards multipurpose systems that seek optimal wood production in combination with soil and water protection, recreation and conservation. Improved silvicultural practices accompanied by enhanced fertility have resulted in a sharp growth across Europe[6].

Forest inventories were established to assess the commercial value of timber long before carbon cycle research came up high on the agenda. Nowadays these inventories constitute 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 forest expansion[10]. We analysed national forest inventory data and timber harvest statistics from the EU-15 countries excluding Luxembourg, plus Norway and Switzerland, over the period of 1950–2000 (see also ref. 11). Data on growing stock, increment, harvest, species composition and forest area were collected through national inventories[12] (see Supplementary Information, Table S3). In their most basic form, inventories measure stand density and tree dimensions (diameter and height) at consecutive dates. These measurements are used to calculate whole tree biomass by means of allometric relationships. Subsequently, tree biomass increments and appropriate turnover rates for leaves and fine roots allow estimates of the litterfall and the net primary productivity[13] (NPP). Finally, using the NPP to derive litter production and a soil carbon model, the net carbon balance of forests can de deduced[3–8]. We used inventory 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, which are usually sample-based. Many countries have improved their inventory over the decades of our study, thus causing methodological differences, but with over 400,000 sample plots these data are still the most reliable source of forest information available for this time period.

BLOOMING GROWTH IS SINKING CARBON

During the last 50 years, Europe has, on average, multiplied the biomass carbon stocks per hectare of forest by 1.75 and the NPP by 1.67 (Fig. 1). Carbon that has accumulated in the trees (2.3 Pg C) represents 10% of the cumulated EU-15 fossil-fuel emissions between 1950 and 2007. Not only have these values increased, but everywhere, the standing biomass stocks have increased linearly with NPP ($R^2_{stock–NPP} = 0.99$; Fig. 1). In each country such a linear relationship between biomass and NPP was observed, but with regionally distinct values of the slope (Fig. 1b,c). The temporal slope of biomass stocks versus NPP differs by 'only' 38% among the 16 European countries (see Supplementary Information, Table S2). This slope hence appears to be relatively robust to regional differences in climate, soil conditions and forest management history. The striking linear evolution of NPP with stocks holds for conifers as well as for broadleaved forests (Fig. 1b,c).

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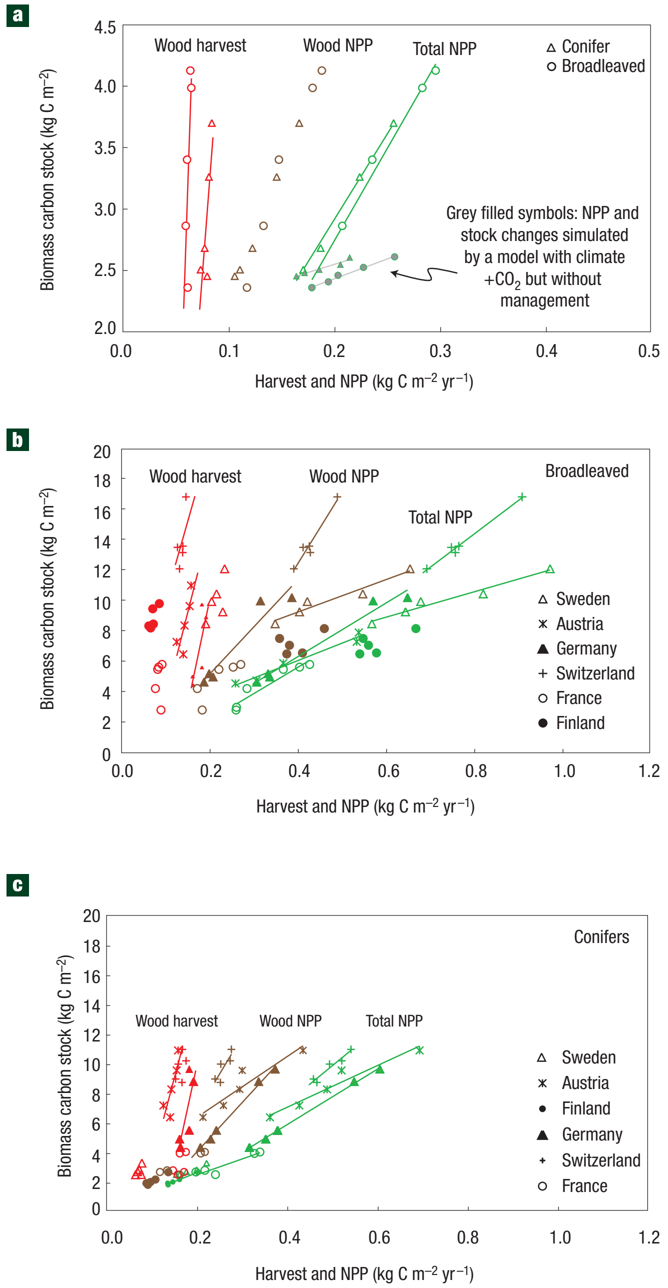

Figure 1 Whole tree standing carbon stocks as a function of total NPP (green), woody NPP (brown) and harvest removals (red). **a**, Data are the average of inventories at ≈10-year intervals for the EU-15, excluding Luxembourg, plus Norway and Switzerland. Note that total NPP is derived from more assumptions (fine roots and leaves) than woody NPP. At a given stock value, the difference between harvest losses and woody NPP gains is the net carbon sink in trees. The linear evolution of stocks versus NPP and the roughly constant harvest compared to woody NPP trend was remarkable, and indicates that harvesting remains well below the biomass annual increment. Grey-filled symbols show the NPP and biomass changes produced by a biogeochemical model forced with increasing CO_2 and changing climate (see text). **b**, Data are for broadleaved forests in selected countries. **c**, Data are for conifer forests in selected countries.

Woody NPP is directly derived from measured tree height and diameter, and corresponds to stems, branches and coarse roots. Woody NPP increased linearly with tree biomass everywhere in the relatively young[5] European forests (Fig. 1b,c). The derivation of total NPP from woody NPP rests on assumptions about foliage and fine root production. These assumptions are quite uncertain: the leaves and fine root productivity is not measured, but it is calculated using fixed mortality rates[13–16]. In reality, large spatial variability in these rates has been reported[17–20] (see Supplementary Information). As an example, the short-lived fraction of the total NPP was fixed to 0.35 in the harmonized inventory data, whereas values of 0.50 for conifers and 0.45 for broadleaved forests are given by a new database of ecological site measurements[21] (see Supplementary Information). Nevertheless, the important point here is that fine root mortality, despite being uncertain, has probably not changed enough over the study period to noticeably affect the tight linear relationship found between total NPP and stocks.

The build-up of biomass stocks in Europe thus appears to result from woody NPP exceeding losses by timber harvest and natural disturbances such as fire and wind throw. Harvest now represents a fraction of 50% of woody NPP for conifers and 34% for broadleaved forests. In the 1950s, the harvested fraction of woody NPP was 1.5 times higher than today, indicating a reduced pressure in exploiting forests timber resources. In other words, harvest did not catch up with the increasing trend of woody NPP (Fig. 1).

MAN OR NATURE?

The sustained accumulation of carbon in trees may result 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 sulphur emissions and sustained high atmospheric nitrogen deposition; and (6) the favourable 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. 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 Fig. 2 where the decadal increments of total and woody NPP shows no significant correlation with coincident changes in area between 1950–2000. For instance, there is a strong increase in both stock and NPP during the period 1970–1990 for conifer forests but no significant increase in area.

There are large uncertainties in the magnitude of the CO_2 fertilization and nitrogen deposition effects. The effects on NPP of climate, with a drying trend near the Mediterranean and wetter conditions in northern Europe[23], and the effects of rising CO_2 were estimated using a biogeochemical model called ORCHIDEE[24]. This model describes the turbulent surface fluxes of CO_2, water and energy, and the dynamics of carbon pools associated with phenology, allocation, growth, natural mortality and soil organic matter decomposition (see Supplementary Information). However, it does not account for forest management. The model was integrated at the scale of the European continent on a 50×50 km grid, with a constant forest area[25] driven by transient climate[26] and rising CO_2 between 1901 to 2000. The modelled (natural) mortality of trees was arbitrarily tuned to reproduce exactly the observed initial standing biomass stock in each country by 1950.

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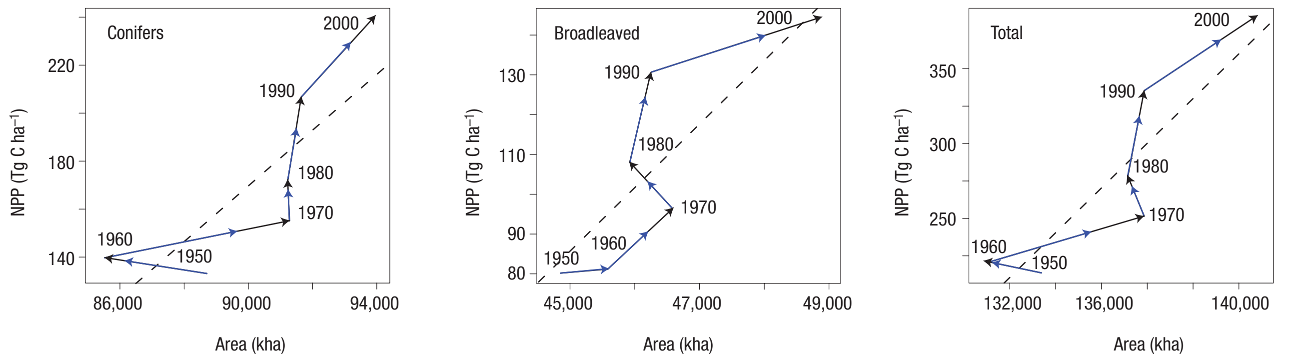

Figure 2 Evolution of NPP as a function of forest area from national data averaged over for the EU-15, excluding Luxembourg, plus Norway and Switzerland. The blue arrows represent the fraction of total NPP change that can be attributed to changes in woody NPP. The dynamics of NPP shows the two active phases of reforestation and afforestation in Europe, during the post-war period in the 1960s (chiefly coniferous species), and during the 1990s (effort was put on broadleaved species probably as a result of the biodiversity concerns and conservation policies). The mean increase in NPP during the period 1970–1990 is not related to any significant change in forest area. Similarly, changes in biomass stock are not significantly related to forest area (data not shown).

These simulations assign 70–80% of the observed increase in NPP over 1950–2000 to changes in climate and to the fertilizing effect of CO_2. In these simulations, however, no nitrogen limitation was considered. The role of nitrogen deposition in increasing NPP and subsequent carbon sequestration in European forests is still a subject of debate. Magnani *et al.*[27] concluded that the residual net carbon sink in European forests, after disturbance effects had been accounted for over the life cycle of the forests, was 'overwhelmingly driven by nitrogen deposition'. But the plausibility of this result was questioned by de Vries *et al.*[28], who estimated a nitrogen contribution to the sink of no more than 10%. A marginal effect of nitrogen deposition in enhancing biomass accumulation, except for high elevation stands, was also noted in a study of the Thuringian forests[29]. Owing to the spatial distribution of nitrogen deposition in Europe, one may expect this factor to contribute more to the NPP trend in Central Europe, while being nearly negligible in boreal Europe, where total inputs remain below 10 kg N ha^{-1} yr^{-1} (see Supplementary Information). These results altogether suggest that climate and CO_2, aided to some extent by increased nitrogen deposition, may explain a significant fraction of the trend in European forest NPP (Fig. 1a).

Interestingly, despite being successful in capturing the NPP trend between 1950 and today without management, the ORCHIDEE model failed to account for the observed biomass sink (Fig. 1a). This incapacity of rising NPP alone to explain the observed sink tentatively suggests that other factors may play an important role, or alternatively, a model shortcoming. At the continental scale, another independent model-based analysis that accounted for changing age-classes, management and land use[30] further indicates that forest NPP increases were mainly driven by climate change and CO_2. Yet, the simulated biomass sink, which agreed well with inventories, was ~50%-related to age structure and management. In summary, environmental factors may explain the upward trend of NPP, whereas the net biomass sink seems to be controlled by foresters and harvesting rates.

UNCERTAINTIES TODAY AND TOMORROW

Methodological differences between inventories over time[31] may produce some spurious carbon stock changes, but these effects are likely to remain limited as all the data were harmonized to follow common international definition[11]. In addition, uncertainties in allometry and in fine root and needle turnover rates further increase the uncertainty of woody NPP and of NPP estimated from diameter increment measurements. Despite these limitations, the basic data from countries that used the same methodology between their last and previous inventory all confirm significant increases in increment[8]. In Germany for example, a net annual stem wood volume increment of 12.1 m^3 ha^{-1} yr^{-1} was measured for 2001–2002, whereas in the previous inventory[32] it was 9 m^3 ha^{-1} yr^{-1} for 1986–1992. In Finland, where no major changes in forest area were observed, the total annual stem wood volume

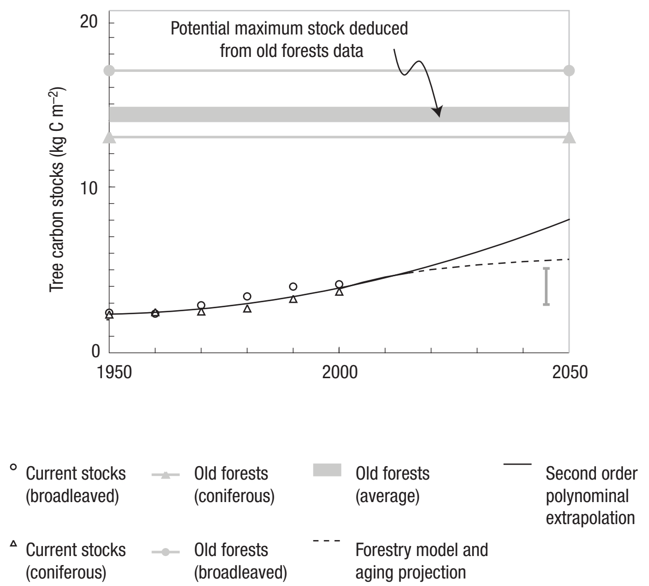

Figure 3 Observed trend of forest biomass stocks and future predictions. The dashed curve is a prediction based on a forestry model, which accounts for forest aging under a moderate harvest scenario, but without any effects of rising CO_2, climate change or nitrogen deposition[38]. The solid curve is a simple quadratic curve fitted to the 1950–2000 data and boldly extrapolated to the future. The grey horizontal lines mark the maximum potential biomass, obtained from old forest data and yield tables. The error bar to the right indicates the uncertainty in this estimate (see Supplementary Information).

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increment was 86.7 million cubic metres for 1996–2003, whereas in the previous inventory it was only 77.7 million cubic metres. Thus, real increases of biomass increment have occurred and are still occurring. This faster growth of European forests monitored by inventories is corroborated by tree-ring studies and by measurements of long-term permanent sample plots[33–37].

In order to evaluate the sustainability of the forest biomass sink in Europe, we compiled biomass data from about a hundred old stands (see Methods). Figure 3 compares these estimates of maximum potential stocks with future projections[38]. Given that the harvested fraction is further reduced, European forests still have the potential to realize a build-up of their carbon stocks by a factor of two, within the next century (Fig. 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 of carbon, typically 15% or less of the carbon sink of European forests, can be accounted for as carbon credit (refs 39,40). However, the potential CO_2 sink is threatened by the proposal of the European Commission[41] to increase the share of renewable energy to 20% of the total energy consumption by 2020. This will almost double the wood demand for biomass energy[42] in the EU-15 from 55% of harvested wood in 2001 to 100% in 2020 at current harvest levels, or may increase harvest above the levels of 1950 and shorten forest rotation length. In addition, drought, wind throw, pathogen attacks[43] and reduced productivity due to climate change and extreme events[44] may lower the carbon gains achieved with decades of carbon-saving management practices.

METHODS

NATIONAL EUROPEAN FOREST INVENTORIES CHARACTERISTICS

The forest inventory data used was made comparable between the countries and the years in ref. 11 and references therein. The way these harmonized figures were used in the calculations of our present manuscript is described in refs 5 and 12. The TBFRA-2000 report[11] describes the national forest inventory systems to some extent. More detailed descriptions on the set up of each inventory, and on the harmonization of these data can be found in ref. 12 and in Supplementary Information, Table S3, and references therein.

FINE-ROOT MORTALITY AND NPP

Fine-root mortality varies between tree species and environmental conditions[17–19]. The spatial variability of this parameter is not known well enough to be included in the NPP calculated from inventory data. Including spatial variations in fine-root production in the NPP computation would require untested hypothesis for an unascertained gain. The uncertainty of 0.06 yr^{-1} on fine-root mortality around a mean turnover value of 0.86 yr^{-1} used in the inventory harmonization[11] is likely to be too optimistic. This error is smaller than the range of fine root mortality values reported in literature data (0.4 to 2 yr^{-1}; see refs 17,19,21). Moreover, the mean turnover value of 0.86 yr^{-1} (ref. 32) yields to a lower fraction of leaf and fine root NPP than the one inferred using a new database of ecological data compiled by Luyssaert *et al.*[21] where all the NPP components were individually assessed. In the inventory derivation of NPP, the ratio of leaf and fine-root NPP to total NPP is 0.35. From the ecological site database[21], this ratio reaches up to 0.5 (0.15–0.86) for conifer forests and 0.45 (0.15–0.85) for broadleaved (see Supplementary Information for uncertainty estimates). This low bias of inventory NPP will affect the slope of biomass stock versus NPP in Fig. 1, but not the linear co-evolution of NPP with standing biomass.

OLD FORESTS BIOMASS CARBON STOCKS

We compiled data of old forest biomass per unit area of forest, for western European tree species, which are summarized in Supplementary Information, Table S1. These estimates were obtained from individual site measurements and yield tables. These forests are not 'old-growth' primary forest stands, but old forests, some of them managed and others not for at least 200 years. Thus, the biomass density of these forest is high (9.5 to 23.5 Kg C m^{-2} in Supplementary Information, Table S1) but not quite as high as that of the rare primary forests encountered in Russia or in the Pacific North West (typical range 20 to 30 Kg C m^{-2})

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