Industrialization, Fossil Fuels, and the Transformation of Land Use

An Integrated Analysis of Carbon Flows in Austria 1830–2000

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Summary

Human-induced changes in global stocks and flows of carbon are major drivers of global climate change. This article presents a comprehensive and systemic account of a nation's carbon budget, comprising socioeconomic as well as ecological carbon flows in a historic time series. The example of Austria 1830–2000, for which excellent databases facilitate a comprehensive assessment, suggests that changes in socioeconomic metabolism during the agrarian—industrial transition are intimately linked with changes in land use and natural carbon flows. In the preindustrial agrarian colonization of Austria (during the thousands of years before 1830), a huge amount of carbon was released due to the expansion of agricultural land. At the dawn of Austria's industrialization (1830–1880), this process was terminated, and carbon inflows and outflows of ecosystems were approximately balanced. With rising fossil fuel consumption, Austria's socioeconomic system added growing amounts of carbon to the atmosphere each year. At the same time, fossil-fuel-powered surges in the productivity of agro-ecosystems facilitated the production of growing amounts of agricultural biomass on shrinking agricultural areas. This greatly enhanced ecological carbon flows and, together with decreasing pressures on forests, allowed ecosystems to recover from past depletion and absorb increasing amounts of carbon. The systematic interlinkage between the socioeconomic energy system and carbon flows in ecosystems, as documented in this study, underlines the need for comprehensive and consistent analyses of society—nature interaction to develop monitoring tools and support strategies aimed at a more sustainable future.

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Introduction

Since its beginnings as a historic singularity in England almost 300 years ago, industrialization has spread across the globe and has affected practically every region of the world. Triggered by a series of technological innovations, in particular those required to extract and utilize fossil fuels (Grübler 1998), industrialization resulted in a transition from agrarian societies to a new production pattern based on large-scale, machine-assisted production of goods. This agrarian–industrial transition included an upsurge of the industrial sector as compared to agriculture and handicraft and allowed for steep increases in labor productivity in both industry and agriculture (Sieferle 2001; Sieferle et al. 2006). As a consequence, the volume of the physical flows between societies and their natural environment—that is, socioeconomic metabolism—grew considerably, and their composition changed radically, as resources extracted from subterranean deposits became available in large quantities (Haberl 2006; Fischer-Kowalski and Haberl 2007).

The growth in socioeconomic metabolism associated with industrialization is altering the functioning of the biosphere, thus contributing to global environmental change (Vitousek 1992; Steffen et al. 2004). The use of carbon-rich fossil fuels derived from coal, oil, and natural gas results in carbon emissions into the atmosphere, mainly in the form of carbon dioxide (CO_2) and methane (CH_4). In addition, industrial processes such as cement manufacture contribute between 3% and 4% to total global industrial CO_2 emissions (Marland et al. 2000). As these emissions exceed the absorption capacity of the biosphere, carbon accumulates in the atmosphere. The resulting alteration of the atmosphere's chemical composition is commonly thought to induce fundamental changes in the global climate system. Climate change not only affects mean temperature and precipitation but also increases the frequency and severity of extreme events such as droughts, storms, and floods (Houghton and Skole 1990; Houghton 1995; IPCC 2001, Steffen et al. 2002; Watson and Noble 2002), thus changing ecosystem functions, affecting the provision of ecosystem services, and potentially jeopardizing human well-being.

The agrarian–industrial transition not only fundamentally alters the patterns and magnitude of socioeconomic metabolism, it is also inextricably linked with fundamental changes in land use (Krausmann and Haberl 2002; Fischer-Kowalski and Haberl 2007). By using the land, humans alter ecosystem patterns and processes, thus directly and indirectly affecting the amount of carbon stored in vegetation and soils (Lambin and Geist 2006). In many cases, land-use change results in net carbon losses into the atmosphere from long-accumulated aboveground or belowground carbon stocks in biota and soils (Erb 2004b). Deforestation, for example, greatly reduces the amount of carbon stored in vegetation and often also results in large carbon flows from soils to the atmosphere. Changes in land management may, however, also result in a net carbon uptake of ecosystems—for example, in the case of reforestation (Schimel et al. 2001). Changes in land use and in socioeconomic metabolism are closely linked to each other through a plethora of systemic and complex interlinkages. Above all, a decisive role is played by changes in the socioeconomic demand for food, feed, fiber and energy, technological innovations, and human interventions in ecosystem processes, which, in turn, affect the ability of ecosystems to provide services. The emergence and role of innovations and their effects related to these processes, in particular to the industrialization process in Austria, have been described in detail elsewhere (Haberl 2001b; Krausmann and Haberl 2002; Krausmann et al. 2003; Fischer-Kowalski et al. 2004; Krausmann 2004; Sieferle et al. 2006).

One can understand these interlinkages particularly well by focusing on carbon: Carbon is a vital element for understanding patterns and dynamics of both socioeconomic and ecological systems. It is a major constituent of biomass (approximately 50%) and fossil fuels (more than 75%). Fuelled by solar energy, the reduction of oxidized carbon (CO_2) to energy-rich compounds in the process of photosynthesis is the starting point for all heterotrophic food chains, a fundamental component of ecological energetics (Lotka 1925; Lindemann 1942;

Odum 1971). Carbon compounds are the energetic basis for the entire basal (food, feed) and most of the extended (technical energy) socioeconomic energy metabolism in all human societies, be they hunter-gatherer, agrarian, or industrial societies (Haberl 2001b). A focus on carbon is therefore particularly useful for the analysis of changes in socioecological systems during agrarian—industrial transitions, a prominent issue addressed by long-term socioecological research (LTSER; Haberl et al. 2006).

One such systemic long-term analysis focusing on Austria is presented in this article. We empirically document changes in socioecological (i.e., ecological and socioeconomic) stocks and flows of carbon in Austria in 1830–2000, a period of time covering Austria's industrialization process from its inception to the present. This period of time has witnessed the industrialization of Austria's production system, in particular of agriculture, as well as the recently accelerating natural and socioeconomic dynamics denoted as global change, including globalization as well as environmental change (climate change, change in biogeochemical cycles, etc.). On the basis of an extensive database, we demonstrate the systemic interrelations between Austria's growing consumption of energy derived from fossil fuels (and the related surge in CO_2 emissions) and the associated changes in the carbon budget of Austria's biota and soils, in particular the emergence of a considerable terrestrial carbon sink.

This article aims at comprehensively quantifying Austria's socioeconomic carbon metabolism and its interrelations with natural carbon flows for the period 1830–2000. Austria, situated in the temperate zone of the northern hemisphere, is a highly industrialized central European country with intermediate population density (area 83,000 square kilometers [km^2][1], population about 8 million, 96 inhabitants per km^2). A large part of the country is dominated by the Alpine mountain arch, which implies 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 the hilly and mountainous areas of central and western Austria, whereas the lowlands are mostly used for intensive agriculture. The availability of rich historic databases, comprising data on socioeconomic metabolism as well as information on land use and land cover, makes Austria a useful case for studying the long-term dynamics of carbon flows (Krausmann 2001; Krausmann and Haberl 2002; Gingrich et al. 2007). With this case study, we aim to empirically analyze the agrarian—industrial transition in Austria and quantify its aggregate effects on the overall carbon budget of Austria.

Methods

For the establishment of a consistent and comprehensive carbon account (see Steffen et al. 1998; Nilsson et al. 2000) for Austria, we follow the systematics of national carbon flows displayed in figure 1. We only discuss flows within Austria's territorial boundaries. Carbon contained in import and export (trade) flows is considered, but indirect carbon flows related to trade (e.g., carbon emissions caused by the production of imported goods) are beyond the scope of this study, as these raise a plethora of methodological problems (Erb et al. 2006). Due to the different nature of the carbon flows in social and natural systems, we use a variety of methods. Socioeconomic carbon flows—flow B in figure 1—include carbon emissions due to fossil fuel combustion, cement manufacture, and the socioeconomic use of biomass. These are quantified in a substance flow analysis that is closely related to the material and energy flow accounting (MEFA) framework (Eurostat 2001; Haberl 2001a; Haberl et al. 2004; Weisz et al. 2006). Much larger uncertainties exist with respect to carbon flows related to biota and soils—that is, flow A in figure 1. These flows, comprising gross primary production (GPP), plant (R_a) respiration, and heterotrophic respiration (R_h), are calculated as average annual net flows for longer periods (decades or more) to reduce their annual and interannual variability.

The area of reference of this study is Austria in its current boundaries. For the province of Burgenland (about 5% of Austria's territory), which belonged to the Hungarian part of the Austro-Hungarian monarchy until its collapse after the First World War (WWI), no consistent data for the entire time series are available. For time points before 1920, natural carbon flows in Burgenland were assessed on basis of average

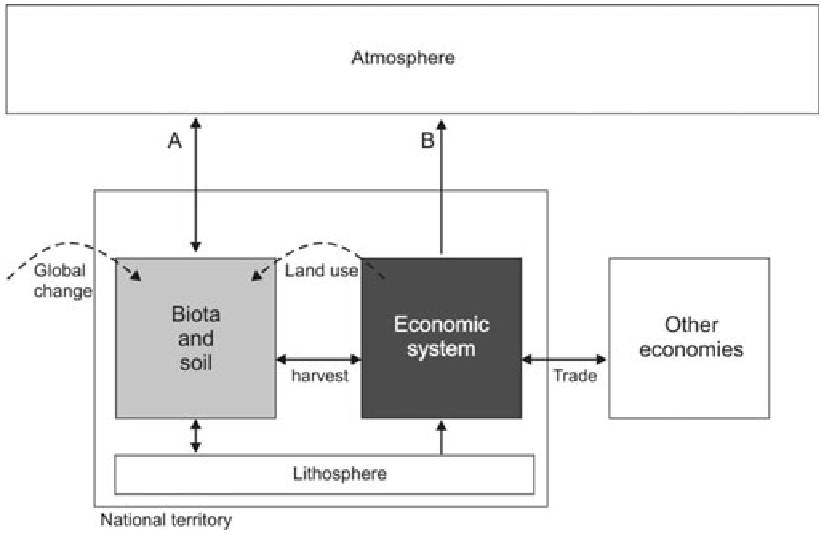

Figure 1 Systematics of the national carbon flows quantified in the study. Solid-line arrows indicate carbon flows. Dashed arrows indicate impacts. A: carbon uptake and release of ecosystems; B: carbon flows resulting from socioeconomic processes.

annual carbon flow data (tC/ha/yr) from the neighboring provinces. Socioeconomic carbon flows were calculated for the entire time series for Austria in its current boundaries (for reference, see Krausmann 2001).

Socioeconomic Carbon Flows

The assessment of socioeconomic carbon flows (i.e., all flows of carbon-rich materials into and out of the socioeconomic system, including import and export) follows the concept of socioeconomic metabolism (Ayres and Simonis 1994; Fischer-Kowalski 1998; Fischer-Kowalski and Hüttler 1998). It is based on an energy flow account (EFA) of Austria from 1830 to 1995 (Krausmann and Haberl 2002) that reports energy flows in gross calorific values (GCV). The data set is based on historical and recent statistical data on the national and—prior to WWI, when Austria in its current boundaries did not exist—regional levels, including the Franciscean Cadastre (Moritsch 1972; Sandgruber 1979). The data set contains data on domestic production, imports, and exports of energy-rich materials until 1995 and was extended to 2000 on the basis of publicly available data (e.g., Statistik Austria 2002). Because the energy content (GCV) of materials is closely related to their carbon content (Machado et al. 2001; Channiwala and Parikh 2002), this data set was suitable to estimate socioeconomic carbon flows. We converted the energetic values of all fossil energy carriers to tons of carbon by applying average carbon contents (BMWA 1990; see table 1). We converted biomass flows from GCV values into dry matter using item-specific conversion factors (for references, see Haberl 2001b) and an average carbon content of dry matter biomass of 50% (Watson et al. 2000). The estimate of carbon flows due to cement production, which is not contained

Table 1 Carbon content and carbon dioxide (CO_2) emissions of fossil energy carriers per unit of gross calorific value (GCV)

Fossil energy carrier	*CO_2 emissions [tCO_2/TJ GCV]*	*C content [tC/TJ GCV]*
Coal	88.2	24.0
Crude oil	66.0	18.0
Natural gas	47.3	12.9

Note: One terajoule (TJ) = 10^{12} joules (J, SI) ≈ 9.48 × 10^8 British Thermal Units (BTU).
Source: Adapted from BMWA 1990.

in this data set, was adopted from the Carbon Dioxide Information Analysis Center (CDIAC) database (Marland et al. 2000).

Carbon Flows Between Ecosystems and the Atmosphere

Before explaining how we proceeded to estimate carbon flows between ecosystems (i.e., biota and soils) and the atmosphere, we here discuss some basic principles of these carbon flows. Carbon flows into ecosystems as green plants take up CO_2 and convert it into energy-rich chemical compounds through photosynthesis, a process denoted as *GPP*. A fraction of *GPP* flows back to the atmosphere as a result of the respiration needed to sustain plant metabolism (autotrophic respiration). The remaining amount of carbon is denoted as net primary production (*NPP*), which provides the basis of all heterotrophic life on earth.[2] *NPP* may accumulate within the ecosystem (Ajtay et al. 1979; Larcher 1984; see figure 4 below) in the form of biomass (denoted as the standing crop of biomass [*SC*]) or as soil organic carbon (*SOC*) in the belowground compartment and build up carbon stocks. Alternatively, *NPP*-related carbon may flow back to the atmosphere as a result of (1) natural processes such as heterotrophic respiration—that is, respiration of wild-living animals, microorganisms, fungi—and natural fires and of (2) socioeconomic processes, most of which are included in socioeconomic metabolism, such as biomass combustion or respiration of livestock and humans (Bolin et al. 1979; Houghton 1995; Steffen et al. 1998; Canadell et al. 2000; Schimel et al. 2001).[3] Equation (1) expresses the relationship of the different carbon flow components between ecosystems and the atmosphere.

$$GPP - R_a = NPP = R_h + NPP_h + \Delta SC + \Delta SOC \qquad (1)$$

GPP denotes gross primary production, R_a plant respiration, *NPP* net primary production, R_h heterotrophic respiration, NPP_h human harvest of biomass, ΔSC the yearly change in standing crop (i.e., the biomass stock of living plants), and ΔSOC the yearly change in soil organic carbon.

Net flows between ecosystems and the atmosphere may be positive (i.e., biota and soil absorb carbon from the atmosphere and act as a "carbon sink") or negative (i.e., biota and soils release carbon into the atmosphere and act as a "carbon source"; Falkowski et al. 2000; Watson et al. 2000). Carbon stocks and flows in biota and soils are simultaneously influenced by natural factors, above all climate, and by human use of ecosystems (i.e., land use). As humans are increasingly altering the climate system, however, human-induced changes in the carbon balance of biota and soils may proceed through both direct (land use) and indirect (global change) pathways (see figure 1; IPCC Working Group I 2003, Field et al. 2004).

Unfortunately, however, many of these flows are not only difficult to assess but also highly variable over the years, above all due to annual variations in climate. As we were interested not in yearly variability but in long-term trends of net carbon flows, we proceeded as follows. As data on *NPP* could be calculated from previous studies (Krausmann 2001), we took these as a basis for approximating *GPP* from *NPP*, assuming the average *GPP*/*NPP* ratio of 2:1 widely used in the literature (e.g., Amthor and Baldocchi 2001). We calculated heterotrophic respiration as the difference between *NPP* and the total of human biomass harvest and average yearly net change in the carbon stocks present in biota and soils; that is, the yearly carbon sink/source of ecosystems, for which we had a reliable time series from previous work (Gingrich et al. 2007). Addition to and depletion of artificial carbon stocks, such as construction wood in buildings, were omitted due to their relatively small role and also due to the methodological intricacies involved in quantifying them (IPCC 2006). Carbon contained in industrial wood harvest and use was added to annual flow compartments.

We calculated the time series of *NPP* in Austria using data from Krausmann (2001), who presented data on aboveground *NPP* based on highly disaggregated data on land use and land cover (discerning approximately 20 categories of arable land, five grassland types [meadows and pastures], permanent cultures, forests, and settlement and infrastructure areas [including vegetated areas along roads, in parks and cemeteries, etc.]) as well as highly disaggregated agricultural and forestry production data. We extrapolated total *NPP* from aboveground *NPP* using root–shoot ratios for each land use category from literature (Saugier et al. 2001). Data on changes in the carbon stock of biota and soils (i.e., on ΔSC and ΔSOC) were taken from a recent comprehensive in-depth study (Gingrich et al. 2007) that quantifies all major components—that is, aboveground standing crop (SC_a), belowground standing crop (SC_b), and soil organic carbon (*SOC*)—for 12 data points in the period from 1830 to 2000. This study is consistent with the above-discussed *NPP* calculation and combined, among others, forest inventories for the period from 1950 to 2000 (Weiss et al. 2000; Schieler and Schadauer 2004), spatially explicit information on forest growth regions (Kilian and Müller 1995), forest yield tables (Marschall 1975), historical land use and production statistics (Sandgruber 1978; Schindler 1885; Schindler 1889), and some ancillary modeling assumptions (Körner et al. 1993; Erb 2004b). Major attention was paid to the distinction between intensively used grassland (meadows mowed more than once yearly) and extensively used grasslands (meadows mowed once a year and pastures) due to their substantial differences in carbon density, particularly in the belowground compartments. We carried out a sensitivity analysis to assess uncertainties (for reference, see Gingrich et al. 2007). Net differences between carbon stocks were calculated for four time periods chosen on the grounds of data availability and economic development: 1830–1880, 1880–1949, 1949–1986, and 1986–2000.

Results

Socioeconomic Carbon Flows

Our results suggest that Austria's carbon budget fundamentally changed in the last 170 years. Socioeconomic carbon flows increased enormously in this period—gradually until 1950, extremely rapidly from 1950 to 1970, and with some signs of saturation afterwards (see figure 2). Carbon flows related to domestic extraction (DE)—that is, domestic harvest and mining (Weisz et al. 2006)—almost doubled in the whole period. Domestic consumption of carbon (DCC)—that is, DE plus carbon imports minus carbon exports—which represents the gross outflow of carbon from socioeconomic metabolism to the atmosphere, grew almost fourfold from 1830 to 2000. This surge in DCC was made possible by imports; exports only become visible in later years.

DCC (see figure 2a) increased steadily from 7.8 MtC/yr[4] in 1830 to 31.5 MtC/yr in 2000, only interrupted by the two world wars in the first half of the 20th century. In 1830, biomass accounted for almost all of Austria's DCC, whereas fossil fuels were negligible and remained so until 1850. From then on, fossil-fuel-derived carbon gained importance, contributing 55% to Austria's DCC in 2000. Coal use increased rapidly in the second half of the 19th century. In the interwar period, coal consumption was significantly lower than before WWI, accounting for only 3.2 MtC/yr in 1920 compared to 9.6 MtC/yr in 1910. Agricultural biomass and wood stayed at a similar level—around 5.0 and 1.5 MtC/yr, respectively. The rapid industrial development of Austria after WWII was fuelled mainly by oil in the first phase—until roughly the mid-1970s—supplemented by natural gas thereafter. Wood consumption first decreased and then increased, agricultural biomass increased steadily over the period. After WWII, DCC almost tripled in only 2 decades, from 1950 to 1970. In 2000, DCC consisted of 30% crude oil, 25% agricultural biomass, 19% wood, 13% natural gas, 11% coal, and 2% from cement manufacture.

Carbon flows in DE (see figure 2b) almost doubled from 7.8 MtC/yr in 1830 to 15.4 MtC/yr in 2000. Whereas DE grew only slightly in the 19th century due to the beginning of coal mining, it rose quickly to 16.3 MtC/yr in 1955. Since the 1950s, DE has remained roughly constant, with a slight decrease in the 1990s. Agricultural production made up the largest share (approximately 50%) of DE for most of the entire period, with the exception of the early 19th century, when wood harvest exceeded agricultural harvest (4.1 MtC/yr wood vs. 3.7 MtC/yr agricultural biomass in 1830). Agricultural production had already surpassed wood harvest in 1850, and it rose particularly rapidly after 1950. Overall, agricultural harvest grew by 230% over the whole period, whereas wood production was approximately constant. Domestic coal production started in 1870, peaked in 1950, and steadily

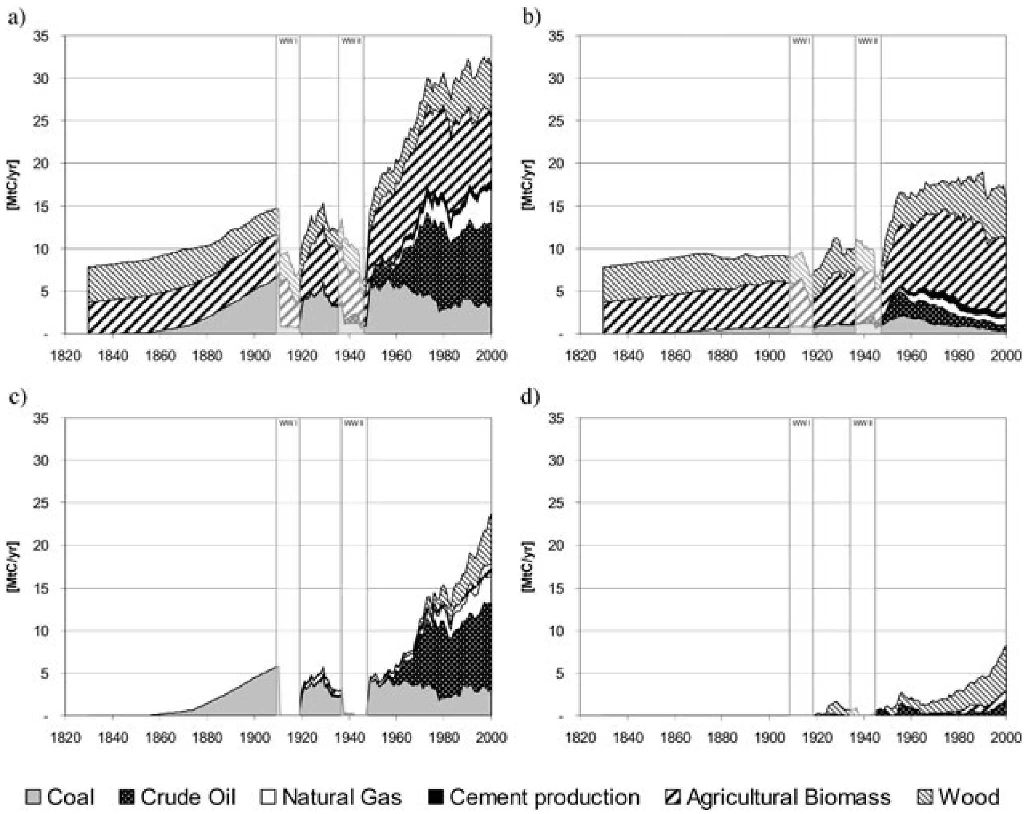

Figure 2 Socioeconomic carbon flows in Austria from 1830 to 2000. a: domestic carbon consumption (DCC) = socioeconomic emissions into the atmosphere; b: domestic extraction (DE); c: imports; d: exports. The bars indicate the two world war periods, which have problematic data quality.

lost importance from then on. Crude oil later replaced domestic coal production and peaked in the 1950s; the DE of natural gas increased and peaked a few decades later.

The surge in DCC was mainly supported by exponentially growing carbon imports (see figure 2c) in the form of fossil fuels, plastics, and biomass. Imports increased from almost nothing in the early 19_{th} century to 23.7 MtC/yr in 2000. Carbon import was dominated by fossil fuels throughout the entire time period. In the 19th century, coal imports were the only important category, rising steeply in the late 19th and early 20th centuries to reach 8.8 MtC/yr in 1910. In the interwar period, coal imports were much lower, at 2 to 4 MtC/yr, supplemented by some biomass imports. In the 1960s, crude oil imports gained importance, outgrowing coal imports in 1968. Natural gas grew slowly at first, gaining importance after the 1970s. Wood imports also gained importance from the 1970s onward.

Compared to imports and DE, the export of carbon-containing materials (see figure 2d) played only a minor role for most of the period, but it reached 8.1 MtC/yr in 2000 (53% of DE). Over the entire period, export was dominated by wood. Some crude oil export took place from the 1940s to the 1960s (1 to 2 MtC/yr), and export increased slightly again recently. Some agricultural biomass was exported from the 1980s onward. Trade with biomass products (wood and agricultural biomass) was roughly balanced over the entire period—that is, imports and exports were of similar magnitude with respect to carbon flows. Whereas in earlier decades wood

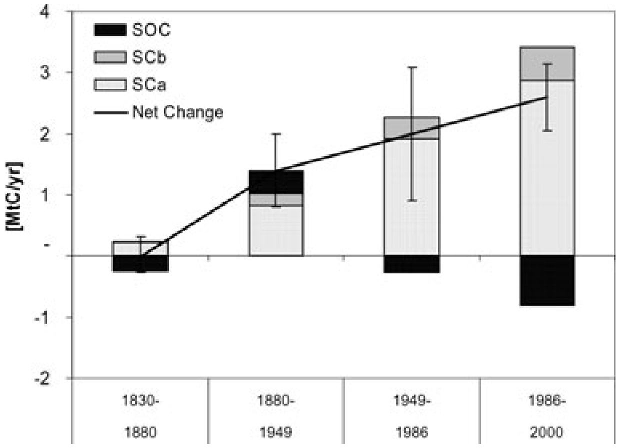

Figure 3 Average annual net carbon flows between the atmosphere and different vegetation compartments in four periods from 1830 to 2000. Positive values indicate carbon sinks (flows from the atmosphere); negative values indicate carbon sources (flows to the atmosphere). The solid line indicates the net carbon flow of the terrestrial ecosystems, and error bars indicate data uncertainty. SOC = soil organic carbon; SC_b = belowground standing crop of biomass; SC_a = aboveground standing crop of biomass.

exports and agricultural imports dominated, in recent times (especially after 1960), import and export have been more or less balanced within each category. Biomass trade volumes grew almost exponentially between 1920 and 2000.

Carbon Flows Between Ecosystems and the Atmosphere

As discussed above, no accumulation of carbon in socioeconomic stocks was considered; that is, DCC was assumed to equal carbon emissions from socioeconomic metabolism. Because carbon contained in biomass was previously taken from the atmosphere during plant growth, it is often assumed that the release of carbon from biomass use does not contribute to the accumulation of carbon in the atmosphere. This assumption, however, is only valid when changes in the carbon stocks of biota (*SC*) and soils (*SOC*) are neglected, because land use affects carbon stocks in ecosystems. In an attempt to establish a comprehensive account (i.e., comprising all carbon flows from and to the atmosphere, as outlined in figure 1), we also quantified carbon flows related to Austria's terrestrial ecosystems. Our results (see figure 3) suggest that Austria's biota and soils served as carbon sinks after 1880, whereas no significant average yearly carbon flows between the atmosphere and ecosystems took place during the time period from 1830 to 1880. Since 1880, the total carbon stock in terrestrial ecosystems has increased by 18%, from approximately 1.04 GtC in 1880 to 1.23 GtC in 2000 (see figure 4). Not only carbon stocks in ecosystems but also the rates at which carbon was accumulated each year increased over the 170-year period, from almost 0 to 2.6 MtC/yr in the last period (see figure 3).

Figure 3 shows that carbon accumulated above all in the biomass fraction (*SC*), in particular in the aboveground compartment (SC_a). In 1830, SC_a amounted to 180 MtC; in 2000, it had almost doubled, to 350 MtC (Gingrich et al. 2007). Average annual net carbon uptake of SC_a amounted to roughly 0.22 MtC/yr in the period 1830–1880 and increased steadily to 2.88 MtC/yr in 1986–2000. Carbon flows in the belowground biomass compartment (SC_b) were much smaller: Annual carbon uptake of SC_b grew from 0.02 MtC/yr in 1830 to 0.55 MtC/yr in 2000. This function of biomass ($SC_{a,b}$) as a net sink for atmospheric carbon was partly counterbalanced by SOC, which served as a carbon source, with the exception of the period between 1880 and 1949. Total SOC stocks declined slightly over the period, from 830 MtC to 820 MtC (Gingrich et al. 2007).

An analysis of the different land use classes reveals that carbon stocks and yearly carbon uptake increased mostly in forests. Carbon stocks in forests increased from 540 MtC in 1830 to 840 MtC in 2000; its contribution to the total carbon stock steadily increased, from 52% to 67%. Not only did carbon stocks increase, but

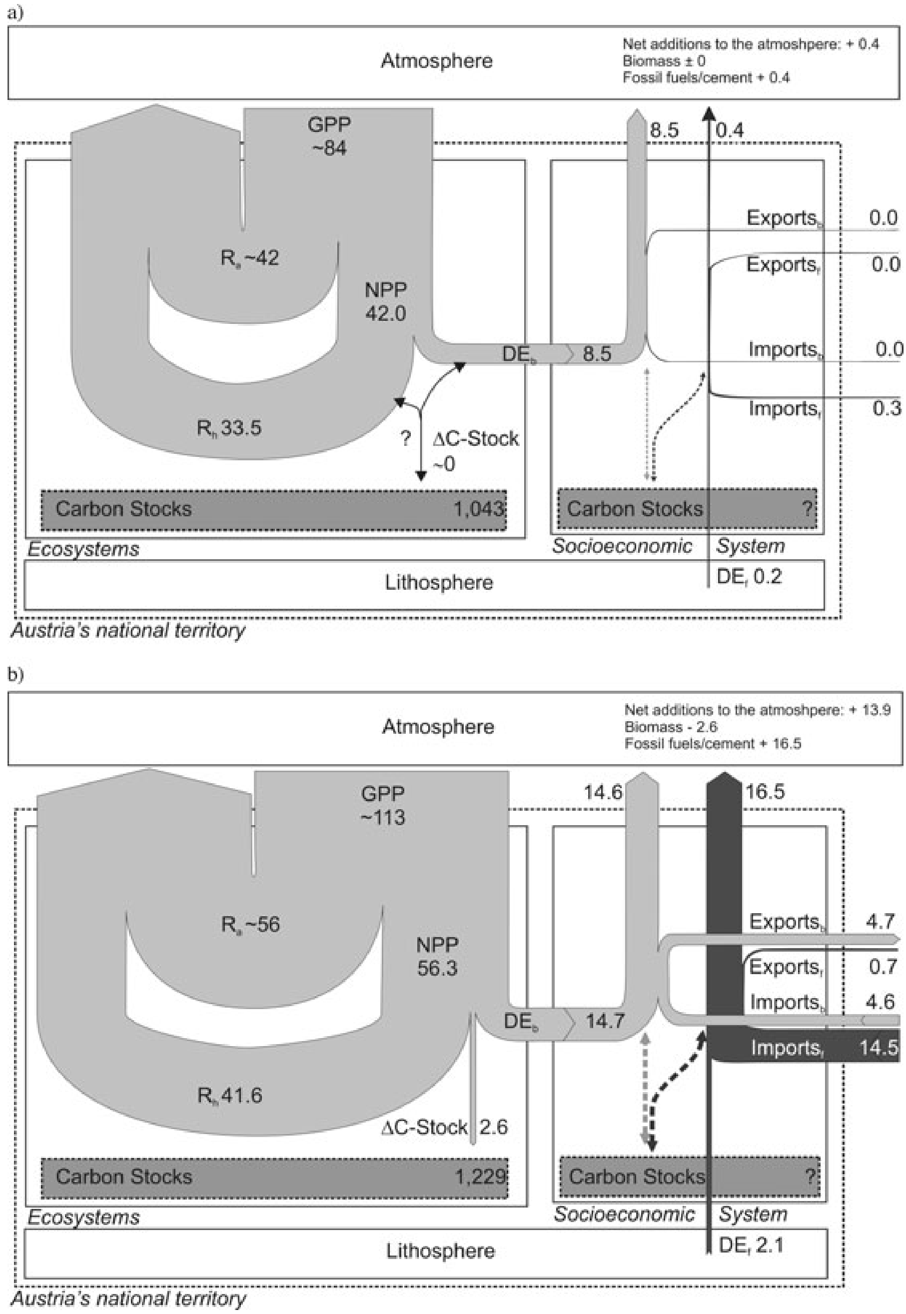

Figure 4 Average annual carbon flows in Austria in the periods 1830–1880 (panel A) and 1986–2000 (panel B). Arrow sizes are proportional to the magnitude of the carbon flows. Flows are reported as MtC/yr, and stocks are reported as MtC. Import/Export$_f$ = foreign trade with fossil fuel products; Import/Export$_b$ = foreign trade with biomass products. Dashed arrows indicate that the flows were not considered. GPP and Ra calculations are provided only for illustrative purposes. The very thin vertical arrow in Figure 4a represents the socioeconomic carbon flow associated with fossil fuel use. GPP = gross primary production; R_a = plant respiration; R_h = heterotrophic respiration; *NPP* = net primary production; ΔC = stock = net change of carbon stocks in ecosystems; DE = domestic extraction.

yearly carbon uptake of forests also grew considerably, from 0.57 MtC/yr in 1830–1880 to 4.22 MtC/yr in 1986–2000. These are by far the highest rates of yearly carbon uptake of all land-use classes. Carbon uptake in forests results from two factors, increases in forest area and increases in forest carbon density (Gingrich et al. 2007). The increase in forest area comes at the expense of grassland and cropland area. Grasslands store significant amounts of carbon in the SOC compartment; extensively used grasslands store much more carbon in SOC per unit area than all other land-use classes. Both the overall reduction of grassland areas and the intensification of grassland use between 1830 and 2000 (Krausmann 2001; Gingrich et al. 2007; see the Discussion section) resulted in a considerable loss of carbon to the atmosphere, visible as carbon source in the SOC compartment in figure 3. Grasslands lost 0.6 MtC/yr as a result of the shift from extensive to intensive use from 1830 to 2000. Contrary to that general trend, however, the area used as intensive grassland grew at the expense of cropland, with a much lower SOC value per unit area in the period 1880–1949, resulting in an overall growth in SOC (i.e., a carbon sink) visible in the second bar of figure 3.

The sensitivity analysis by Gingrich and colleagues (2007) confirmed that, despite the existing uncertainties, it is very likely that Austria's vegetation has acted as a carbon sink since 1880. As shown in figure 3, however, data quality is not sufficient to decide whether biota and soils acted as a carbon source or sink in the period 1830—1880 due to the large uncertainty range, when net flows were close to zero. After 1880, however, the uncertainty range was never large enough to question the result that biota and soil acted as a carbon sink.

The Integrated Socioecological Account

By combining the results presented in figures 2 and 3 we can reconstruct a comprehensive view of the major carbon flows between Austria's socioeconomic and ecological systems and the atmosphere for the whole period (see figures 4 and 5). Figure 4 compares the early (pre-industrial) period to the late (fully industrialized) period. The preindustrial period (1830–1880) was characterized by negligible carbon flows from fossil fuels, which amounted to an annual emission of 0.4 MtC to the atmosphere. Imports and exports, of both biomass products and fossil fuels, were of negligible magnitude. Solar-energy-driven carbon flows (biomass) by far dominated the picture. This was fundamentally different in the period 1986–2000 (see figure 4b). As expected, one finds considerable flows associated with fossil fuel use, but flows through ecosystems were also considerably larger than in the pre-industrial period. Carbon flows through ecosystems, such as *GPP* and *NPP*, were 34% larger than in the preindustrial period. Socioeconomic harvest of biomass (NPP_h) even increased by 70%: Whereas NPP_h amounted to 21% of *NPP* in the early period, it had grown to 26% of *NPP* in the later period. Trade of fossil fuel and biomass, which was negligible in the early period, was of significant magnitude later on. Fossil energy consumption reached a magnitude similar to that of overall socioeconomic biomass consumption but—in contrast to biomass flows—represented a direct net addition to the global stock of atmospheric carbon. Carbon stocks in vegetation were approximately constant in the preindustrial period, but its trajectories changed fundamentally during industrialization: In the period 1986–2000, approximately 5% of total *NPP* was allocated to stock accumulation each year. As a result, carbon stocks in vegetation were substantially (18%) larger in 2000 than in 1830.

Figure 5 presents a comprehensive view of the net carbon flows between Austria's socioeconomic and ecological systems and the atmosphere during the whole period from 1830 to 2000. It shows that the net emissions of carbon (i.e., the sum of the flows A and B in figure 1) from Austria's territory to the atmosphere were dominated by carbon emissions from fossil fuel use. Despite the significant net carbon uptake of biota and soils during the whole period (see figures 3 and 5) and despite the large yearly carbon exchanges between the atmosphere and biota/soils (see the left part of figure 4), the overall trend was clearly driven by the net carbon emissions from socioeconomic metabolism, above all resulting from the combustion of fossil fuels.

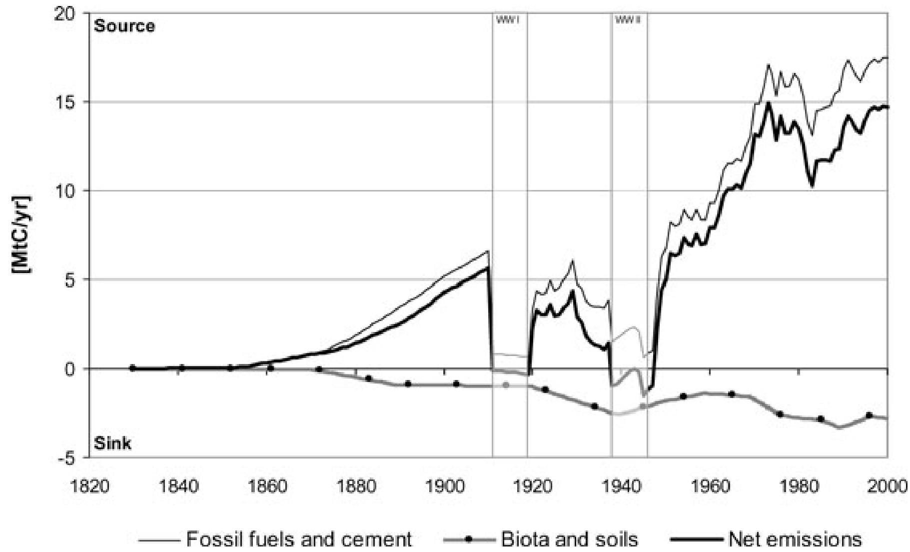

Figure 5 Annual net carbon flows in Austria from 1830 to 2000: Net carbon uptake of biota and soils and carbon emissions from fossil fuel consumption and cement manufacture. The bars indicate the two world war periods, which have problematic data quality.

Discussion

Our results show that Austria's socioeconomic carbon metabolism changed profoundly in magnitude and composition during the agrarian—industrial transition. Industrialization started around 1850, about 100 years later than in the United Kingdom (Sieferle et al. 2006), supported by surging use of fossil fuels, which were, to a large extent, imported. Biomass harvest also increased considerably, even allowing significant biomass export in later years. In 1830, socioeconomic carbon metabolism was dominated by biomass. Biomass was the dominant source of energy, fossil fuels contributed less than 1% at that time, and foreign trade with biomass was negligible. As fossil fuels gained importance later on, they not only dominated carbon outflows from socioeconomic metabolism to the atmosphere but also fundamentally altered the overall dynamics and scale of carbon flows between Austria's ecosystems and the atmosphere: GPP and *NPP* increased by 34% over the entire period.

The Austrian economy in the early 19th century may be considered to represent the mature stage of a preindustrial socioecological regime based on a solar energy system (Sieferle et al. 2006). At that time, total socioecological flows of carbon (i.e., socioeconomic and ecological flows) appeared to be largely balanced (i.e., carbon-neutral with respect to the atmosphere), because carbon stock changes in biota and soils were negligible and biomass represented by far the most important energy source. The accumulated impacts of the agrarian regime with respect to carbon flows into the atmosphere were significant, however: The land-use system prevailing in the early 19th century represents the outcome of a process of agricultural colonization that lasted several thousands of years in central Europe and was completed around 1800. Most of the land clearing, however, happened during the last 2 millenia before 1800, when land clearing, population growth, and an intensification and optimization of preindustrial agriculture proceeded (Boserup 1981; Bork et al. 1998). Over the centuries, this process was related to considerable carbon losses in vegetation and soils due to the expansion of croplands and pastures with low carbon density at the expense of carbon-rich forests. In the Austrian case, the magnitude of the accumulated flows over this period can be roughly quantified. An assessment of the amount of carbon in biota and soils in the absence

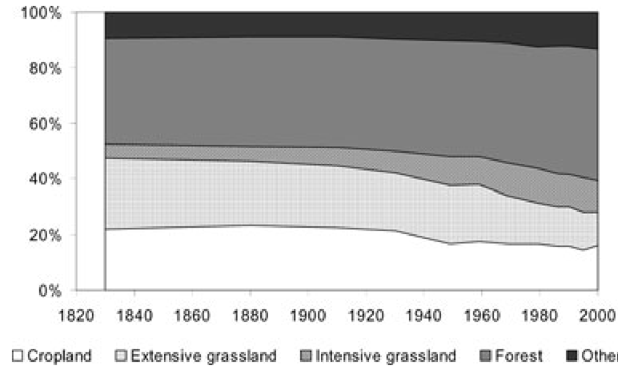

Figure 6 Land-use change in Austria 1830–2000. Source: Krausmann (2001).

of human land use (i.e., potential vegetation; Erb 2004b; Gingrich et al. 2007) indicates that ecosystems stored approximately 2,000 MtC.[5] In 1830, forests had been reduced from originally over 85% to some 30% of the total land area, mostly to gain agricultural land. This resulted in a reduction of carbon stocks by 50% (approximately 1,000 MtC). In other words, 2,000 years of agrarian colonization had resulted in a cumulative net carbon emission to the atmosphere of approximately 1,000 MtC, although at a low annual rate (around 0.5 MtC/yr on the average). It may be assumed that in the late 18th century, forest area had been reduced to a minimum, and the process of carbon emissions related to land-use change had been terminated. With the increasing exploitation of fossil fuels in the mid-19th century, however, the probably short period of a carbon-neutral socioecological regime in Austria ended—in this case, due not to the extension of agricultural areas but to the advent of a new, fossil-fuel-based energy system (Sieferle et al. 2006).

The aggregate amount of carbon contained in fossil fuels that was mobilized from chemically largely inert, fossilized subterranean carbon stocks to support socioeconomic activities between 1850 and 2000 in Austria amounted to 951 MtC. This amount of carbon that flowed to the atmosphere during 150 years of industrialization was of a magnitude similar to that of the aggregate carbon emissions due to land clearing during the 2,000 years of the pre-industrial period. Industrialization has thus greatly increased the annual rate at which humans put pressures on the atmosphere's carbon balance.

This fundamental change of the overall carbon budget of Austria resulted in the emergence of a terrestrial carbon sink in vegetation and soils, which can be seen as a recovery from past depletions. Our results show that this is mainly due to the re-growth of forests, a process that is denoted as *forest transition* in the literature (Mather 1992; Mather and Needle 1998). Forest transitions have been empirically documented in a large number of national and regional case studies, mainly located in the northern hemisphere and in industrialized countries (e.g., Rudel et al. 2005; Kauppi et al. 2006; Krausmann 2006). Just like in those countries, Austria's forest area grew considerably (23%) in the last 170 years, at the expense of agricultural areas (see figure 6), resulting in the terrestrial carbon sink. In our view, however, forest dynamics are not directly interlinked with social or economic parameters such as population density or income (Mather et al. 1999; Uusivuori et al. 2002) but rather are associated with a transition in the socioecological regime from the agrarian to the industrial mode of subsistence (Krausmann 2006; Sieferle et al. 2006; Fischer-Kowalski and Haberl 2007).

This regime transition fundamentally alters the role of ecosystems, in particular forests, for society. Under the conditions of an agrarian socioecological regime, as it prevailed in Austria in the early 19th century, socioeconomic energy supply came almost exclusively from agriculture and forestry. Forests played an important role: Wood served as the main source of process heat and space heating, and forests were also indispensable for nutrient provision in agriculture—for example, through litter outtake and forest grazing (Weiss et al. 2000; Stuber and Bürgi 2001). The consequent intensive use of forests led to a degradation of wood stocks on forested areas, resulting in carbon densities that were significantly lower than today. In the course of industrialization, fossil energy replaced wood as the key energy source, international trade rendered foreign wood resources accessible and—due to the comparably expensive wood harvest in Austria owing to its topography—economically advantageous, and surges in agricultural feed production helped the country abandon forest grazing. As a consequence, socioeconomic pressures on forests decreased, and forests recovered from intensive, multi-functional use—changes in forest management that can largely explain the growth in carbon densities.[6] Together with the increase in forest area, this vegetation thickening led to a fundamental change in the role of ecosystems for the carbon balance, including the emergence of a considerable carbon sink in Austria's biota and soils.

The mechanisms behind these changes, triggered by the availability of fossil fuels and the host of technologies that arose with their utilization (Grübler 1998), are intricate, highly complex, and intimately interlinked. In general, three fundamental mechanisms relating to land use can be identified:

1. Fossil fuels allowed for a direct substitution of biomass as a material and energy resource. The subsequent decrease in biomass demand in certain sectors was—in most cases—immediately compensated by other sectors that utilized biomass as a resource for other applications. For example, the substitutions of fossil fuels for fuel wood did not result in a decrease of wood harvest but granted the Austrian pulp industry enhanced access to fiber resources, which led to an economic growth and differentiation of wood-consuming industries and subsequently to surges in timber consumption (Krausmann 2001; Krausmann et al. 2003).
2. Fossil-fuel-based technologies brought about tremendous increases in area and labor productivity of agriculture and forestry. Agricultural yields increased by a factor of 1.87 between 1830 and 2000, on average (Krausmann 2001). Despite a decreasing agricultural labor force (from between 70% and 80% in 1830 to approximately 3% in 2000), overall biomass harvest in forestry and agriculture rose by 70%. These developments were possible thanks to increased abilities to counteract nutrient depletion and soil degradation with agrochemicals—produced in energy-intensive chemical processes such as the Haber–Bosch process—and enhanced mechanical capacities in land use. The radical replacement of draft animals by tractors increased available power by two orders of magnitude and released large fodder production areas.
3. Fossil-fuel-powered transport systems made—for the first time in history—long-distance transport of bulk material, such as biomass, economically feasible. These technological innovations allowed agrarian societies to overcome prohibitive transport costs (Boserup 1981; Grigg 1992), which ultimately determined land use patterns (e.g., von Thünen 1875). With fossil fuels, an area-independent energy carrier became available, which reduced transport costs and led to a fundamental restructuring of the spatial organization of society, across all spatial scales, from the local and regional to the national and global (Fischer-Kowalski and Erb 2003). This process rendered feasible a global division of agricultural production based on large-scale biomass transfers and even facilitated the decoupling of production systems from the availability of domestic resources (Fischer-Kowalski and Erb 2003; Erb 2004a; Sieferle et al. 2006).

The synergistic effect of these interlinked mechanisms triggered a process termed *agricultural adjustment* (Mather and Needle 1998)—that is, the disintegration of traditional land-use systems, including the spatial separation of cropland, livestock husbandry, and forestry and the subsequent reforestation of marginal land. This spatial reorganization and optimization of land use led to a process that supported a growing population and improvements in diets through an increased production of meat, milk, and eggs (Krausmann and Haberl 2002; Krausmann 2004). As an aggregate result of these mechanisms, the availability and usability of fossil fuels allowed human societies to overcome the constraints and sustainability problems (so-called Malthusian traps) of the solar-based agrarian regime (Sieferle et al. 2006) but also created new types of global environmental problems and sustainability threats.

From this long-term historical view, it becomes evident that the currently observed function of terrestrial ecosystems as net carbon sinks is a by-product of fossil-fuel-powered industrialization of agriculture and can be interpreted as a reversal of the past carbon depletion during the expansion of agriculture in the preindustrial period. Although agricultural adaptation results in a reforestation of parts of the agricultural land and in increasing carbon densities in forests, it is evident that the carbon sequestration potential of this process is limited. The increase of both forest area and carbon density is subject to restrictions: Society will always require significant nonforested areas for settlement and food production, and vegetation thickening is constrained by ecological limits. Thus, only a reduction of carbon emissions from fossil fuel combustion can succeed in alleviating problems resulting from the accumulation of carbon in the atmosphere, whereas afforestation and other land-use changes in industrialized countries (which are ongoing irrespective of climate policy) are of minor importance and not adequate options to mitigate climate change.

Our results underline the need for comprehensive and consistent analyses of the society—nature interaction. The long-term analysis exposes systemic interlinkages between the socioeconomic energy system and pattern and processes in ecosystems. It demonstrates that medium- to long-term climate change mitigation must rely on "decarbonization" of socioeconomic energy supply, which makes the development of innovative energy systems indispensable. Terrestrial carbon sinks can only play a minor, transitory role. Our results indicate that researchers must cautiously and systematically scrutinize effects of innovative energy systems on the overall carbon balance to support strategies aimed at a more sustainable future.

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Notes

1. One square kilometer (km^2, SI) = 100 hectares (ha) ≈ 0.386 square miles ≈ 247 acres.
2. *Heterotrophic* refers to organisms that are—in contrast to autotrophs (e.g., plants)—unable to synthesize nutritive organic compounds from simple inorganic molecules and thus depend on energy from other organisms.
3. Human-induced fires are of minor importance in Austria due to its humid climate and were neglected. Harvest losses and other flows of by-products were not explicitly addressed and are included in heterotrophic respiration (R_h).
4. MtC = megatons of carbon = one million tons of carbon = 10^6 t C = 10^{12} g C.
5. The concept of potential vegetation (Tüxen 1956) refers to ecosystem processes and patterns at current climatic conditions. In the absence of better data, we use this concept as a proxy for conditions prevailing at the beginning of the large-scale expansion of agriculture (i.e., deforestation) in central Europe.
6. In principle, this vegetation thickening can result from two factors: (1) consequences of global environmental change, in particular a possible carbon fertilization effect due to a higher carbon concentration in the atmosphere (e.g., Caspersen et al. 2000; Schimel et al. 2000; Sitch et al. 2003), and (2) changes in forest management. It was beyond the scope of this article to separate and quantify the contribution of these two mechanisms. There are,

however, good reasons to assume that the growth in carbon densities is attributable to a large extent, but not entirely, to changes in forest management (Gingrich et al. 2007).

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