Reg Environ Change
DOI 10.1007/s10113-007-0024-6

ORIGINAL ARTICLE

Long-term dynamics of terrestrial carbon stocks in Austria: a comprehensive assessment of the time period from 1830 to 2000

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Received: 23 November 2006 / Accepted: 18 January 2007

Abstract This article presents a comprehensive data set on Austria's terrestrial carbon stocks from the beginnings of industrialization in the year 1830 to the present. It is based on extensive historical and recent land use and forestry data derived from primary sources (cadastral surveys) for the early nineteenth century, official statistics available for later parts of the nineteenth century as well as the twentieth century, and forest inventory data covering the second half of the twentieth century. Total carbon stocks—i.e. aboveground and belowground standing crop and soil organic carbon—are calculated for the entire period and compared to those of potential vegetation. Results suggest that carbon stocks were roughly constant from 1830 to 1880 and have grown considerably from 1880 to 2000, implying that Austria's vegetation has acted as a carbon sink since the late nineteenth century. Carbon stocks increased by 20% from approximately 1.0 GtC in 1830 and 1880 to approximately 1.2 GtC in the year 2000, a value still much lower than the amount of carbon terrestrial ecosystems are expected to contain in the absence of land use: According to calculations presented in this article, potential vegetation would contain some 2.0 GtC or 162% of the present terrestrial carbon stock, suggesting that the recent carbon sink results from a recovery of biota from intensive use in the past. These findings are in line with the forest transition hypothesis which claims that forest areas are growing in industrialized countries. Growth in forest area and rising carbon stocks per unit area of forests both contribute to the carbon sink. We discuss the hypothesis that the carbon sink is mainly caused by the shift from area-dependent energy sources (biomass) in agrarian societies to the largely area-independent energy system of industrial societies based above all on fossil fuels.

Keywords Carbon stock · Terrestrial carbon sink · Forest transition · Environmental history

Introduction

Terrestrial vegetation plays a crucial role in the global carbon cycle. Plants and soils contain carbon and represent large carbon pools. Gross primary production (GPP) and ecosystem respiration are major global carbon flows between biota and the atmosphere. Human activities affect these stocks and flows of carbon, both directly and indirectly, thus inducing changes in the size of the carbon pools related to biota and soils and thereby altering the global biogeochemical carbon cycle (Watson et al. 2000; Schimel 1995; Houghton et al. 1983). Land-use related changes in the carbon cycle occur at an increasing rate around the globe, with remarkable regional variations, especially between industrialized and developing countries (Houghton 2005). In the northern hemisphere, biota and soils are currently thought to absorb considerable amounts of carbon each year, thus acting as carbon sink (Dixon et al. 1994; Goodale et al. 2002). This function of vegetation has been recognized in the Kyoto protocol

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which allows countries to get credits for defined land-use induced carbon sinks (i.e. the net effect of afforestation, reafforestation and deforestation), in effect lowering the targets of many industrialized countries to reduce greenhouse gas emissions resulting from fossil fuel combustion or industrial processes such as cement manufacture.

The mechanisms underlying vegetation's medium-term carbon uptake are at present only partly understood, however. Important questions that have still not been entirely clarified are, among others, why, how, since when, and through which compartments biota serve as carbon sinks and, in particular, how this process is related to socioeconomic activities. The forest transition hypothesis (Mather 1992; Rudel et al. 2005; Kauppi et al. 2006) relates the carbon sink function of forests with recent processes of economic development in the so-called developed countries. In our study, we aim to contribute to this debate by empirically quantifying the extent and historical dynamics of the terrestrial carbon sink in Austria in a long historic time series ranging from 1830 to the year 2000.

Several studies have analysed the effects of climate change on the dynamics of carbon stocks with process-based models that are able to simulate carbon pools and fluxes in biota and soils, generally using data on soils and climate as input parameters (Bugmann and Pfister 2000; Schmid et al. 2006; Sitch et al. 2003). Complementary to these modelling exercises we here present a databased assessment focused on the effects of land use and its dynamics in the last two centuries. We empirically assess the amount of carbon stored in biota and soils in Austria in the period 1830–2000 based on the vast historical databases available in Austria. The *Franciscean Cadastre* (‘‘Franzisceischer Kataster’’) contains information on land use and land cover for all Austrian cadastral municipalities (today approximately 7,850) in the early nineteenth century, a time when Austria's industrialization was about to take off. By combining data from this source with official historical and recent statistics and forest inventory data we compile a consistent time series for the last 170 years. This allows to assess the dynamics of terrestrial carbon stocks from a pre-industrial point in time to the year 2000, thus shedding light on the long-term effects of the industrialization process on a country's carbon stocks. In order to provide insight into the changing role of natural, semi-natural and managed ecosystems in the Austrian land use system, we complement this assessment with an estimate of the country's potential carbon stock in soils and biota; that is, the carbon that would be stored in the—hypothetical—absence of human activities.

The rare occurrence of such a rich historic database as the *Franciscean Cadastre* makes Austria a useful case for studying the long-term dynamics of terrestrial carbon stocks. Austria is a small, highly industrialized Central European country, with medium population density (area 83,000 km^2, current population about 8 million, 96 inhabitants per km^2). It is situated in the temperate zone of the northern hemisphere. A large part of the country is dominated by the Alps, which implies the existence of complex, three-dimensional continua of abiotic gradients, e.g. along mountain slopes, and a heterogeneous mosaic of land cover and land use. Austria has today a comparably high share of forest cover of 47% (the EU-average is 40%). Forests prevail mainly in hilly and mountainous areas of central and western Austria, whereas the lowlands are characterized by intensive agriculture.

Materials and methods

The aim of this study is to create a consistent time series of carbon stocks in Austria's biota and soils from the early nineteenth century until today that includes all important carbon pools: aboveground and belowground standing crop and soil organic carbon. The study is based on a simple accounting approach. Carbon stocks in terrestrial vegetation are estimated by (a) segmentation of the area into units assumed to be homogenous with respect to carbon density [= carbon stock per unit area, (kg C/m^2)] and (b) assessing and modelling of typical carbon densities for these spatial units. Special methodological attention was paid to the aboveground carbon density of forests, because forests store 10 to 20-times more aboveground carbon per unit area than all other land use types (Olson et al. 1983). The study is restricted to terrestrial ecosystems and excludes water bodies.

Land use

The area of reference in this study is Austria in its current boundaries, excluding the province of Burgenland (approximately 5% of Austria's area). The Burgenland belonged to the Hungarian part of the Austro-Hungarian Monarchy until its collapse after the First World War; therefore, no consistent data are available there. Starting point of the assessment is a consistent land-use dataset for the period 1830–2000 that distinguishes the categories arable land, grassland, forest, alpine pastures, water bodies (which we excluded) and settlement/infrastructure area (subsequently referred to as ‘‘built-up land’’) (Krausmann

2001). The time cuts in this data set (1830, 1880, 1910, 1930, 1959, 1969, 1979, 1986, 1990, 1995 and 2000) refer to years of good data availability, i.e. of cadastral surveys.

This dataset does not differentiate between commercial and non-commercial forests and between extensively and intensively used grassland. As carbon densities of these subcategories differ considerably, we extended the original land-use dataset as follows. Based on land-use and forest statistics, ''grassland'' was split into ''intensive grassland'' (meadows mowed more than once yearly and fertilized pastures) and ''extensive grassland'' (meadows mowed once yearly and unfertilized pastures), and ''forest'' was split into ''commercial forest'', referring to all managed forests used for wood extraction, and ''non-commercial forest'', i.e. forested areas not available for use. Figure 1 displays the land use data set of Austria from 1830 to 2000 used in this study.

Aboveground standing crop

Carbon densities of aboveground standing crop (SC_a) were assessed for all land-use categories mentioned above. For the calculation of aboveground carbon densities of forests, data on standing timber volumes were collected from the literature and databases for all data points. When data available did not fully match the time cuts of the land-use dataset used in this study, they were projected to the nearest time cut of the land-use dataset by linear interpolation. Differences in data quality, aggregation, and coverage made it necessary to follow three different approaches in the calculation of aboveground carbon stocks in forests, one for the year 1830, another for 1880 and a third for the period 1959–2000. Table 1 summarises data sources and coverage used for the different periods.

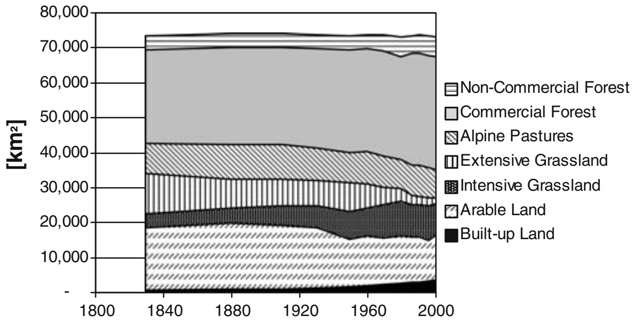

Fig. 1 Land use in Austria 1830–2000. Sources: Krausmann (2001), own calculations (split-up of grassland and forest ecosystems). For details, see text

For the year 1830, we used historical forest data from the *Franciscean Cadastre* (for detailed descriptions of this source see Moritsch 1972; Sandgruber 1979). The statistical body of the *Franciscean Cadastre* (the so-called *Catastral-Schätzungs-Elaborate*), was collected in the period 1830–1850 and is available for all Austrian provinces except Styria, Tyrol and Vorarlberg. In this cadastre, detailed information on forests is given on the level of cadastral municipalities, including values on forest area, rotation period, rotation age, gross harvest at the end of the rotation period, tree species composition, type of use, side uses and descriptions of soil and topography. The information is only available for cadastral municipalities and has so far not been aggregated to higher-level administrative units (i.e. municipalities, districts, provinces, the national level).

As data extraction from the *Franciscean Cadastre* is tedious and work-intensive, we selected a representative sample of cadastral municipalities. From this sample, the information was then extrapolated to the national territory. In a first step, municipalities were selected in those provinces for which *Catastral-Schätzungs-Elaborate* exist (Lower Austria, Upper Austria, Carinthia and Salzburg), based on a systematic sampling approach on a grid with cells sized 20 × 20 km. Within each of the municipalities selected, one or two cadastral municipalities were randomly chosen. This sample was complemented with additional municipalities in order to represent more ecological diversity by including more forest growth regions (Kilian and Müller 1995) and regions near provinces for which no data are available. Figure 2 depicts all municipalities in which one or more cadastral municipalities were selected. Furthermore, Fig. 2 shows the borders of Austria's forest growth regions, and the grid used for the systematic sample approach. In total, data were gathered from 84 cadastral municipalities. Forest area in this sample covers approximately 3% of Austria's forest area in the mid-nineteenth century (Wessely 1853).

Wood dendromass volumes, i.e. standing volumes of bole wood including bark, were calculated for each cadastral municipality on the grounds of the information on dominant tree species and gross harvestable stock at the end of the rotation period (Dm_t), denoting the amount of wood harvestable at the end of the rotation period of the respective forest stand. Historic dendromass volume units [*Klafter 30zöllige Scheite*] were converted to the SI measure of volume (m^3) using a conversion factor from the literature (Sandgruber 1978). Forests do not only consist of mature forest stands, but rather also of a variable distribution of all

Table 1 Data used for the reconstruction of wood stocks in the different points in time and provinces

	km^2	Percent of forest area		
		1830	1880	1960–2000
Lower Austria, incl. Vienna	19,593	3% (n = 35[a])	4%	100%
Upper Austria	11,987	5% (n = 21[a])	16%	100%
Salzburg	7,154	5% (n = 13[a])	53%	100%
Carinthia	9,536	5% (n = 15[a])	4%	100%
Styria	16,392	Modelled	6%	100%
Tyrol	12,648	Modelled	11%	100%
Vorarlberg	2,601	Modelled	2%	100%
Burgenland	3,966	Not covered	Not covered	Not covered
Austria total	83,871			
Austria without Burgenland	79,905	3% (n = 84[a])	10%	100%

Sources: 1830: Franciscean Cadastre, 1880: Schindler (1885), 1960–2000: Forest Inventories

[a] n denotes the number of cadastral communes used as samples

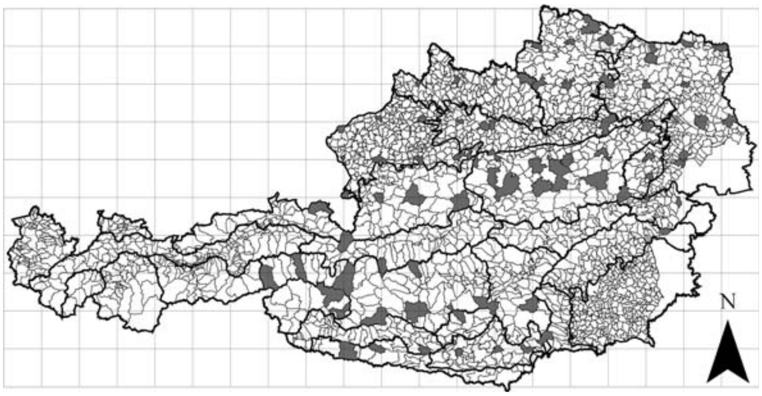

Fig. 2 Sample of political municipalities for the assessment of the 1830 wood density. *Thin contours*: boundaries of the municipalities, *thick contours*: forest growth regions after Kilian and Müller (1995)

age classes. In order to assess the distribution of age classes in Austria's forests around 1830, data on age class distribution of Lower Austria, the province with the most detailed data sources, were compiled for all municipalities available. In almost half of the forests (48%), age distribution was denoted as homogeneous, while young stems dominated in 23% of the forest area, and old stems in 10%. Nineteen percent of the area was described as coppice or alluvial forest. Thus, for the calculation of actual wood stocks, the biomass volumes of younger forest stands ($\sum$Dm) were estimated assuming equal age distribution.

Based on forestry yield tables (Marschall 1975) that give information on biomass volumes according to tree species, growth class and forest stand age, data on gross harvestable stock and dominant tree species were used to calculate the biomass volumes of pre-mature forest stands according to the identified growth classes. In order to reflect the fact that actual forests are not fully stocked but thinned out by competition between individuals, disturbances etc., values of ''mass remaining stock'' were derived from the forest yield tables, instead of ''mass total stock''. Total biomass volume ($\mathrm{DM_a}$) was then calculated as the sum of standing volumes of all age classes, including half of the gross harvestable stock, divided by the rotation period (t), which reflects maximum stand age. This calculation was performed using the following equation:

$$\mathrm{Dm_a} = \frac{\left(\sum \mathrm{Dm} + \mathrm{Dm}_t/2\right)}{t}. \tag{1}$$

Average dendromass volumes per unit area were calculated for the different forest growth regions (Kilian et al. 1994; Kilian and Müller 1995) in order to reflect differences in wood stocks in different biogeographic conditions. Total standing volumes of wood were then calculated by multiplying dendromass density by forest area (Wessely 1853) for each forest growth region in each province. For provinces with no data, wood densities of the same or—if unavailable—of similar forest growth regions in adjacent provinces were used to estimate total volumes of standing wood.

For 1880, standing wood volumes were derived from a nation-wide database (Schindler 1885, 1889) that contains data on forests in governmental tenure (''*Staats- und Fondsforste*'') and covers 10% of Austria's total forest area in this period (Wessely 1882). Data on wood densities were applied to total forest area, thus obtaining an estimate of the total dendromass stock.

From 1961 onwards, regular forest inventories for Austria's forests were carried out by the Institute for Forest Inventory (*Institut für Waldinventur*) at the Research and Training Centre for Forests, Natural Hazards and Landscape. Detailed data on forest stocks, age distribution, tree species distribution and forest management are available for the inventory periods 1961–1970, 1971–1975, 1976–1980, 1981–1985, 1986–1990, 1992–1996 and 2000–2002. The dendromass volume estimates of these inventories have been standardized and made available in a consistent manner (Weiss et al. 2000).

Aboveground forest carbon stocks were calculated from dendromass stocks using IPCC standard methodology (Penman et al. 2003), assuming a carbon content of biomass of 50% and applying IPCC biomass expansion factors in order to reflect biomass compartments such as branches and twigs, leaves, fruit, blossoms, and understorey: 1.3 for coniferous and 1.4 for non-coniferous forests (Penman et al. 2003).

The standing crop of agricultural areas was calculated as maximum carbon stocks, i.e. as the standing biomass at the time of harvest (Erb 2004a), in order to be consistent with the forestry carbon stock assessment, which includes annual biomass fractions. Agricultural carbon stocks were assessed on the basis of estimates of agricultural productivity (Krausmann 2001), applying factors to reflect pre-harvest losses due to insectivory. Other non-forest ecosystems were calculated based on typical carbon density values of different ecosystems taken from a previous study (Erb 2004a). With respect to alpine pastures we took into account the supposition that the tree line was higher in earlier periods (Ellenberg 1996), assuming a decrease of shrub cover in this ecosystem type of 20% in the period before 1960. Extensive grassland was assumed to contain 10% forest cover (which we did not assume to exist in intensive grasslands), in order to account for the higher biomass density caused by the extensive use. Average carbon densities of forests in the respective year were applied to estimate carbon stocks of the forested fraction of extensive grasslands. For non-commercial forests, we used the average carbon density of the potential vegetation in Austria (Erb 2004a). Standing crop on built-up land was calculated assuming that one third of its area was covered by vegetation, which was in turn assumed to consist of equal shares of grassland and forest. The carbon densities of all land-use categories are depicted in Table 2.

Belowground carbon stocks

Belowground carbon stocks formed by living plants (belowground standing crop, SC_b) were calculated as percentage of the aboveground carbon density of the respective land-use type based on factors published in

Table 2 Carbon densities of aboveground standing crop (SC_a), belowground standing crop (SC_b) and soil organic carbon (SOC) in different land-use types, 1830–2000

	Built-up land	Arable land	Intensive grassland[a]	Extensive grassland	Alpine pastures	Commercial forest	Non-commercial forest[a]
SC_a [kg C/km^2]							
1830	1.4	0.2	0.3	0.5	0.6	4.0	13.0
1880	0.9	0.2	0.3	0.6	0.4	4.3	13.0
1910	1.0	0.3	0.3	0.5	0.3	5.1	13.0
1930	1.1	0.3	0.3	0.6	0.3	5.5	13.0
1949	1.2	0.4	0.3	0.6	0.2	5.9	13.0
1959	1.2	0.4	0.3	0.6	0.2	6.3	13.0
1969	1.2	0.4	0.3	0.6	0.2	6.5	13.0
1979	1.3	0.5	0.3	0.6	0.2	6.8	13.0
1986	1.4	0.5	0.3	0.6	0.2	7.3	13.0
1990	1.5	0.5	0.3	0.6	0.2	7.4	13.0
1995	1.5	0.5	0.3	0.6	0.2	7.5	13.0
2000	1.5	0.5	0.3	0.7	0.2	8.2	13.0
SC_b [% of SC_a]							
All years	20	15	70[b]	70[b]	75[c]	20	20
SOC [kg C/m^2]							
All years	6.7	6.7	13.5	16.2	14.2[d]	11.4	11.4

Sources: Erb (2004a), Krausmann (2001), own calculations

[a] In intensive grassland and non-commercial forests, the same carbon densities were used for the entire time period

[b] In the years 1830 and 1880, SC_b was assumed to amount to 50% of SC_a in all grasslands

[c] In the years 1830 and 1880, SC_b was assumed to amount to 70% of SC_a in alpine pastures

[d] Average, see text

the literature (Körner et al. 1993; Jonas and Nilsson 2001). According to historic changes in the intensity of land use in grasslands and alpine pastures, slightly lower percentages were applied in these land use categories for the nineteenth century than for the twentieth century (see Table 2).

For soil organic carbon (SOC), the available site-specific data (Umweltbundesamt 2006) could not be used for our landscape-wide assessment due to the large variability in the primary data. As our dataset does not include information on the exact points in time or place at which land-use changes occurred, management-related changes in SOC densities (Guo and Gifford 2002; Murty et al. 2002) could also not be considered.

Instead, we followed a vegetation approach, assuming typical carbon densities (Körner et al. 1993) for the ecosystem types discerned in our land-use dataset for all points in time. The only exception was made in alpine pastures where we supposed that the increase in dwarf-shrubs in the twentieth century (Ellenberg 1996) influenced SOC densities (Körner et al. 1993). To account for this effect we assumed SOC in alpine pastures to rise from 13.4 kg C/m^2 in 1830 to 16.8 kg C/m^2 in 2000. In the absence of better data, we assumed that the SOC value of built-up land was equal to that of arable land. The carbon densities of SOC are summarized in Table 2.

In order to assess uncertainties of our results with reference to changes in SOC—the compartment with the largest uncertainties—we carried out the following sensitivity analysis: We varied assumptions on SOC density for all land-use classes according to the variability in SOC density data reported in the Austrian Carbon Database ACDb (Jonas and Nilsson 2001) without changing all other parameters (area of the land-cover classes, SC_a and SC_b). In order to estimate the lower boundary of the carbon sink strength, the lowest SOC values for all land-use classes that increased in area during the period of analysis and the highest SOC value for all land-use classes that decreased in area were assumed. For the estimate of the upper boundary of the carbon sink strength, we used the opposite assumption. This analysis was carried out to assess yearly sink strengths of SOC for two periods differing in carbon uptake and data reliability: 1830–1949 and 1949–2000.

Potential carbon stock

Complementary to the time series, we also estimated the potential carbon storage in Austria's terrestrial vegetation, i.e. the carbon stock that would prevail in Austria's vegetation in the—hypothetical—absence of human activities. This calculation was based on an existing assessment of potential aboveground standing crop (Erb 2004a) and completed by an estimate of the belowground fractions, i.e. SC_b and SOC. For the assessment of these compartments, the above-discussed factors and multipliers were used.

Results

According to our results, current carbon stocks in Austria's biota and soils currently amount to only 62% of the potential carbon stock (Fig. 3). Austria's potential vegetation—that is, the vegetation thought to prevail in the absence of human activities—and the soils thought to prevail under these conditions, were found to contain 2,023 MtC. This carbon stock was about equally distributed between aboveground and belowground compartments. Human impacts on carbon stocks are particularly significant in the plant compartments, i.e. SC_a and SC_b, whereas SOC seems to be almost unchanged by human activities. SOC amounts to approximately 800 MtC, representing a major share of the carbon stocks present over the entire period. Results in SOC stocks need to be interpreted particularly cautiously, as only rough proxies of carbon densities in the different land use types were used.

From 1830 to 1880, carbon stocks in Austria's vegetation were found to be approximately constant around 1,042 MtC. Since then, carbon stocks increased

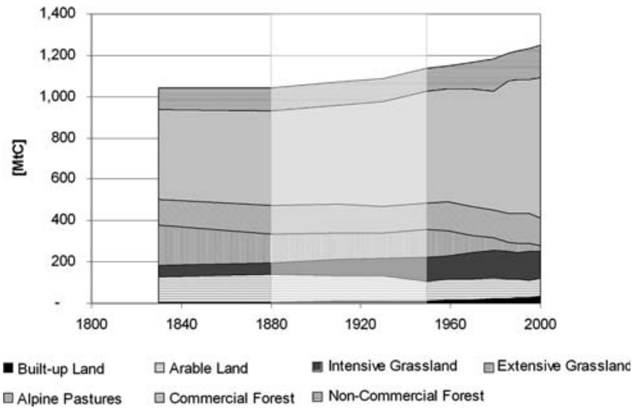

Fig. 3 Potential, historic and current carbon stocks in Austria's vegetation, broken down to aboveground and belowground compartments. Data on carbon density, a major determinant of the carbon stocks depicted here, were interpolated for the period from 1880 to 1950 (*shaded area*). Source: own calculations, see text

monotonously to 1,249 MtC in the year 2000. Note that for the period between 1880 and 1960, no data are available on carbon densities of forests. For this period, biomass density data were interpolated linearly; the results depicted in Fig. 3 for that period, thus, do not reflect possible short-term fluctuations of carbon densities. It can nevertheless be clearly seen that carbon stocks were significantly lower in 1880 than in 1960. As shown in Fig. 3, total carbon stocks in Austria's vegetation increased by 20% or 206 MtC from 1880 to 2000. Growth of the aboveground compartment (SC_a) contributes 87% to the overall increase, the belowground biomass stock (SC_b) accounts for another 16%, whereas our calculation of SOC changes resulted in a slight carbon loss of approximately 7 MtC that reduced the overall carbon gain by some 4%.

The main drivers behind the increasing carbon stocks of Austria's vegetation are the increase in area and aboveground carbon densities of commercial forests. These two drivers result in a massive increase of 58% or 250 MtC carbon stock in this land use category, as Fig. 4 reveals. This expansion also changes the share of commercial forests in the overall terrestrial carbon stocks, which increased from 42% in 1830 to 55% in 2000. Non-commercial forests play only a much smaller role, contributing 10% in 1830 and 12% in 2000 to the overall carbon stock. The amount of carbon stored in non-commercial forests nevertheless grows by 42% over the period due to the increase of its area. Overall, the share of forested ecosystems in the total carbon stock increased from 52% in 1830 to 67% in the year 2000.

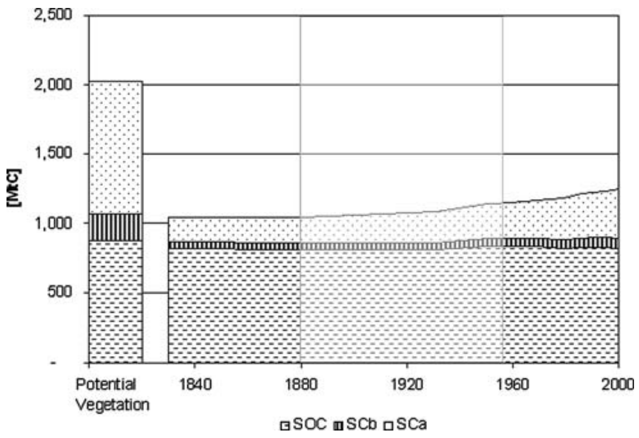

Fig. 4 Contributions of different land-use types to Austria's terrestrial carbon stocks from 1830 to 2000. Data on carbon density, a major determinant of the carbon stocks depicted here, were interpolated for the period from 1880 to 1950 (*shaded area*). For abbreviations and sources see text. Source: own calculations, see text

Figure 5 compares the increase in forest area with the increase in wood stocks per unit area (= carbon densities, see Table 2) of all forests, commercial and non-commercial. Both forest area and forest carbon densities increased significantly over the entire period: Carbon density grew by 26% since the year 1830, while forest area rose by 23%. The increase in forest carbon densities is due to increases in standing crop (SC_a and SC_b), which have more than doubled over the period of investigation. While forest carbon densities increased only slightly in the nineteenth century, they grew significantly (on average by 0.1% per year) in the period from 1880 to 1960. After 1960, forest carbon densities have kept on growing at increasing pace, reaching a level of 84% of the carbon density in potential forest vegetation in 2000. Forest area grew more slowly than forest carbon density in the twentieth century and has caught up only recently.

Increases in the amount of carbon stored in forests are partially counterbalanced by losses of belowground carbon stored in grasslands. Grasslands are particularly important due to their high carbon density in SOC, a value that is also affected by changes in land-use intensity (see Table 2). Grassland areas decreased over the entire period by about 30% (Krausmann 2001). This decrease, however, was combined with a shift in grassland composition: Intensive grassland doubled in area from 3,900 km^2 in 1830 to 8,900 km^2 in 2000 at the expense of extensive grasslands that decreased by about 86% from 11,500 to 1,600 km^2. This land-use change resulted in a carbon release of roughly 100 MtC.

Carbon stocks in arable land are of less importance than those of forests and grasslands. They decreased by 24%, almost all of which was due to a decrease in the

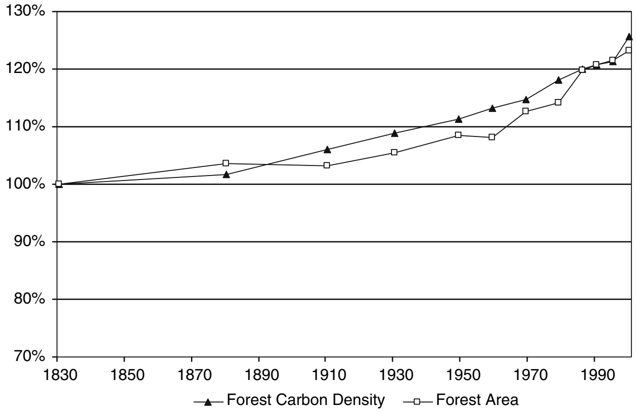

Fig. 5 Changes in carbon density and area of Austria's forests since 1830. Sources: forest area: Krausmann (2001), carbon density in forests: own calculations, see text

area of arable land (minus 27% from 1830 to 2000). Carbon density of croplands increased slightly due to productivity gains (see Table 1; Krausmann 2001). Carbon stocks on arable land contribute 7–12% to the overall carbon storage in Austria. Built-up area is the least important land-use type with respect to the amount of carbon stored. This land-use category grew most strongly, however. The amount of carbon stored in this type of land use increased by more than 500% from 6 MtC in 1800 to 31 MtC in 2000, owing to expansions of the area covered by this land-use category.

The sensitivity analysis on the possible effect of uncertainty in assumptions on SOC densities of the different land-use categories on the temporal development of SOC showed that these uncertainties were not large enough to reverse the result. According to the sensitivity analysis, Austria's biota and soils have acted as a carbon sink for both periods, 1830–1949 and 1949–2000 (see Fig. 6). In the earlier period, yearly carbon uptake amounted to 0.82 MtC/year with an uncertainty range of 57% (0.5 MtC/year). From 1949 to 2000, carbon uptake was two times higher with 2.1 MtC/year, whereas uncertainty was relatively lower at 45% (0.9 MtC/year).

Discussion

Our results demonstrate that land-use induced changes in carbon stocks in Austria's biota and soils are significant and have been so during the last 170 years. While in the nineteenth century, carbon stocks have stayed roughly constant; they have been growing continuously since then. In 1830 and 1880, carbon stocks in biota and soils amounted to only 51% of those thought to be present in the absence of land use. By 2000, carbon stocks had already grown to 62% of potential terrestrial carbon stocks. This long-term increase is to a large extent due to the growth of aboveground carbon stocks in forests. Therefore, the discussion on carbon stock changes in Austria needs to focus on Austria's forest growth dynamics.

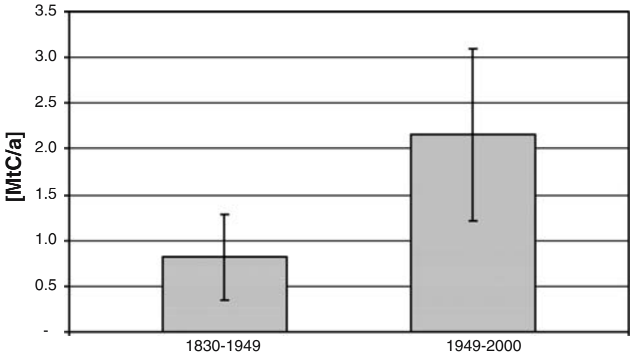

Fig. 6 Estimate of the aggregate (above- and belowground) yearly carbon uptake of Austria's vegetation 1830–2000. Source: own calculations, see text

The results are consistent with previous studies (Erb 2004a; Erb et al. 2007); the general trend—growing carbon stocks—seems to be robust. However, the precise numbers, particularly those referring to the early data points, have to be interpreted cautiously because the original data used for calculating SC_a and SC_b of forests were collected in a different context and on another spatial scale than the data underlying the forest inventories of the second half of the twentieth century. In order to test the robustness of results with respect to factors used to convert dendromass volume to SC_a and SC_b stocks, we also performed these conversions using alternative assumptions and factors (Körner et al. 1993; Erb 2004a). Using these different assumptions resulted in slight changes in the overall mass of SC_a and SC_b but did not affect the observed trend over time.

The assessment of SOC stocks is most uncertain. Particularly, we could not take into account changes in SOC densities due to changes in land management beyond the distinction of intensive and extensive grasslands. We nevertheless believe that the use of static SOC density values is reasonable because improved management might lead to increases or decreases in SOC (Dersch and Böhm 2001) and available data are not sufficient to decide which of the possible effects could be more pronounced. The sensitivity analysis described earlier reveals that uncertainties related to our assumptions on SOC densities are not sufficient to reverse the observed general trend of carbon stock increase in Austria's vegetation: The use of different assumptions can reverse the slightly negative trend of SOC stocks. Even the most conservative assumptions on SOC stocks, however, do not reverse the overall trend of growing carbon stocks in Austria's terrestrial vegetation.

The forest transition hypothesis describes the phenomenon of forest growth in developed countries in the course of industrialization, based on a large number of national and regional case studies (Mather 1992; Mather and Needle 1998; Rudel et al. 2005; Kauppi et al. 2006). Our findings support this hypothesis: Just like in many other industrialized countries of the northern hemisphere, Austria's forest area has grown considerably (+23%) in the last 170 years. This growth in forest area has contributed significantly to the forests' function as carbon sink. Our data suggest that the process of carbon stock reduction must have taken place before the starting point of our investigation or during the period between the first two data points. There must have been a "turning point"—i.e. a minimum of carbon stocks in Austria's biota and soils—most probably in the early or mid-nineteenth century. At that point, Austria's biota and soils turned from a net carbon source to a net carbon sink.

A potential driver for the observed increase in terrestrial carbon stocks could, in principle, also be the externalisation of pressures on land resulting from increased imports of biomass-derived products. This explanation is not convincing in the case of Austria, however, because imports and exports of biomass, and even wood and wood-related products, are roughly balanced and have been so throughout the twentieth century (Erb 2004b).

Both forest area growth and forest carbon density increase, were about equally important drivers of the growth in carbon stocks. In principle, growth in the forests' carbon densities can result from two factors: (a) effects from global environmental change, in particular a possible carbon fertilization effect (e.g. Caspersen et al. 2000; Schindler et al. 2000; Sitch et al. 2003), (b) changes in forest management. It is evident that it is not possible to discern these two effects on the basis of the methods used in this study: This could only be achieved through an effort that would combine the data-driven approaches used here with process-based modelling—an endeavour that was beyond the scope of this study.

There are good reasons, however, to assume that changes in forest management have contributed significantly to the growth in carbon densities in forests, even if this factor may not entirely explain this trend. During the last 170 years, Austria underwent a transition from a barely industrialized country mainly based on an agrarian subsistence economy to a highly industrialized, fossil-fuel powered economy—a transition that profoundly changed Austria's "energetic metabolism" (Krausmann and Haberl 2002). On the one hand, industrialization brought about land-saving technological innovations in agriculture that allowed to gain much more agricultural produce on ever-smaller areas, thus allowing for a considerable increase in forested area (Krausmann 2001; Krausmann and Haberl 2002; Krausmann et al. 2003). On the other hand, the availability of fossil fuels has also greatly mitigated the pressure on forests to deliver fuel wood for domestic and industrial consumption and has freed forests from the side uses prevailing in agrarian societies, thus contributing to increasing carbon stocks per unit of forest area.

This is closely related to the transition of the socioecological regime during industrialization (Krausmann 2006; Sieferle et al. 2006): Under the conditions of an agrarian socioecological regime, as it prevailed in Austria in the early nineteenth century, socioeconomic energy supply came almost exclusively from agriculture and forestry. Forests played an important role: Not only did wood serve as the main source of technical and heating energy before the use of coal gained importance, but forests were also used in various other ways, such as nutrient provision (litter outtake) and grazing. [For detailed descriptions of forest conditions in Austria and the changing uses in the course of industrialization see the extensive treatment of regional forest history in Österreichischer Forstverein (1983) for Austria as a whole, Oberrauch (1952) for Tyrol, Johann (1968) for Carinthia, Hafner (1979) for Styria, and Koller (1970) for the Salzkammergut region]. The intensive use of forests resulted in a degradation of wood stocks on forested areas, leading to carbon densities that were significantly lower than today. In the course of industrialization, as area-independent fossil energy carriers became available for more and more technical processes, replacing wood as key energy source, societal pressure on forests decreased. Therefore, it seems plausible that at least a considerable proportion of the observed vegetation thickening is due to the fact that forests were allowed to recover from intensive, multi-functional use, thus gaining in carbon densities. In line with observations by Wernick et al. (1998) in the United States, our data suggest that this process took place in Austria primarily in the twentieth century.

Just like the increase of carbon densities, the increase of forest area can be understood as a side-effect of industrialization: As area productivity in agriculture rose due to the intensification of agriculture, areas formerly used as agricultural land were abandoned or actively reforested, resulting in an increase of forest area. While the process of vegetation thickening is constrained by ecological upper limits (aboveground forest carbon density in Austria already amounts to 78% of that of potential vegetation), the growth of forest areas could—in theory—go on, continuously resulting in a carbon sink. However, the share of forest cover in Austria is already relatively high (47%), in some regions even posing problems to rural development, so, the future forest area growth may be constrained by social factors.

Erb et al. (2007), have described the phenomenon of growing carbon stocks in vegetation in the course of industrialization as "fossil-fuel powered carbon sink" (see also Haberl 2001). In our view, forest dynamics are not directly interlinked with one social or economic parameter such as population density or income (Mather et al. 1999; Uusivuori et al. 2002), rather they are associated to socioecological regimes (Fischer-Kowalski and Haberl 2007; Krausmann 2006; Sieferle et al. 2006). In this context, growth in area and carbon density of forests does not reflect a release of environmental pressure, but rather a shift of these pressures: instead of relying on the area for the provision of energy, as agrarian societies do, industrial societies draw most of their technical energy from fossil fuels; that is, deposits accumulated in the past. The negative environmental effects of energy use in industrialized countries no longer act on the area directly, but operate on a different scale, for example as changes in the chemical composition of the atmosphere, thus inducing climate change.

What do these insights mean for future carbon stock development in Austria? As we consider recent forest growth to be a side effect of Austria's transition towards a CO_2-emitting industrialized energetic metabolism, we do not believe measures to enhance forestation to be a promising political option for mitigating global warming. Instead, a more sustainable society needs to find ways to 'decarbonize' the socio-economic energy supply or to reduce energy consumption, or both, in order to avoid major atmospheric changes resulting from CO_2 emissions. On the other hand, increased use of biomass is often discussed as one important option to enhance the use of renewable energy. This would, however, again result in increasing pressures on ecosystems, and also on terrestrial carbon stocks, particularly with respect to the aboveground standing crop. Thus, some of the observed trends in terrestrial carbon stocks might be reversed if the socioecological regime changes towards an energy system based to a larger extent than today on biomass use, thus jeopardizing the currently existing carbon sink (Haberl et al. 2003). The careful analysis of such possible feedbacks is one important example of how a long-term socioecological research agenda (Haberl et al. 2006) could contribute to a better understanding of the complex processes of society–nature interaction that have resulted in the currently unsustainable state of the world. Only improved understanding of such feedbacks can ultimately provide a knowledge base for a transition towards a more sustainable future.

Acknowledgments This study is based on research conducted in the project "Carbon household and socio-economic change" funded by the Austrian Academy of Science. It contributes to the Global Land Project (http://www.globallandproject.org) and to ALTER-Net, "A Long-Term Biodiversity, Ecosystem and Awareness Research Network" (http://www.alter-net.info/) launched within the EU's 6th Framework Programme. The authors want to thank Prof. Hubert Sterba for his support and two anonymous reviewers for their helpful comments.

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