Forest Ecology and Management xxx (2009) xxx–xxx

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Carbon gains and recovery from degradation of forest biomass in European Union during 1990–2005

Aapo Rautiainen [*], Laura Saikku, Pekka E. Kauppi

University of Helsinki, Faculty of Biosciences, Finland

A R T I C L E I N F O

Article history:
Received 19 January 2009
Received in revised form 17 July 2009
Accepted 20 July 2009

Keywords:
Forested landscape
Carbon reserves
Biomass carbon balance
Carbon sequestration

A B S T R A C T

The net gain of carbon in European Union (EU) forest vegetation during 1990–2005 was estimated at 360–400 Tg CO_2 year^{-1} by analysing international data. This amount is at low end of the range of recent corresponding estimates, but greater than earlier estimates published for the period 1971–1990. The sequestration took place almost exclusively in areas which were already forested in 1990. In 2005, new plantations, established after 1990, contributed only about 8% to the estimated net gain. The sequestration was estimated to be the greatest in Germany, France, Italy, Finland and Poland regardless of data source and method of estimation. On a *per capita* basis, the sequestration was estimated to be the greatest in Finland and Latvia. Carbon sequestration in forests is an important component of the long-term carbon balance of the EU. Carbon sequestration in forests is partly driven by a recovery of the ecosystems from human-induced degradation in the 19th century and the first half of the 20th century. Forest management has affected carbon sequestration and merits attention in climate policy presuming that new policies and measures are reconciled with those already in place for the promotion of the diverse goals of land management in Europe.

1. Introduction

Research over the past two decades has consistently shown that European forest vegetation sequesters a significant amount of carbon dioxide from the atmosphere (FAO, 2006). The main drivers of the carbon sink are less clear. Attention has been increasingly directed to the impacts of long-term changes of land use (Kandler, 1992; Kauppi et al., 2006; Ciais et al., 2008). Young stands grow vigorously, but even old-growth forests can act as a carbon sink (Luyssaert et al., 2008). It is important to compare the relative role in carbon sequestration of young *vs.* old forests, in order to predict the future development of sequestration given the anticipated dynamics of the forest landscape. This analysis is relevant for climate policy, because it contributes to the understanding of the impacts of forest management on long-term removal of carbon from the atmosphere.

According to FAO (2006), forests in the 27 countries, which in 2008 were members of the European Union (=EU27), cover 156 million hectares and represent approximately 4% of global forest area and 5% of global growing stock volume.

Net expansion of forest biomass has sequestered carbon dioxide, which annually corresponds to 8–10% of EUs fossil carbon dioxide emissions (Ciais et al., 2008; Nabuurs et al., 2008). Hence, the magnitude of the forest vegetation sink is approximately on par with EUs targeted emission reductions as agreed in the Kyoto protocol. If fossil emissions are lowered successfully, the relative contribution of forests will increase—assuming no absolute change in the rate of sequestration. It is important to understand the drivers of this sequestration flux, the threats to sequestration processes, and the long-term possibilities of maintaining and/or increasing the rate of carbon sequestration.

Globally, the gross losses of approximately 13 million hectares per year dominate the planetary forest change. Most deforestation occurs in the tropics: between 2000 and 2005, Brazil and Indonesia together accounted for approximately two-thirds of global forest area losses, primarily due to the conversion of forests to agricultural land. By contrast, over the same time span, EU27 accounted for 12% global afforestation—a figure three times larger than its share of global forest area. The expansion of forests in reviving regions such as EU and China did not compensate for losses of forest area elsewhere. The reported global net loss was −7.3 million forest hectares per year, an area slightly smaller than Scotland—down from −8.9 million hectares per year in the 1990s (FAO, 2006).

The development of the forest carbon stock, however, is primarily driven by changes of timber volume and biomass rather than forest area (Dixon et al., 1994). The timber volume in EU forests available for wood supply roughly doubled between 1950 and 2000. Also Net Annual Increment (NAI) increased substan-

---

[*] Corresponding author at: P.O. Box 27, 00014 University of Helsinki, Finland. Tel.: +358 9 1911.
E-mail address: aapo.rautiainen@helsinki.fi (A. Rautiainen).

0378-1127/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.foreco.2009.07.043

Please cite this article in press as: Rautiainen, A., et al., Carbon gains and recovery from degradation of forest biomass in European Union during 1990–2005. Forest Ecol. Manage. (2009), doi:10.1016/j.foreco.2009.07.043

tially, while the respective change of forest area was 15–20% (Gold, 2003; Gold et al., 2006) (Figs. 1 and 2).

Forests expanded in the European Union during the second half of the 20th century despite the growth of cities and settlements and the construction of roads, rail tracks, power lines and other infrastructure. The area of national parks and preserved forests, which are not available for wood supply, also expanded during the 20th century. The general trends in Figs. 1 and 2 are consistent with similar earlier assessments (e.g., Kuusela, 1994).

After the most recent ice age, as the glaciers retreated from Central and Northern Europe, forest cover gradually advanced northward. Later, as agriculture and permanent human settlements spread throughout the continent, virgin forests gave way for farmland. Therefore, gains in forest area must be perceived as a recovery from deforestation, while an expansion of biomass per hectare can be interpreted as a recovery from forest degradation. Historically, the forests of present-day EU27 ceased to shrink and started to expand in the 19th or early 20th century depending on the region (Kandler, 1992; Mather, 1992, see also Kauppi et al., 2009, this volume). After deforestation was brought to a halt, rising average density, as a result of a recovery from long-endured forest degradation, has become the defining feature of forest change in the region.

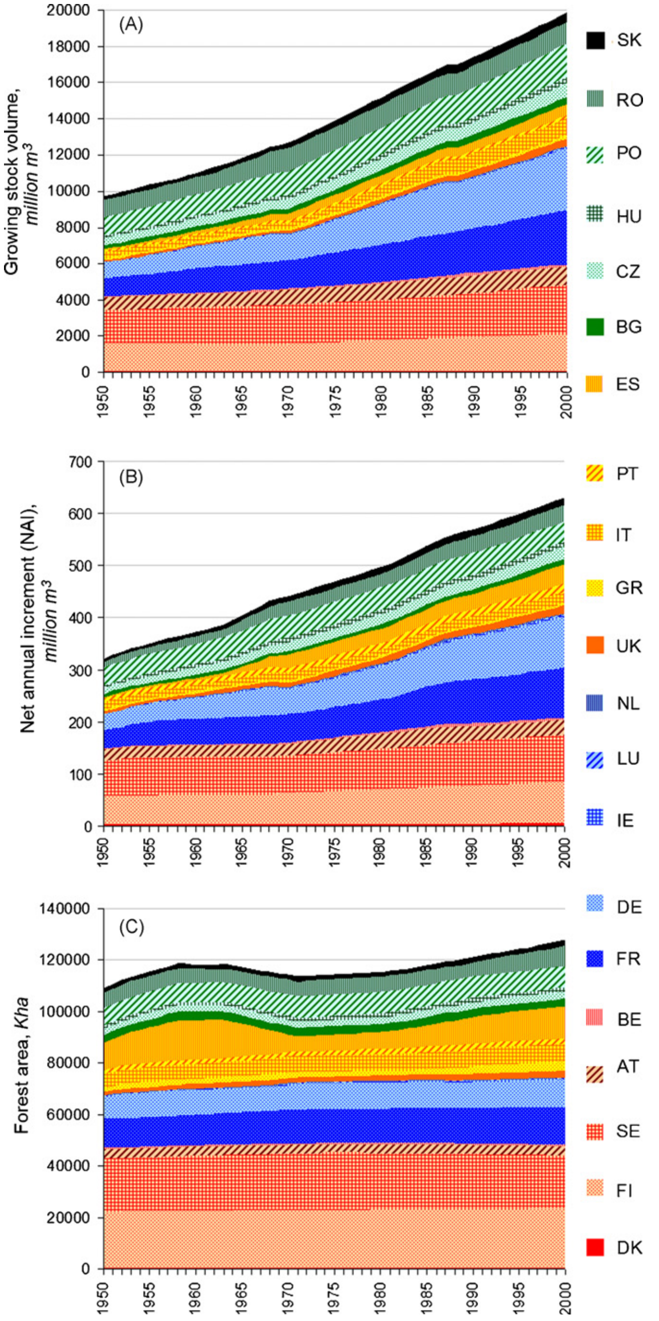

Fig. 1. The development of forest area, growing stock volume and net annual increment in forests available for wood supply from 1950 to 2000 in 21 EU27 countries. In the year 2000 these 21 countries constituted 94% of forest area and 92% of all growing stock in the EU27. Source: Gold (2003). The gaps in data were filled by interpolating linearly between reported years, and extrapolating at both ends of the time-series.

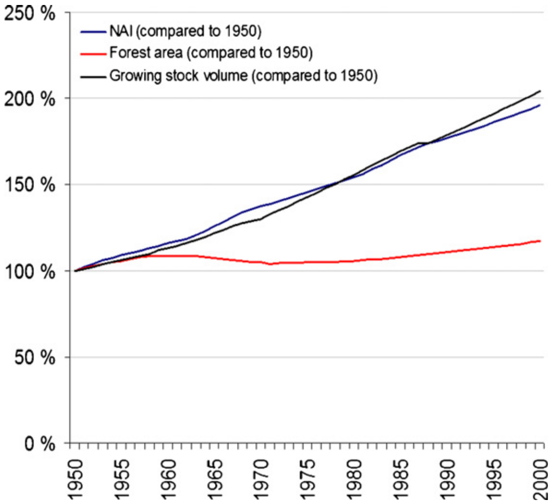

Fig. 2. Total forest area, growing stock volume and net annual increment in forests available for wood supply compared to the initial 1950-level in 21 EU27 countries. In the year 2000, these 21 countries constituted 94% of forest area and 92% of all growing stock in the EU27. Source: Gold (2003). The gaps in data for individual countries were filled by interpolating linearly between reported years, and extrapolating at both ends of the time-series.

The analyses in this paper are based on international data collected by two United Nations' organizations, Food and Agriculture Organization of the United Nations (FAO) and United Nations Framework Convention on Climate Change (UNFCCC). UNFCCC is an international treaty organization for stabilizing greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. For monitoring purposes, the organization of the Climate Convention (UNFCCC) gathers data on the sequestration of carbon in terrestrial ecosystems for estimating the impacts of Land Use, Land-Use Change and Forestry (LULUCF) on the atmosphere. The data are based on countries' official submissions of GHG emissions/removals. Global Forest Resources Assessments (FRAs) are based on FAO data, which countries provide in response to a questionnaire by the FAO. Among other things, the FAO data include information on forest area and growing stock volume. In this paper, we present a method to estimate carbon in forests, and to distinguish between the impacts of short-run areal change and growth in volume, using these data.

We analyse the most recent changes in EU27 forests as documented by two UN organizations, FAO and UNFCCC, with the principal focus on the change in the carbon stock in woody biomass. We address the following questions:

1) How did the carbon stock of forest vegetation develop within EU27 and within each EU country during 1990–2005, in comparison to forest change over a longer period of time?
2) How much did new forests, which were established since 1990 contribute to carbon sequestration in 1990–2005?

Please cite this article in press as: Rautiainen, A., et al., Carbon gains and recovery from degradation of forest biomass in European Union during 1990–2005. Forest Ecol. Manage. (2009), doi:10.1016/j.foreco.2009.07.043

3) How consistently can the rate of carbon sequestration be estimated based the available sources of international data, FAO-FRA and UNFCCC-LULUCF?

2. Materials and methods

Using the Forest Identity method (Kauppi et al., 2006; Waggoner and Ausubel, 2007) the total stock of sequestered forest carbon (Q) can be presented as:

$$Q = A \times D \times B \times C \quad (1)$$

where A = forest area, (ha); D = density, V (growing stock volume, m^3)/A (ha); B = allometric ratio, M (biomass, ton)/V (m^3); C = carbon concentration, Q (carbon, ton)/M (biomass, ton).

The advantage of the Forest Identity method is that it breaks down the forest carbon stock to its four main attributes (Table 1). Studying the rates of change of these attributes enables us to identify the main drivers of forest change and carbon sequestration. The annual rates of change of each component are denoted by lower-case letters. They are obtained by dividing the log-percent change between two data points by the length of the time interval in years. The rate of change in the stock of forest carbon (q) can be expressed as the sum of the log-percent changes in each of the four components [2].

$$q = a + d + b + c \quad (2)$$

Using this formulation, the annual carbon sequestration (S) can be expressed as the product of the existing carbon stock, Q, and its rate of change, q.

$$S = q \times Q \quad (3)$$

Table 2
A list of countries, where some component(s) of the allometric ratio were adopted from another country.

Country	Missing component	
	Below-ground living biomass	Dead wood
AT	Ratio adopted from CZ	Ratio adopted from DE
BG		Ratio adopted from RO
CY		Ratio adopted from IT
DK		Ratio adopted from NL
FX		Average of ratios in DE and IT
GR		Ratio adopted from IT
HU		Average of ratios in CZ and RO
IE		Ratio adopted from UK
LU		Ratio adopted from BE
PT		Ratio adopted from IT
ES		Ratio adopted from IT

We used FRA2005 data for forest area (A) and growing stock volume (V) in 1990, 2000 and 2005 (FAO, 2006). The values used for these attributes are given in Table 1. For the carbon content of dry biomass we assumed a constant of $C = 0.5$ based on the findings of Birdsey (1992) who estimated that the ratio may vary between 0.48 and 0.53 tons of carbon per ton of biomass. Departing from the original Forest Identity, we adjusted our method to incorporate country-specific allometric ratios (B). In this paper, the allometric ratio is rather broadly defined as the sum of the ratios of above-ground biomass, below-ground biomass and dead wood to growing stock (tons/m^3). These were estimated using forest biomass data from FRA 2005 country tables. Where data were not available (most often for dead wood), the ratio was adopted from the country with the most similar climate and forest management history (Table 2 and Fig. 3).

The rate of change of the allometric ratio (b), is approximated as a function of the change in average density (d), so that:

$$b = \beta_1 \times d \quad (4)$$

where β_1 is a parameter that describes a linear dependency between b and d. In the original presentation of the Forest Identity (Kauppi et al., 2006), it is assumed that $\beta_1 = -0.3$ and is constant for

Table 1
Values of key attributes and country-specific β_1-coeffiecients for EU27 countries (excluding Malta).

Country (abbreviation)	Growing stock volume (million m^3)			Forest area (kha)			B	β_1
	1990	2000	2005	1990	2000	2005	2005	2000
Austria (AT)	3776	3838	3862	947	1088	1159	0.84	−0.45
Belgium (BE)	677	667	667	128	157	172	0.77	−0.37
Bulgaria (BG)	3327	3375	3625	405	526	568	1.06	−0.27
Cyprus (CY)	161	173	174	7	8	8	0.74	−0.35[c]
Czech Rep. (CZ)	2630	2637	2648	625	699	736	1.03	−0.42
Denmark (DK)	445	486	500	65	74	76	0.71	−0.42
Estonia (EE)[a]	2163	2243	2284	–	458	447	0.78	−0.19
Finland (FI)	22194	22475	22500	1907	2070	2158	0.77	−0.22
France (FR)	14538	15351	15554	2079	2254	2465	1.06	−0.32
Germany (DE)[b]	10741	11076	11076	2759	3381	-	0.73	−0.36
Greece (GR)	3299	3601	3752	156	170	177	0.77	−0.35
Hungary (HU)	1801	1907	1976	288	325	337	1.11	−0.29
Ireland (IE)	441	609	669	52	60	65	0.62	−0.36[c]
Italy (IT)	8383	9447	9979	1051	1289	1447	0.99	−0.35
Latvia (LT)	2775	2885	2941	451	546	599	0.79	−0.15
Lithuania (LV)	1945	2020	2099	320	372	400	0.70	−0.19
Luxembourg (LU)	86	87	87	20	26	26	0.75	−0.38
Netherlands (NL)	345	360	365	52	61	65	0.83	−0.26
Poland (PL)	8881	9059	9192	1485	1736	1864	0.97	−0.28[c]
Portugal (PT)	3099	3583	3783	238	313	350	0.76	−0.17[c]
Romania (RO)	6371	6366	6370	1348	1346	1347	0.98	−0.41
Slovakia (SK)	1922	1921	1929	402	463	494	0.89	−0.40
Slovenia (SI)	1188	1239	1264	273	335	357	0.96	−0.41
Spain (ES)	13479	16436	17915	592	790	888	1.09	−0.17
Sweden (SE)	27367	27474	27528	2791	3034	3155	0.95	−0.27
UK (UK)	2611	2793	2845	266	308	340	0.67	−0.36

[a] Analysis for Estonia conducted using growing stock data for 2000 and 2005.

[b] Analysis for Germany conducted using growing stock data for 1990 and 2000.

[c] Insufficient data for species-composition of forests. For these countries β_1-coefficients were adopted from neighbouring countries (except for Poland, for which it was approximated by taking the average of German and Lithuanian β_1-coefficients).

Please cite this article in press as: Rautiainen, A., et al., Carbon gains and recovery from degradation of forest biomass in European Union during 1990–2005. Forest Ecol. Manage. (2009), doi:10.1016/j.foreco.2009.07.043

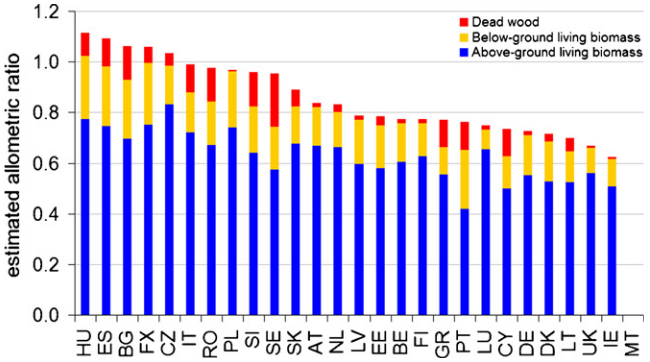

Fig. 3. Estimated country-specific allometric ratios and their components for EU27 countries (excluding Malta).

forests in all countries. This implies that a 10% increase in the average density of forest results in a 3% decline in the allometric ratio (Brown and Schroeder, 1999). For a single species forest, with homogenous growth conditions and a stand-level BEF function of the form (5) Eq. (4) holds, regardless of the age-distribution of the forest.

$$\ln(B) = \beta_0 - \beta_1 \times \ln(D) \tag{5}$$

Unlike the age-structure, the species-composition of forests, however, does affect the rate of change of the allometric ratio (Waggoner and Ausubel, 2007). To control for this effect, we estimated country-specific β_1-coefficients using information on the species-composition of forests in different countries provided in the FRA. The species were grouped into four forest types with distinct BEF functions of the form of equation [4]. The country-level β_1-coefficients were calculated as a weighted average (by growing stock share) of the respective coefficients from these functions. For Central European deciduous forests, which resemble the hardwood forests of eastern US, we used the same β_1-coefficient as Kauppi et al. (2006) based on Brown and Schroeder (1999). There are other BEF functions that would give a better proxy for deciduous forests in Central Europe, but the desired functional form compatible with the Forest Identity (Kauppi et al., 2006) restrains us from using these functions. The other three β_1-coefficients (for pine, spruce and fir, and Northern deciduous forests) were derived from Lehtonen et al. (2004). Country-specific β_1-coefficients are given in Table 1.

Forest inventory practices across EU member states vary both in quality and in terms of measurement frequency, accuracy and precision. Moreover, the Forest Identity method is sensitive to variation of forest density between different stands and regions, since a uniform forest density is assumed in the FI method in all forests of a country. To tackle this problem, three variants of the Forest Identity were introduced in this study. All three variants use country-specific allometric ratios and country-specific β_1-coefficients as described earlier. In Variant 1A the growing stock gains in new forests were assumed zero, and change in growing stock volume was attributed solely to forests, which existed at the beginning of the study period (1990). In contrast, and in line with the original method, Variant 1B did not distinguish between “new” and “old” forests (Kauppi et al., 2006). In Variant 2, if forest area was lost, the average density was assigned to the lost forest as reported for the forests existing in the country in the year 1990. If forest area was gained, a low average density of 12 m^3/ha (an average for all age classes 0–15 the year in 2005) was assigned to the additional forest area beyond 1990. In Variant 2, the contribution of “old” forests (which existed prior to 1990 and remained through 2005) was assessed as the difference between carbon in all forests minus that in “new” forests (age class 0–15). In this way an estimate of the contribution of “expanding forest area” relative to “thickening in pre-existing forests” to carbon sequestration was obtained. The Variants are presented in more detail in the online supplement.

Using Variants 1A, 1B and 2, annual carbon sequestration was estimated from FAO data. Finally, the results were compared with LULUCF estimates as collected and published by the UNFCCC (2008). In order to make the LULUCF data comparable with the FAO based estimates, changes in soil carbon were omitted. For the calculation of *per capita* sequestration, population data for EU member states were obtained from Eurostat (2008).

3. Results

According to Forest Identity Variants 1A, 1B and 2, expanding forest vegetation sequestered 360, 400, and 370 Tg CO_2 in 2005 in the EU, respectively. Biomass expansion took place mainly in forests, which already existed in 1990. The contribution of new forests, which were established since 1990, to carbon sequestration in EU27 was approximately 8% in 2005. Even in countries where new forests were actively created in the 1990s, such as Ireland, Greece and Spain, the sequestration impact of more mature forest stands dominated (Fig. 4).

Apart from a few anomalies, such as Sweden, Spain and Portugal, the Forest Identity estimates based on FAO data were lower than those reported within LULUCF-UNFCCC (Fig. 5). For example, UNFCCC figures were 15% higher than the estimates calculated using Variant 2 (Fig. 6). UNFCCC reported the annual sequestration of EU27 (soil excluded) at 430 and 495 Tg CO_2 for the years 2000 and 2005, respectively. For a majority of member states, including five countries with the greatest annual sequestration, LULUCF estimates for 1991, 2000 and 2005 indicated an accelerating rate of sequestration (Fig. 6).

Based on all methods, a high annual rate of sequestration was observed in Germany, France, Italy, Finland and Poland. On a *per capita* basis the sequestration was estimated to be large in Finland and Latvia (Fig. 7).

4. Discussion

From 1990 to 2005, expanding forest biomass in the EU27 annually sequestered 360–495 million tons CO_2 from the atmosphere. This range implies an accelerated net gain of carbon in EU forests noting the corresponding estimate for a slightly larger area in Europe during 1971–1990: 275–385 million tons CO_2 (Kauppi et al., 1992). Furthermore, the UNFCCC-LULUCF figures for 1991, 2000 and 2005 suggests an escalating trend in carbon sequestration in recent years. Even though it is premature to conclude firmly that the rate of sequestration has increased, there is no evidence in our analysis to suggest that the rate of biomass increase is

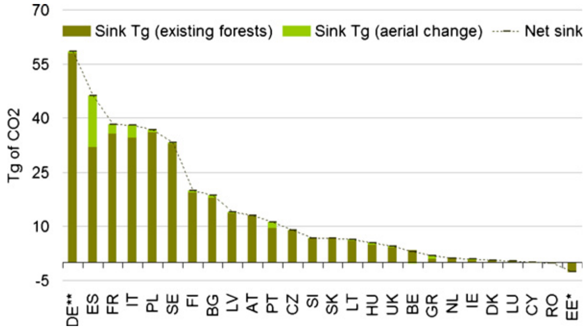

Fig. 4. The contribution of pre-1990 and post-1990 forests to the annual carbon sequestration in 2005 (Tg CO_2), Variant 2. For country abbreviations see Table 1.

Please cite this article in press as: Rautiainen, A., et al., Carbon gains and recovery from degradation of forest biomass in European Union during 1990–2005. Forest Ecol. Manage. (2009), doi:10.1016/j.foreco.2009.07.043

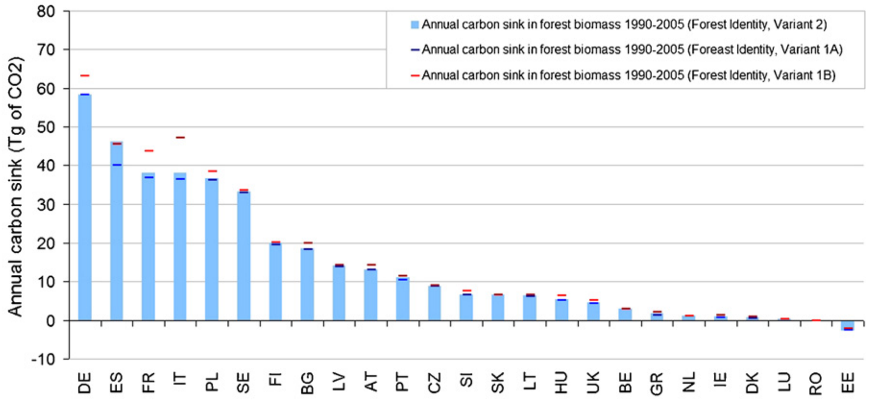

Fig. 5. Annual forest carbon sequestration in EU27 (excl. CY and MT). Annual carbon sequestration in forest vegetation according to Variant 2 (blue bars). Results of Variants 1a and 1b are shown as a comparison. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

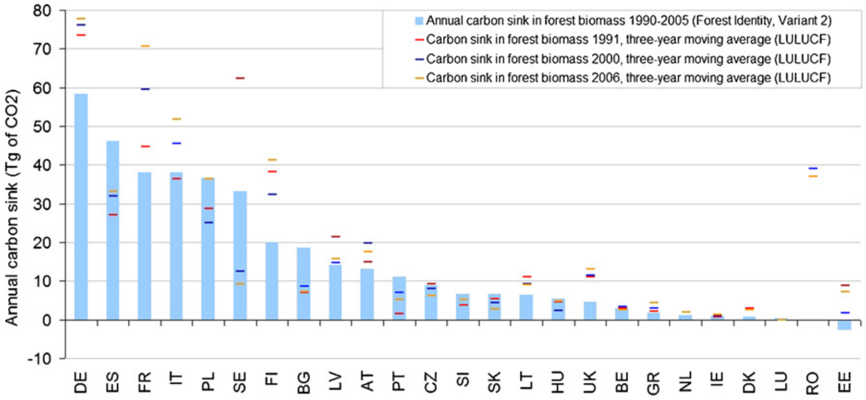

Fig. 6. Annual forest carbon sequestration in EU27 (excl. CY and MT). Annual carbon sequestration in forest vegetation according to Variant 2 (blue bars). Three-year moving averages based on LULUCF-data are included for comparison. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

declining. The carbon stock in European forests has increased at an annual rate of 0.5–1.0% in the second half of the 20th century. Changes in harvests, stochastic storms, and variation in growing conditions such as those in temperature, precipitation and drought affected sequestration at regional and short-term scale.

During the first half of the 20th century, the rate of sequestration must have been slower. Between 1950 and 2000, growing stock volume in forest available for wood supply increased from less than 10 to about 20 billion m^3 (Fig. 2). The role of establishing nature reserves and national parks is unclear. Nevertheless, the rate of biomass and carbon gains in Europe cannot have been as high in the earlier half of the 20th century as they are here estimated for 1990–2005. Projecting backwards from 1950 towards the year 1900, this would imply a negative vegetation stock in the year 1900 which is, of course, implausible. From these data we conclude that a long-term increasing trend of carbon sequestration has persisted for a century since the year 1900. It is unclear, however, whether an improvement of the data quality may have affected the latest estimates for 1990–2005. The drivers of change act at a time-scale of decades or even centuries,

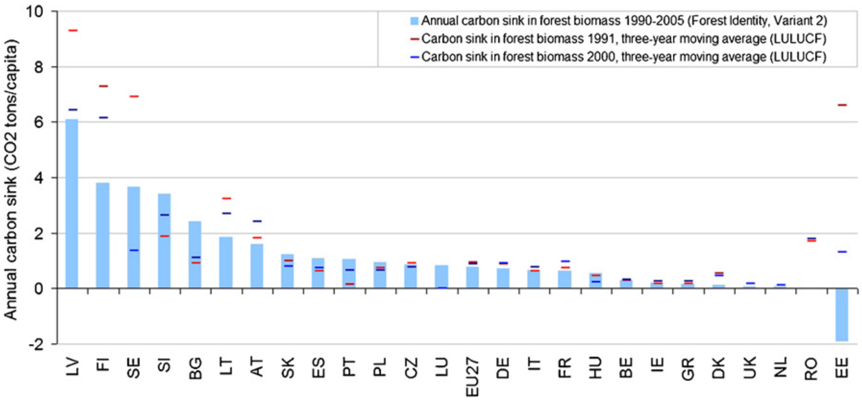

Fig. 7. Sequestration of carbon in forest vegetation *per capita* (based on population in 2005) in EU27 (excl. CY and MT).

Please cite this article in press as: Rautiainen, A., et al., Carbon gains and recovery from degradation of forest biomass in European Union during 1990–2005. Forest Ecol. Manage. (2009), doi:10.1016/j.foreco.2009.07.043

and the change in forests occurs only gradually in the long term (Kandler, 1992; Mather, 1992; Houghton, 1994; Grainger, 1995; Kauppi et al., 2009, this volume).

Large differences in the land-use history between both countries and continents, as well as disparities in climatic and economic conditions hamper extrapolations of these results to other regions of the World. In the EU, forest biomass will almost certainly continue expanding in the forthcoming decades, given the age-structure of forest stands, the current patterns of Net Annual Increment, the programs for improving nature conservation and the moderate timber demand in Europe. In the long run, forest management can significantly contribute to EUs effort to control its net emissions of greenhouse gases (Peters et al., 2009).

Several concrete changes in the European landscape have played a role in determining sequestration development in recent times: (1) marginal agricultural lands were abandoned from 1960 to 1980 and earlier. Forests, which then emerged, are now sufficiently mature to accumulate biomass; (2) forests recovered from selective felling, cattle grazing and other forms of land use, which prevailed in Europe during the 19th and 20th centuries, just as they prevail in many developing countries today; (3) forestry operations in the latter half of the 20th century favoured high stocking densities as they supported profitable harvest; (4) nature reserves were expanded; (5) primary production of forest vegetation increased in response to improved silviculture, plant breeding, CO_2 fertilization, N deposition and climatic warming; (6) Coarse Woody Debris (CDW) increased since the 1980s, not only in protected areas—the expanded living biomass eventually generates more debris; (7) the number and average size of trees increased in woodlands, parks, residential areas, and elsewhere outside the forest proper. The relative contribution of such changes to the observed trends is difficult to assess (Binkley et al., 1997).

During the latter half the 20th century in the EU, the forest area expanded by 15–20%, while the growing stock more than doubled (Fig. 2). The sequestration in Europe between 1990 and 2005 took place in relatively mature forest stands, which existed already in 1990, whereas the most recent expansion of forest area had a marginal effect on the carbon budget of the EU by 2005. Europe gained forest area due to planting, landscape restoration and a spontaneous expansion of forests (FAO, 2006). Notably, the same development has been documented for the US and China (Smith et al., 2002; Fang et al., 2001). Forests, which were planted much earlier, such as those established in the 1950s, were sufficiently mature by 1990–2005 to contribute to biomass accumulation significantly. Analogously, newly established forests will contribute to the expansion of biomass in future decades.

Carbon sequestration has been, at least in some regions, a cobenefit of general forest management striving to promote a recovery of forests from degradation in the distant past (Kauppi et al., 2009, this volume). Policies which enhance and promote forest carbon stocks can be implemented. Until recently, European climate policy has largely ignored considering improvements in land management. Expanding forest biomass may produce cobenefits as well as adverse side effects regarding the large array of ecosystem services of forests (for example hydrological and radiative regulation, provision of goods and commodities, and cultural and aesthetic services).

International forest data are deficient especially regarding tropical regions (Grainger, 2008). Also, our estimates of annual carbon sequestration contain uncertainties arising from both from both data source and method of estimation. Even if the data are precise, some imprecision remains in estimates based on the Forest Identity, because highly aggregated data are used. Forests of large geographical areas, e.g., entire countries, have very diverse growing conditions and the species-composition and the age-structure of forests vary significantly between individual stands. When country-level aggregated data are used, information details are lost. For instance, in this study, the average country-level β_1-coefficients were calculated using growing stock shares of species as weights for each species group. To obtain more accurate estimates, the distribution of the gains in growing stock volume among different species groups should also be taken into account. (To enlighten this point, assume that there are only two species groups that both contain half of the initial growing stock volume. The forests in the first group are predominantly mature, slow-growing forests, while the second group is composed of rapidly growing forests. Thus, most of the growing stock gains will occur in the second group, and its impact on the change of the aggregate allometric ratio will also be greater.) However, as the age-structure and the species-specific age-distributions are unknown, using growing stock shares as weights is a feasible approximation. The accuracy of the estimates can be improved by using specific stand-level data. From the viewpoint of new research, it is important to harmonize the monitoring methods within the EU.

Likewise, there are similar sources of imprecision in the UNFCCC-LULUCF data. The accuracy and precision of both data sets ultimately depend on the quality of the national forest measurements upon which the reported figures are based, and hence, the same caveats apply. Due to slight differences in the reporting practices and the categories for which data are reported or estimated, these data are not fully comparable between distinct countries. Also, national forest inventories are carried out at a differing pace and differing time intervals across EU member states. Hence, the data *reported* for a specific year are based on measurements that date further back—with a differing delay in different countries. On average, FAO data are based on older inventory data than those from UNFCCC-LULUCF. The data are often extrapolated using the most recent observations, which may be several years old. FRA data are reported for the years 1990–2005. However, the data at the end of the time interval have been extrapolated using older inventories. Synchronizing the estimates to the exact same period is difficult. The LULUCF data for 2005 is generally based on more recent data. This may partially explain the differences in the magnitude of the estimates.

Janssens et al. (2003) reported dominance of tree biomass in carbon sequestration noting large uncertainty in assessing changes in the soils of croplands, grasslands and forests, and in changes in peat reserves. The effect of soil carbon on sequestration is not addressed in this study.

Understanding forest carbon and the time-scale of its evolution is relevant to the planning and implementation of climate policy. For example, it is important to understand the limitations of the carbon potential of newly established forests in affecting the carbon balance in the near future. With the three Variants of the Forest Identity introduced in this study, it is possible to estimate the size of carbon pool in forest and differentiate the impacts of aerial change *vs.* thickening of forests in the short term. The presented method provides rough estimates for the sequestration of carbon in forests. However, improving the accuracy of the estimates and narrowing the uncertainties requires the use of more detailed and comprehensive data.

As important as it is for policy makers to understand the current state of forests and consider their sequestration potential in the short run, the objectives of the underlying climate policies are for the long run. Forests tend to change slowly. The documented sequestration in EU27 forests is a result of the forest policies implemented over past century. Likewise, despite the meagre contribution of newly established forests to carbon sequestration at the present, their role in sustaining the rate of net carbon sequestration in the future can become significant. In order to realize the full potential of forest management as a tool for long-

Please cite this article in press as: Rautiainen, A., et al., Carbon gains and recovery from degradation of forest biomass in European Union during 1990–2005. Forest Ecol. Manage. (2009), doi:10.1016/j.foreco.2009.07.043

run climate policy, it is imperative to coordinate sequestration goals with other objectives of European land use.

Acknowledgement

We gratefully acknowledge Finnish Ministry of Environment and Academy of Finland (grant 117822) for funding.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.foreco.2009.07.043.

References

Binkley, C.S., Apps, M.J., Dixon, R.K., Kauppi, P.E., Nilsson, L.-O., 1997. Sequestering carbon in natural forests. Critical Reviews in Environmental Science and Technology 27 (Special), S23–S45.

Birdsey, R.A., 1992. Carbon Storage and Accumulation in United States Forest Ecosystems. General Technical Report W0-59. US Department of Agriculture Forest Service, Washington, DC.

Brown, S.L., Schroeder, P.E., 1999. Spatial patterns of aboveground production and mortality of woody biomass for Eastern US Forest. Ecological Applications 9, 968–980.

Ciais, P., Schelhaas, M.J., Zaehle, S., Piao, S.L., Cescatti, A., Liski, J., Luyssaert, S., Le-Maire, G., Schulze, E.-D., Bouriaud, O., Freibauer, A., Valentini, R., Nabuurs, G.J., 2008. Carbon accumulation in European forests. Nature Geoscience 1, 425–429.

Dixon, R.K., Brown, S., Houghton, R.A., Salomon, A.M., Trexler, M.C., Wisniewski, J., 1994. Carbon pools and flux of global forest ecosystems. Science 263, 185–190.

Eurostat, 2008. Eurostat population database, demography—national data: population by sex and age on 1 January of each year. http://epp.eurostat.ec.europa.eu/.

Fang, J., Chen, A., Peng, C., Zhao, S., Ci, L., 2001. Changes in forest biomass carbon storage in China between 1949 and 1998. Science 292, 2320–2322.

FAO, 2006. Global forest resources assessment 2005: progress towards sustainable forest management. FAO Forestry Paper 147. Food and Agricultural Organization of the United Nations, Rome. http://www.fao.org/forestry/site/fra2005/en/.

Gold, S., 2003. The Development of European Forest Resources, 1950–2000: A Better Information Base. Geneva Timber and Forest Discussion Paper 31. FAO, Geneva.

Gold, S., Korotkov, A.V., Sasse, V., 2006. The development of European forest resources, 1950 to 2000. Forest Policy and Economics 8, 183–192.

Grainger, A., 1995. Forest transition: an alternative approach. Area 27, 242–249.

Grainger, A., 2008. Difficulties in tracking the long-term global trend in tropical forest area. Proceedings of the National Academy of Sciences http://www3.interscience.wiley.com/cgi-bin/fulltext/118895833/main.html,ftx_abs—q6#q6 105, 818–823.

Houghton, R.A., 1994. The worldwide extent of land-use change. Bioscience 44, 305–313.

Janssens, I.A., Freibauer, A., Ciais, P., Smith, P., Nabuurs, G.-J., Folberth, G., Schlamadinger, B., Hutjes, R.W.A., Ceulemans, R., Schulze, E.-D., Valentini, R., Dohlman, A.J., 2003. Europe's terrestrial biosphere absorbs 7 to 12% of European anthropogenic CO_2 emissions. Science 300, 1538–1542.

Kandler, O., 1992. Historical declines and die-backs of central European forests and present conditions. Environmental Toxicology and Chemistry 11, 1077–1093.

Kauppi, P.E., Mielikäinen, K., Kuusela, K., 1992. Biomass and carbon budget of European forests, 1971 to 1990. Science 256, 70–74.

Kauppi, P.E., Ausubel J.H., Fang, J., Mather, A., Sedjo, R.A., Waggoner, P.E., 2006. Returning forests analyzed with the Forest Identity. Proceedings of the National Academy of Sciences http://www3.interscience.wiley.com/cgi-bin/fulltext/118895833/main.html,ftx_abs—q6#q6 103, 17574–17579.

Kauppi, P.E., Rautiainen, A., Korhonen, K.T., Lehtonen, A., Liski, J., Nöjd, P., Tuominen, S., Haakana, M., Virtanen, T., 2009. Changing stock of biomass carbon in a boreal forest over 93 years. Forest Ecology and Management (this issue), doi:10.1016/j.foreco.2009.07.044.

Kuusela, K., 1994. Forest resources in Europe 1950–1990. Cambridge University Press, Melbourne.

Lehtonen, A., Mäkipää, R., Heikkinen, J., Sievänen, R., Liski, J., 2004. Biomass expansion factors (BEF) for Scots pine, Norway spruce and birch according to stand age for boreal forests. Forest Ecology and Management 188, 211–224.

Luyssaert, S.E., Schulze, D., Börner, A., Knohl, A., Hessenmöller, D., Law, B.E., Ciais, P., Grace, J., 2008. Old-growth forests as global carbon sinks. Nature 455, 213–215.

Mather, A.S., 1992. The forest transition. Area 24, 367–379.

Nabuurs, G.J., Thürig, E., Heidema, N., Armolaitis, K., Biber, P., Cienciala, E., Kaufmann, E., Mäkipää, R., Nilsen, P., Petritsch, R., Pristova, T., Rock, J., Schelhaas, M.J., Sievänen, R., Somogyi, Z., Vallet, P., 2008. Hotspots of the European forests carbon cycle. Forest Ecology and Management 256, 194–200.

Peters, G.P., Marland, G., Hertwich, E.G., Saikku, L., Rautiainen, A., Kauppi, P.E., 2009. Trade, transport, and sinks extend the carbon dioxide responsibility of countries: An editorial essay. Climatic Change. In Press.

Smith, W.B., Miles, P.D., Vissage, J.S., Pugh, S.A., 2002. Forest Resources of the United States, General Technical Report NC-241 (US Department of Agriculture, Forest Service, North Central Research Station, St. Paul, MN).

UNFCCC, 2008. Annex 09 CRF Tables LULUCF v2.1: sectoral background data for land use, land-use change, and forestry.

Waggoner, P.E., Ausubel, J.H., 2007. Quandaries of forest area, volume, biomass, and carbon explored with the forest identity. Connecticut Agricultural Experiment Station Bulletin 1011, 1–13.

Please cite this article in press as: Rautiainen, A., et al., Carbon gains and recovery from degradation of forest biomass in European Union during 1990–2005. Forest Ecol. Manage. (2009), doi:10.1016/j.foreco.2009.07.043