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The importance of three centuries of land-use change for the global and regional terrestrial carbon cycle

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Abstract Large amounts of carbon (C) have been released into the atmosphere over the past centuries. Less than half of this C stays in the atmosphere. The remainder is taken up by the oceans and terrestrial ecosystems. Where does the C come from and where and when does this uptake occur? We address these questions by providing new estimates of regional land-use emissions and natural carbon fluxes for the 1700–2000 period, simultaneously considering multiple anthropogenic (e.g. land and energy demand) and biochemical factors in a geographically explicit manner. The observed historical atmospheric CO_2 concentration profile for the 1700 to 2000 period has been reproduced well. The terrestrial natural biosphere has been a major carbon sink, due to changes in climate, atmospheric CO_2, nitrogen and management. Due to land-use change large amounts of carbon have been emitted into the atmosphere. The net effect was an emission of 35 Pg C into the atmosphere for the 1700 to 2000 period. If land use had remained constant at its distribution in 1700, then the terrestrial C uptake would have increased by 142 Pg C. This overall

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difference of including or excluding land-use changes (i.e. 177 Pg C) comes to more than half of the historical fossil-fuel related emissions of 308 Pg C. Historically, global land-use emissions were predominantly caused by the expansion of cropland and pasture, while wood harvesting (for timber and fuel wood) only played a minor role. These findings are robust even when changing some of the important drivers like the extent of historical land-use changes. Under varying assumptions, land-use emissions over the past three centuries could have increased up to 20%, but remained significantly lower than from other sources. Combining the regional land-use and natural C fluxes, North America and Europe were net C sources before 1900, but turned into sinks during the twentieth century. Nowadays, these fluxes are a magnitude smaller than energy- and industry-related emissions. Tropical regions were C neutral prior to 1950, but then accelerated deforestation turned these regions into major C sources. The energy- and industry-related emissions are currently increasing in many tropical regions, but are still less than the land-use emissions. Based on the presented relevance of the land-use and natural fluxes for the historical C cycle and the significance of fossil-fuel emissions nowadays, there is a need for an integrated approach for energy, nature and land use in evaluating possible climate change mitigation policies.

1 Introduction

The increasing atmospheric carbon dioxide (CO_2) concentration—from its pre-industrial level of 280 parts per million (ppm) to the current level of 380 ppm—has led to a warmer climate (Hegerl et al. 2007). Although fossil-fuel emissions dominate this CO_2 increase, land use also plays a substantial role (Denman et al. 2007). Land-use conversions, such as deforestation and agricultural expansion, have contributed considerably to the cumulative atmospheric CO_2 increase (see for example, Achard et al. 2002; Houghton 2003). At the same time, natural vegetation, forest plantations and other land covers sequester carbon (C), resulting in a slowing down of the atmospheric CO_2 increase.

The role of the energy sector is dominant in the literature on increasing CO_2 concentrations, resulting in consistent estimates of historical energy emissions (e.g. Marland et al. 2008). In contrast, there are large uncertainties in the estimates of historical land-use emissions and the natural C sink. With respect to land use, historical changes, first of all, are difficult to assess, given the lack of data for many regions. To date, only two accepted global land-use datasets have been compiled (Ramankutty and Foley 1998; Klein Goldewijk 2001). Second, the processes underlying historical land-use change are diverse and hard to track. For example, deforestation for timber use has a very different impact on the C cycle than deforestation for agricultural expansion. Third, different methodologies have been used in estimating the historical land-use emissions. Houghton (2003), Fearnside (2000a, b) and Ramankutty et al. (2007), for example, used book-keeping methods with fixed C densities to estimate historical land-use emissions, ignoring feedback mechanisms between atmospheric CO_2, climate and terrestrial C dynamics. This approach leads to high emissions, since compensating responses by the terrestrial system are ignored. Achard et al. (2002) and DeFries et al. (2002) applied remote sensing techniques, showing smaller deforestation areas and consequently lower land-use emissions. Finally, also important for the outcome are the model type used, the choice of processes included and the assumptions made. With respect to the processes, McGuire et al. (2001), for example, excluded the harvesting of timber and fuel wood, and therefore turned up a relatively low historical deforestation in the twentieth century.

The consequences of these uncertainties can be illustrated by the broad range of land-use emissions that exists, even for the last few decades. For example, the estimated global emissions for the 1980s vary from 0.6 (DeFries et al. 2002) to 2.4 Pg C year^{-1} Fearnside (2000a, b).[1] Likewise, the range for the 1990s goes from 0.6 Pg C year^{-1} Achard et al. (2002) to 2.2 Pg C year^{-1} (Houghton 2003).

With respect to the historical natural sink, the variation in the C cycle per ecosystem type contributes to the uncertainty in terrestrial C fluxes. Furthermore, the variation in terrestrial C fluxes can be explained by the numerous ecological processes involved that change over time and space, and thus result in different sink estimates. An example of this is the response of natural ecosystems to changes in climate varies over time and space (Zaehle et al. 2005; Stephens et al. 2007).

The number of uncertainties, as mentioned above, have led to the recommendation by Ramankutty et al. (2007) to develop more coherent and consistent land-use emission estimates using three criteria: (1) consider the full land-cover dynamics during and following deforestation (including effect on soil carbon); (2) consider explicitly historical land-use changes, and (3) accurately estimate the fate of cleared carbon. Only a methodology applying these three criteria is believed to deliver "realistic" estimates of the role of historical land-use change in the global carbon cycle.

In this paper, we propose a methodology that allows for analyses over a period of 300 years, explicitly taking into account historical land-use change, changes in environmental conditions and the complete life cycle of cleared carbon. Moreover, we use a terrestrial C-cycle model (Klein Goldewijk et al. 1994) that considers land-use dynamics after deforestation (including re-growth of natural vegetation, Van Minnen et al. 2000). The model also includes many feedbacks between atmosphere and the terrestrial system (Leemans et al. 2002). By using this C-cycle model in a geographically explicit manner and applying it to the historical land-use data set HYDE (Klein Goldewijk 2001), we establish a consistent experimental set-up that meets the criteria, as defined by Ramankutty et al. (2007). Moreover, the geographical explicitness of this approach enables a regional comparison of the major C fluxes.

In Section 2, the methodology of this approach is explained in further detail. Results and a discussion on these results are given in Section 3. Finally, Section 4 draws conclusions from this methodology.

2 Methodology

In order to assess the carbon cycle over the past three centuries, the integrated assessment model IMAGE 2 (Integrated Model to Assess the Global Environment; MNP 2006) has been coupled to the HYDE database (History Database of the Global Environment; Klein Goldewijk 2005; Klein Goldewijk et al. 2007), which

[1]Note that studies such as DeFries et al. (2002) and Fearnside (2000a, b) provide emissions for tropical regions, assuming negligible emissions in the remainder of the world.

includes land-use information for cropland and pasture. Land-use information for wood harvest (for timber and fuel wood) was estimated in IMAGE 2. Various parts of IMAGE 2 were by-passed and replaced by external input (see section on model set-up).

2.1 Historical land-use change

Figure 1 depicts the estimated development of agricultural and pasture land worldwide over the past three centuries at four moments in time, as developed by HYDE. HYDE is a historical database covering the period from 1700 to 2000, and includes land-use information on cropland and pasture (Klein Goldewijk 2001; Klein Goldewijk et al. 2007). For the year 1700, an area of about 2.6 Mkm^2 of cropland and about 2.8 Mkm^2 of pasture has been estimated, mainly in India, eastern China and Europe. This area is considerably smaller than the estimates of Houghton et al. (1983). This difference is, for example, due to the fact that Houghton et al. (1983) estimated 0.24 Mkm^2 pasture in Oceania for 1700, which seems very high since the first settlers arrived in Australia and New Zealand only at the end of the eighteenth century. For the early nineteenth century it is estimated that large parts of Russia and of the African coastal areas became colonized. Agriculture in the US, South America and India rapidly developed in the second half of the nineteenth century. Vast land-use changes in tropical regions started early in the twentieth century. Over the last half century, some parts of the agricultural land in the USA, Europe and Asia were abandoned, resulting in new forests and natural grasslands. Globally, HYDE estimates that there is now about 15 Mkm^2 of cropland around the world

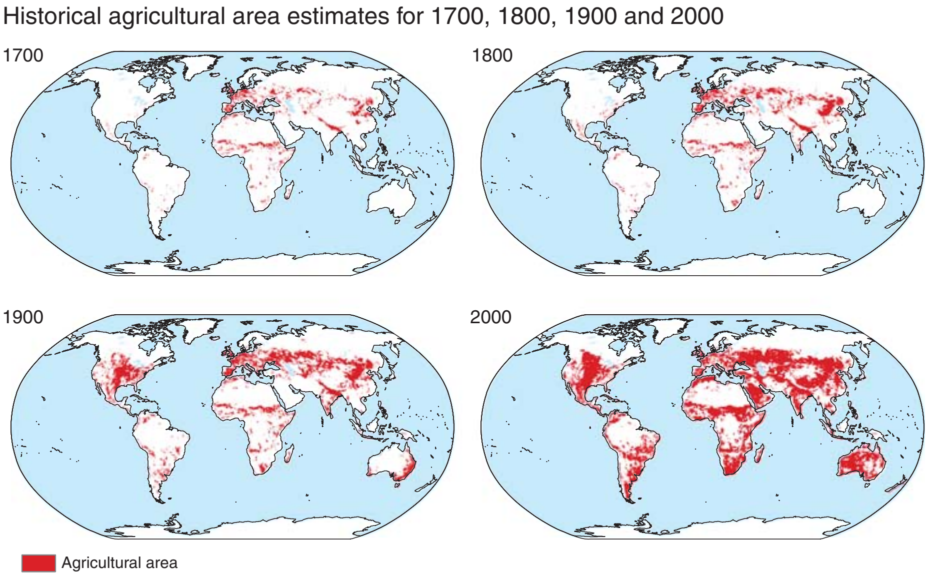

Fig. 1 Reconstructed agricultural area (cropland and pasture) in 1700, 1800, 1900 and 2000 based on HYDE and aggregated to 30 min resolution

and 16 Mkm^2 of grassland pasture (compared to 34 Mkm^2 of total grassland, based on FAO information).

The HYDE data for cropland for the period 1961–2000 are based on FAO statistics for arable land and permanent crops (FAO 2006). Because many regions reported by FAO show an overestimation of the permanent pasture area (e.g. Middle East, Australia), we chose not to use the FAOs totals for permanent pasture only, but to adjust them with an overlay of 'real' grassland areas, as defined by satellite-based maps (Loveland et al. 2000; Bartholome et al. 2002). The overlay analysis with these remote sensing data sets showed that large areas of the permanent-pasture category of the FAO are more or less natural land-cover types (such as savanna). For this study, this resulted in the use of a much smaller extent of pasture areas for the last decades than the FAO estimates (i.e. globally 46% lower in the year 2000).

For the pre-1960 period several additional data sources have been used for allocating land (Klein Goldewijk et al. 2007). Global dataset were used from the comprehensive historical statistics of Mitchell (1993, 1998a, b) and Richards (1990), while regional information from Richards and Flint (1994) has been used for Asia, and information from Houghton (1991) and Houghton (2003) for historical land use in Latin America.

Because historical land-use information is rarely geographically explicit, four assumptions have been used in HYDE for allocating the historical information over a geographical 0.5° by 0.5° grid. Firstly, coastal areas and river plains with fertile soils are the most favorable for early settlement. Secondly, historical (rural) population densities and agricultural activities are strongly correlated. For this reason, historical population-density maps (also part of HYDE) have been used as a proxy for the land-use allocation. Thirdly, historical agricultural activity started near freshwater resources (rivers and lakes). Fourthly, old-growth forests are less prone to conversion to agriculture than other land-cover types (Klein Goldewijk et al. 2007). All of these assumptions were transformed into single weighting maps for cropland and pasture for each historical time step, for which the statistical land-type allocation was carried out (Fig. 1).

In addition to land-use changes for cropland and pasture, we also deal in this study with the consequences of wood harvest (i.e. timber and fuel wood) for the carbon cycle. For this purpose, the timber demand in all IMAGE-2 regions has been estimated on the basis of a linear increase between 1700 (no demand) and 1970, followed by the FAO statistical information up to 2000. Likewise, the demand for fuel wood linearly increased between 1700 (no demand) and 1970, followed by internal estimates of the energy model of IMAGE 2.

2.2 Natural vegetation

After allocation of arable land and pasture, the other areas are covered by one out of 14 natural ecosystems or biomes. The distribution of these biomes is computed by using the BIOME model in IMAGE 2 (Leemans and van den Born 1994). BIOME is a static biogeographical model that uses climate information (i.e. temperature, precipitation, cloudiness) and atmospheric CO_2 concentration to estimate the (equilibrium) biome distribution worldwide. Vegetation dynamics are introduced in IMAGE 2 by using transition rules to mimic different migration and establishment capabilities of species (Van Minnen et al. 2000). We assume, for example that the conversion of tundra into boreal forest occurs more rapidly than the conversion of one forest type to another.

The combination of HYDE and the natural vegetation model of IMAGE 2 provided the estimated land-use and land-cover patterns for the period 1700–2000. These patterns were updated every 5 years, allowing for four land-use transitions: (a) natural vegetation changes towards cropland or pasture; (b) forest change to 're-growth forests' due to timber and fuel wood harvest; (c) agricultural land converting back to natural vegetation cover because of land abandonment and (d) conversions of one natural-vegetation type into another due to climate change.

2.3 Consequences for the C cycle

The main objective of this study is to assess the role of land-use change and natural responses to environmental changes in the historical C cycle. The historical atmospheric CO_2 concentration is estimated by taking into consideration (a) the biosphere[2] - atmosphere and the ocean - atmosphere carbon exchange, and (b) the historical energy and industry-related emissions. The ocean - atmosphere carbon exchange is computed using the ocean model of IMAGE 2, taking into account temperature and the atmospheric CO_2 concentration. The carbon exchange between the biosphere and atmosphere is computed with the terrestrial C-cycle model of IMAGE 2 (Klein Goldewijk et al. 1994; Van Minnen et al. 2000, 2006), using changes in land cover, climate, and atmospheric CO_2. This model is described here in more detail, because of its relevance to the objectives of this paper.

The driving force of the IMAGE-2 C-cycle model is Net Primary Productivity (NPP), i.e. the photosynthetically fixed C minus C losses due to plant respiration. NPP is a function of atmospheric CO_2, climate, soil nutrient and moisture status, biome type, and the development stage of a biome. The next important process is the Net Ecosystem Production (NEP), which is the net C flux between the atmosphere and terrestrial ecosystems (often called residual sink). NEP is calculated as NPP minus the C losses due to heterotrophic soil respiration. Soil respiration depends on the C stocks in three different soil compartments (i.e. litter, humus, and charcoal), their turnover rates, and environmental conditions (i.e. soil water availability and temperature). All fluxes are calculated on a monthly time step, whereas the carbon pools are updated annually.

The IMAGE-2 terrestrial C-cycle model deals explicitly with the four land-cover transitions, as described above. During a conversion towards agricultural land, the C pools in leaves and roots are transferred as slash and dead organic matter to the soil humus pools. In the case of tropical regions, stems and branches partly enter the soil pool and partly disappear into the atmosphere (mimicking burning). For the other regions, it is assumed that the woody biomass is used to satisfy the regional and global wood demand. During the land-cover conversion towards "re-growth forest", the C pools are initially reduced due to wood harvest, and followed by re-growth. After a certain period, these 're-growth forests' turn back to one of the main forest types and can then, potentially, be used again. Leaves and roots enter the soil C pools

[2]We define the biosphere as that part of the terrestrial earth within which life occurs, and in which biotic processes, in turn, alter or transform (http://en.wikipedia.org/wiki/Biosphere).

again, stems are either stored as pulpwood and particles (with a lifetime of 10 years), or veneer, and saw logs (with a lifetime of 100 years). The natural conversions alter the carbon dynamics in such a way that characteristics slowly convert from the old to the new biome using conversion-specific transient periods (Van Minnen et al. 2000).

2.4 Model set-up and experimental design

For the historical analysis presented here, various parts of IMAGE 2 have been by-passed and replaced by external input for the period 1700 to 2000 (Fig. 2). Furthermore, an additional growth factor has been added to the terrestrial C-cycle model.

The external information deals with the historical land use for cropland and pasture (from HYDE), historical energy-related greenhouse gas emissions, and climate. The energy-related emissions are taken from Marland et al. (2008), who presented emissions per country for the period from 1751 to 2000. The emissions were hindcasted back to 1700 by computing the per capita emissions for 1751, and multiplying them with the population figures provided by HYDE for the period 1700 to 1750, assuming constant per capita emissions. The climate information (i.e. monthly temperature, precipitation and cloudiness) for the period from 1900 to 2000 was taken directly from New et al. (2000), using decadal means. For the climate before 1900 we simply assumed a constant climate based on the 1900–1930 average of New et al. (2000), because of the limited variation in the long-term pre-industrial climate (Levy et al. 2004).

With respect to the terrestrial C-cycle model, we added an autonomous factor—affecting the NPP in a grid cell—to account for the non-climate related historical growth stimuli. Various studies (e.g. Kaipainen et al. 2004; Milne and van Oijen 2005; De Vries et al. 2006) have suggested that nitrogen deposition and management changes have been very relevant for the growth increase in various ecosystems in

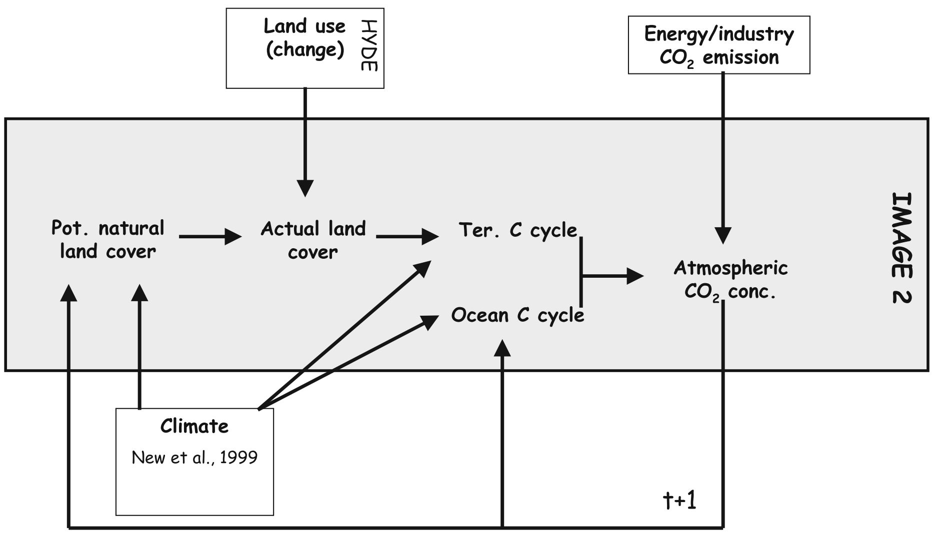

Fig. 2 Experimental set-up to assess the historical C cycle

Table 1 Overview of experiments included in this study

Experiment	Description
Default	1700–2000 experiment using FAO statistics and satellite information in HYDE for historical cropland and pasture, respectively. Areas harvested for timber and fuel wood are estimated internally in IMAGE 2
NoLUC	1700–2000 experiment with no historical land-use changes, neither for cropland, pasture, nor timber (i.e. the 1700 land-use pattern is used for entire period)
WoodHarvOnly	1700–2000 experiment considering only land-use emissions from wood harvest (timber & fuel wood). Crop and pasture use is kept constant, adhering to the 1700 pattern
Sensitivity analysis	
FAOpasture	1700–2000 experiment using alternative historical land-use pattern for pasture in HYDE based on statistical FAO information for the last three decades. Historical crop land and wood harvest is identical to the default simulation
NoAddGrowth	Excluding the autonomous growth factor accounting for nitrogen fertilization and management changes in mid and high latitude forests
NoFert	Disabling the response of the land cover to changes in climate and atmospheric CO_2
ShortLifetime	Using shorter lifetimes for wood products (1 and 10 years for pulp and sawlogs, respectively, instead of 10 and 100 years)

mid-latitudes, as observed during the twentieth century. This information has been adopted here by considering a 10% to 40% NPP increase during the twentieth century for boreal, cool, and temperate forest types and a 13% increase for agriculture.

In order to assess the role of land-use change and natural ecosystems in the historical global C cycle, we carried out two additional simulations next to the default simulation described above (Table 1). In the first experiment, cropland and pasture were kept constant in their 1700 pattern and wood harvest for fuel wood and timber was excluded ('NoLUC'). This shows the overall relevance of land use across different world regions. In the second experiment, we kept cropland and pasture constant for the 1700 pattern, and only included land use for timber and fuel wood ('WoodHarvOnly') in order to show the role of wood harvest for the historical C cycle.

In order to test the robustness of our findings, a number of sensitivity runs were included, though a systematic uncertainty analysis is beyond the scope of this study. With respect to input data, we applied an alternative historical land-use pattern for pasture, based on statistical FAO information ('FAOpasture'). This experiment has been included because of the large uncertainty in historical pasture (Klein Goldewijk et al. 2007). A detailed analysis of the model uncertainties within the terrestrial carbon cycle in IMAGE 2 has been presented in Van Minnen et al. (2006). Here, we included three experiments where we varied parameter settings of the carbon cycle that are relevant in the context of this study (Table 1). In a first experiment we kept the autonomous growth factor constant that accounts for historical nitrogen fertilization and management changes ('NoAddGrowth'). Secondly, we excluded the response of the biosphere to changes in atmospheric CO_2 ('NoFert'). This experiment has been chosen because various other studies have shown the importance of this feedback process to the future carbon cycle (e.g. Van Minnen et al. 2006; Denman et al. 2007). Finally, we shortened the lifetime of the harvest products by a factor of 10 ('ShortLifetime') to assess the relevance of the wood cycle to the outcomes. Including timber harvest is one novel aspect in this study.

3 Results and discussion

3.1 Global assessment

Figure 3 depicts the simulated CO_2 concentrations for the period from 1700 to 2000, and Figs. 4 and 5 and Table 2 all show different aspects of relevant carbon fluxes. The land-use emissions over the last three centuries have been 140 Pg C, which along with the energy-related emissions (i.e. 308 Pg C, Marland et al. 2008) amounts to the total of emissions of 448 Pg C. Thus land-use emissions have been about 30% of the historical CO_2 emissions. Due to the uptake by oceans and the terrestrial ecosystems, only 44% of the total emissions are estimated to have remained in the atmosphere, resulting in a 92 ppm increase in atmospheric CO_2 concentration between 1700 and 2000 (Fig. 3). This is well in line with observed atmospheric CO_2 records (Mann 2002; Keeling et al. 2008).

Taking into account the land-use emissions from the expansion of cropland and pasture, and from wood harvest (i.e. 140 Pg C) and terrestrial sink (i.e. 105 Pg C), the terrestrial biosphere is estimated to have emitted 35 Pg C over the period from 1700 to 2000 (Table 2, Fig. 4). Land-use emissions were found to increase especially beyond 1850. Two main increases in land-use emissions due to considerable land-cover conversions were computed, first in mid-latitudes (around 1900) and then in tropical regions (after 1950). After 1970 the total estimated land-use emissions decreased again to 1.3 Pg C year^{-1} (during the 1980s and 1990s). After 1950 the terrestrial biosphere turned into a net carbon sink (Fig. 5).

The estimated land-use emissions are considerably lower than in Houghton (2003) (Table 2, Fig. 4). Firstly, the difference is both the result of different deforestation

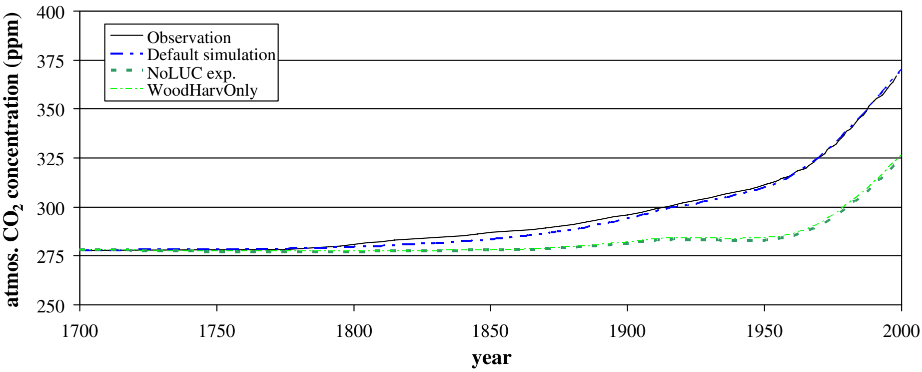

Fig. 3 Simulated historical CO_2 profile for the default simulation and the two land-use experiments (see Table 1) compared to observations (Mann 2002; Keeling et al. 2008)

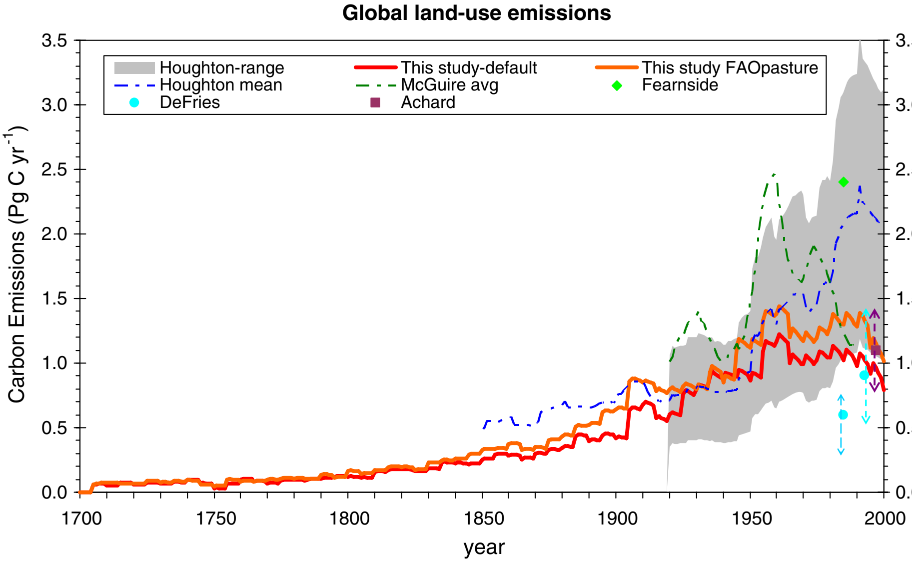

Fig. 4 Historical CO_2 emissions from land use compared to various other sources. Note that two simulated CO_2 fluxes are presented using alternative land-use patterns. Data sources are: Fearnside (2001), McGuire et al. (2001), Achard et al. (2002), DeFries et al. (2002), Houghton (2003), as given by Ramankutty et al. (2007). Studies included in the figure represent the emission ranges given in Table 2

estimates and the consideration of afforestation. Although it is too early to state that Houghton (2003) had overestimated historical deforestation (Denman et al. 2007), the rates are 30% to 60% higher than in most other studies. The high deforestation rates, based on national reports/statistics, were often compiled without checking consistency between countries (see also Denman et al. 2007; Ramankutty et al. 2007). Secondly, Houghton (2003) used fixed C densities for different land-cover categories, whereas these vary in time and space due to climate variation, different stages of the ecosystem (i.e. young versus old), and different environmental conditions. Our estimated land-use emissions for the 1980s and 1990s are slightly higher than the values given by McGuire et al. (2001) and Achard et al. (2002). This might be caused by the explicit consideration of the long-term land-cover changes in our analysis. Ramankutty et al. (2007) identified this as one of the critical issues for an accurate estimation of historical land-use emission. Furthermore, we have included land-use emissions associated with forestry activities. These emissions are substantial in mid- and high-latitude regions. Many studies, including McGuire et al. (2001) and Achard et al. (2002) have, however, ignored these emissions.

When changes in land use were not considered, either for cropland, pasture, or wood (i.e. timber and fuel wood), the C storage in the biosphere was estimated to increase by 142 Pg C during the period from 1700 to 2000, instead of decreasing by 35 Pg C (Table 2). This difference of 177 Pg C is little more than half the historical fossil-fuel related emissions of 308 Pg C for the period from 1700 to 2000, illustrating the significant contribution of historical land-use changes to the observed increase in atmospheric CO_2. Excluding land-use changes results in a considerably

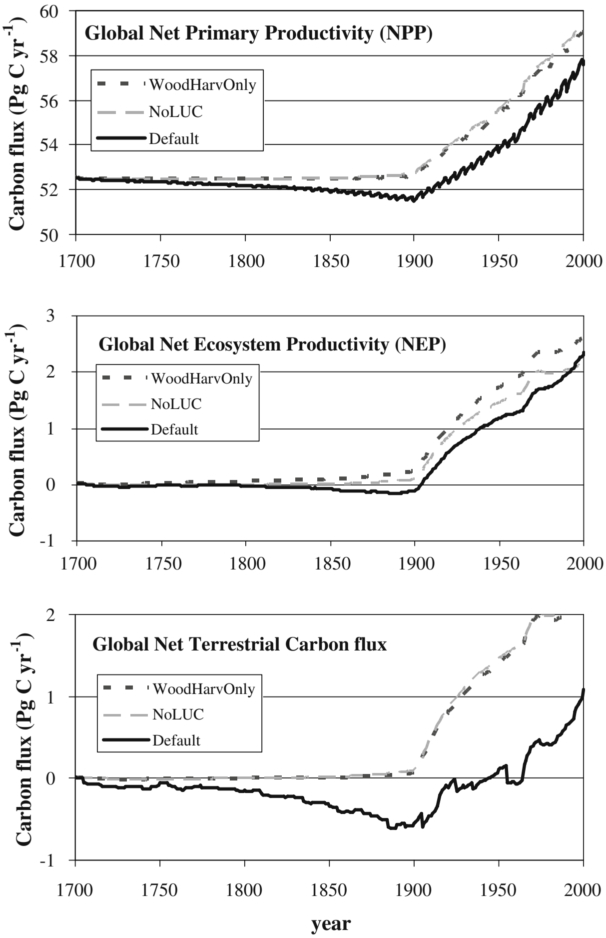

Fig. 5 Global carbon fluxes over the period from 1700 to 2000 under the default simulation and different assumptions for historical land-use change (in Table 1). Note that a positive value represents a terrestrial uptake

lower CO_2 profile, ending with a concentration of 325 ppm in 2000 (Fig. 3). Direct land-use emissions are responsible for 80% of this difference, while 20% is caused by a reduced uptake by natural ecosystems (e.g. less C stored in wood and soil) (Fig. 5). Note that without land-use changes, the ocean uptake is reduced by about 50% (Table 2) due to the lower CO_2 concentration in the atmosphere. Without this feedback, the atmospheric CO_2 concentration profile would be even lower.

A comparison of the different causes of changes in land use shows on the global level a dominant role for cropland and pasture, compared to wood (Table 2). Allowing only wood harvest, and keeping cropland and pasture constant at its 1700 pattern, results in a land-use flux of 44 Pg over the past three centuries. These emissions are, however, almost compensated by an increased biospheric uptake, which is the result of more young re-growing forests. In total, the CO_2 concentration profile is comparable to the profile excluding any land-use changes (Fig. 3).

The overall biospheric carbon uptake or residual sink (i.e. NEP) is estimated to be 105 Pg C over the period from 1700 to 2000 (Table 2). If we exclude land-use changes, the uptake comes to 142 Pg C. The largest terrestrial uptake is found to

Table 2 Global C budget

Results of the default experiment in comparison with the literature

	1700–2000 (Pg C)		1850–2000 (Pg C)			1980s (Pg C year^{-1})					1990s (Pg C year^{-1})				
	Default	Ref6	Default	Ref1	Ref6	Default	Ref1, 5	Ref2, 4	Ref 7	Ref8	Default	Ref1	Ref3, 4	Ref 7	Ref8
Atmosheric increase	197		185			3.2	3.3			3.3 ± 0.1	3.4	3.2			3.2 ± 0.2
Energy emissions	308		299			5.6	5.4			5.4 ± 0.3	6.4	6.3			6.4 ± 0.4
Ocean-atmos.	−146		−127			−1.9	−1.7		−1.8 ± 0.8	−1.8 ± 0.8	−2.2	−2.4		−2.1 ± 0.7	−2.2 ± 0.4
Land-atmos.	35	97	13		51	−0.5	−0.4		−0.3 ± 0.9	−0.3 ± 0.9	−0.8	−0.7		−1.0 ± 0.8	−1.0 ± 0.6
LUC emis.	140	222	123	150	172	1.3	2.0–2.4	0.6–0.8	0.9–2.8	1.4 ± 1.0	1.3	2.2	0.9–1.1	1.4–3.0	1.6 ± 1.1
Res. terrestrial sink	−105	−125	−110		−121	−1.8	−2.4		−4.0 to −0.3	−1.7 ± 1.5	−2.1	−2.9		−4.8 to −1.6	−2.6 ± 1.7

Alternative land-use assumptions:, no land-use changes at all (‘NoLUC’), only land-use changes for wood harvest (‘WoodHarvOnly’)

	1700–2000 (Pg C)		1850–2000 (Pg C)		1980s (Pg C year^{-1})		1990s (Pg C year^{-1})	
	NoLUC	WoodHarvOnly	NoLUC	WoodHarvOnly	NoLUC	WoodHarv-only	NoLUC	WoodHarvOnly
Atmosheric increase	100	103	100	103	2.5	2.5	2.8	2.9
Energy emissions	308	308	299	299	5.6	5.6	6.4	6.4
Ocean-atmos.	−66	−70	−57	−60	−1.1	−1.2	−1.5	−1.5
Land-atmos.	−142	−135	−142	−136	−2.0	−1.9	−2.1	−2.0
LUC emis.	0	44	0	38	0	0.4	0	0.5
Res. terrestrial sink	−142	−180	−142	−174	−2.0	−2.4	−2.1	−2.5

occur in the twentieth century (Fig. 5). Until 1900 the estimated global NEP and underlying NPP fluxes slightly decreased due to the changes in land use. During the twentieth century, the global NPP flux increased from about 52 Pg C year^{-1} up to 58 Pg C year^{-1} in 2000. These NPP values fit well with the ranges of a model intercomparison (44–66 Pg C year^{-1}, Cramer et al. 2001) and with those synthesized recently by the IPCC (54–63 Pg C year^{-1}, Fischlin et al. 2007). The estimated NEP flux is found to increase from about zero around 1900 up to 1.8 and 2.1 Pg C year^{-1} averaged over the 1980s and 1990s, respectively (Table 2). This estimated sink increase is the result of a combination of climate, CO_2 fertilization, land use (e.g. abandoned agricultural land in the early twentieth century, resulting in new forests, Fig. 1), and the autonomous growth factor accounting for nitrogen fertilization and management changes in mid- and high-latitudinal forests. This corresponds with the literature, suggesting that changes in climate (Churkina et al. 2005), atmospheric CO_2 (Nemani et al. 2003; Nowak et al. 2004), ecosystem management (Kaipainen et al. 2004; Phat et al. 2004) and nitrogen availability (Milne and van Oijen 2005; De Vries et al. 2006) are the main drivers of the observed biospheric C uptake. Note that the CO_2 fertilization effect on the terrestrial uptake is larger in the default experiment than when we exclude land-use changes; this is because the latter results in 65 ppm lower atmospheric CO_2 concentration in 2000 (Fig. 3).

3.2 Regional assessment

Here we provide regional explicit information on land use and natural C fluxes for the period from 1700 to 2000. Only a few studies have provided such historical information (e.g. Houghton 2003; House et al. 2003; Ramankutty et al. 2007). These studies, in general, have various disadvantages with respect to the limited time period, approach used (seldom integrated), and spatial focus. Nevertheless, we will use these sources for comparison wherever possible.

Large regional differences were found for the natural carbon fluxes and land-use emissions over the past three centuries (Fig. 6a, Table 3). Concerning land-use emissions, Europe and especially North America showed high emissions by the end of the nineteenth century, whereas tropical regions—especially South America—became carbon emitters mainly in the twentieth century. The land-use emissions form the most relevant contribution by tropical areas—especially Africa and South America—to the increase in atmospheric CO_2. Although energy and industry-related emissions are increasing in many of these regions, these are still relatively low in countries where land-use changes occur (Table 3).

The estimated land-use emissions in most regions across the world have stabilized or even decreased over the past decades. The land-use emissions in the US, for example, peaked around 1900 (0.17 Pg C year^{-1}) and dropped down to about 0.13–0.15 Pg C for the 1980s and 1990s, well within the range of figures provided by Houghton (2003) (i.e. 0.12 ± 0.2 Pg C). Likewise, the estimated land-use emissions in Brazil (and other parts of South America) peaked in the 1980s, followed by a considerable decrease. Note that the estimated emissions for South America are substantially lower than in Houghton (2003)—possibly due to his high deforestation rates (Denman et al. 2007; Ramankutty et al. 2007)—but in line with House et al. (2003). Exceptions for the stabilizing or decreasing land-use emission trends are

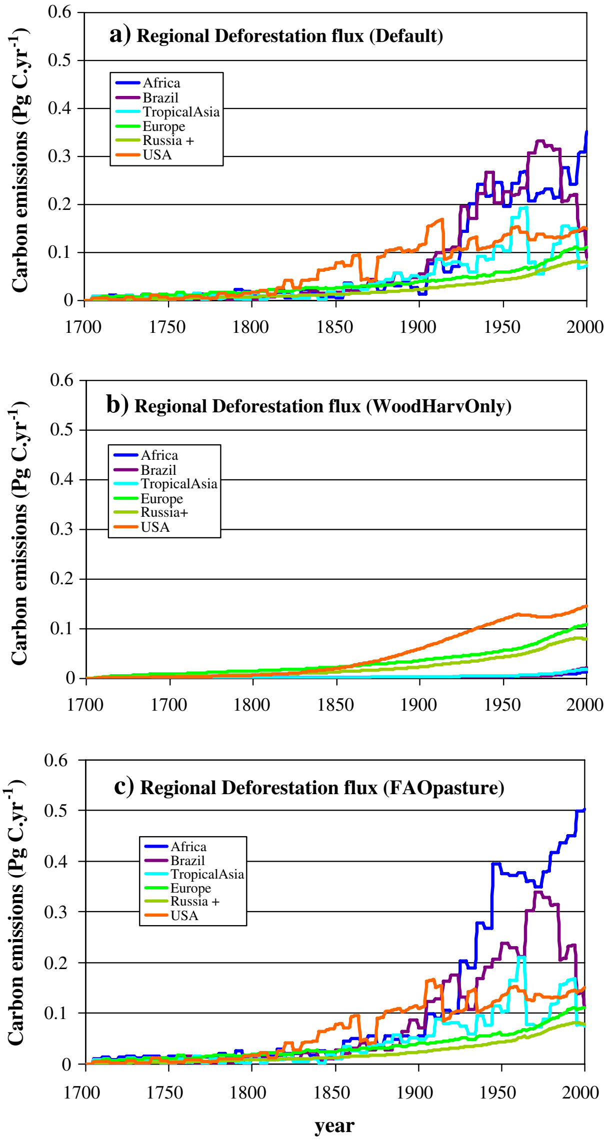

Fig. 6 Regional carbon fluxes from land-use change under the default simulation (**a**), with wood harvest only (**b**) and for the FAOpasture sensitivity experiment (**c**). Russia + is Russia plus other countries of the FSU, Tropical Asia is South-East Asia plus Indonesia

found for Africa and China, where large-scale land-use changes are estimated to continue to occur, resulting in increasing emissions (Fig. 6, Table 3).

In most tropical regions, the estimated land-use emissions have been caused mainly by land conversions for additional cropland and pasture. Timber played a more important role in many temperate regions of North America, Europe and Russia. The increasing timber demand in these regions has resulted in land-use emissions that have counterbalanced the decreased emissions from agriculture and pasture, caused by increasing abandonment of agricultural land (Fig. 6b, Table 3).

The estimated C fluxes of natural ecosystems have also shown a considerable regional variation (Table 3). Although the highest NPP rates were found for tropical

Table 3 Regional terrestrial and fossil-fuel C fluxes for different periods within the past three centuries (in Pg C year^{-1}) (a positive number represents emissions into the atmosphere)

Region	Average 1700–1800	Average 1800–1850	Average 1850–1900	Average 1900–1950	1980s	1990s
Land-use emissions						
Europe	0.02	0.02	0.03	0.05	0.10	0.11
Russia	0.01	0.01	0.02	0.03	0.07	0.08
US	0.04	0.04	0.08	0.12	0.13	0.15
China	0.0	0.0	0.01	0.02	0.07	0.09
South America	0.03	0.03	0.08	0.25	0.41	0.32
Tropical Asia	0.01	0.01	0.04	0.08	0.14	0.11
Africa	0.01	0.01	0.03	0.14	0.25	0.28
Net land-atmosphere flux						
Europe	0.02	0.04	0.04	−0.04	−0.13	−0.13
Russia	0.0	0.01	0.01	−0.16	−0.33	−0.34
US	0.01	0.08	0.24	0.12	−0.21	−0.22
China	0.0	0.0	0.0	−0.08	−0.13	−0.11
South America	0.01	0.03	0.07	0.24	0.51	0.28
Tropical Asia	0.01	0.01	0.04	0.08	0.10	0.07
Africa	0.01	0.0	0.0	0.07	0.09	0.03
Fossil fuel emissions						
Europe	0.0	0.02	0.15	0.40	1.21	1.15
Russia	0.0	0.0	0.0	0.04	0.64	0.48
US	0.0	0.0	0.06	0.43	1.23	1.41
China	0.0	0.0	0.0	0.01	0.55	0.85
South America	0.0	0.0	0.0	0.01	0.14	0.19
Tropical Asia	0.0	0.0	0.0	0.0	0.08	0.17
Africa	0.0	0.0	0.0	0.01	0.16	0.20

Ref1: Houghton (2003); Ref2: McGuire et al. (2001); Ref3: Achard et al. (2002); Ref4: DeFries et al. (2002); Ref5: Fearnside (2000a,b); Ref6: Levy et al. (2004);
Ref7: House et al. (2003); Ref8: Denman et al. (2007), based on averaging Houghton (2003) and DeFries et al. (2002)

regions, the largest NPP increase and terrestrial C sink were found for middle- and high-latitude ecosystems. Up to 1900, most ecosystems around the world are estimated to have been approximately carbon neutral. The uptake rates in Europe, Russia and the US increased up to 0.24, 0.42 and 0.37 Pg C year^{-1}, respectively, in the 1990s (comparing Table 3). This increase was less in tropical regions, sometimes significantly, down to only 0.04 Pg C year^{-1} in tropical Asia and South America. This spatial differentiation is caused by the fact that all aforementioned factors (i.e. CO_2, climate, growing season, land use, and nitrogen) have stimulated the uptake in middle and high latitudes, whereas in tropical regions mainly CO_2 has affected the carbon cycle. Land use has contributed to these changes in multiple ways. On the one hand, it has led to less natural forest, and as such to less carbon storage, for example, in many tropical regions in Asia and South America. And so, avoiding further land-use changes in these regions would effectively limit further increase of atmospheric CO_2 because productive forests would remain. On the other hand, land use can result in more young and re-growing ecosystems (e.g. through the abandonment of agriculture and pasture). In such ecosystems, NPP and soil respiration (and thus

NEP) are out of equilibrium (i.e. soil respiration increases slower than NPP) resulting in additional C uptake. Furthermore, land-use emissions lead to a higher atmospheric CO_2 concentration, which increases the natural C uptake through CO_2 fertilization. Net, land-use changes have resulted in a 78% lower C uptake in the US, averaged over the past three centuries. For most other temperate regions in China, Europe, and Russia, we estimated a 0% to 15% decrease in NEP due to changes in land use.

Combining land-use and natural C fluxes, we found that many regions in the world functioned as a net land-related carbon source between 1700 and 2000 (Fig. 7, Table 3). Exceptions are Europe (approximately C neutral), Russia, and China (sequester 24 and 10 Pg C, respectively). The development of the estimated trends over time varies, however, across the globe (Fig. 7, Table 3). Temperate regions are found to have been major carbon sources in especially the nineteenth century, but turned into C sinks during the twentieth century. We found an uptake of 0.8 Pg C year^{-1} in temperate regions for the 1990s (Table 3). Without land-use emissions from forestry, we estimated a sink of 1.2 Pg C year^{-1}. These sink estimates for temperate regions are at the low end of the range recently given by Stephens et al. (2007) on the basis of inverse model comparison (sink from 0.5 to 4 Pg C year^{-1}).

On a country/regional scale, the US emitted 17 Pg C before 1900, with a peak of 0.3 Pg C year^{-1} at the end of the nineteenth century, mainly due to changes in land use. This overall C source turned into a C sink around 1940, and has now reached an annual uptake of about 0.2 Pg C year^{-1}. This current sink in the US has not yet compensated its estimated historical land-related C emissions. Likewise, the estimated C flux in Europe turned from a small C source before 1910—emitting in total about 7 Pg C—into a sink, sequestering 8 Pg C over the twentieth century, with an annual uptake of 0.13 Pg C year^{-1} after 1980 (Table 3). This is at the low end of the range from Janssens et al. (2003)—based on various measurements—and at the high end of the range from House et al. (2003)—based on a modeling exercise. Many tropical regions were found to become net C sources in the twentieth century, although an increasing natural uptake partly compensates for the large land-use emissions (Fig. 7, Table 3). The overall tropical net emissions are estimated to have been 0.7 and 0.38 Pg C year^{-1} for the 1980s and 1990s, respectively (Table 3). The estimated decreasing C source (Fig. 7) is caused by both a lowering of the land-use emissions (especially in South America) and an increasing natural uptake (especially in Africa). The tropical land-use emissions for the 1990s (i.e.

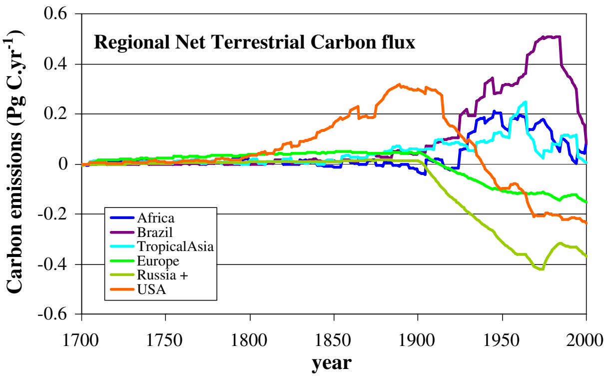

Fig. 7 Terrestrial net carbon fluxes for different regions in the world, including deforestation and residual natural sink (Pg C year^{-1}). Note that a positive number represents a flux from the biosphere to the atmosphere

0.8 Pg C year^{-1}) are comparable with the estimates of Achard et al. (2002) and DeFries et al. (2002) (about 1 Pg C year^{-1}), while the estimated net flux (emitting 0.38 Pg C year^{-1}) is in line with the findings of Stephens et al. (2007), based on an inverse modeling comparison. Without land-use changes, regions in the world seem to be small (especially tropical regions such as tropical Asia, which sequesters about 3 Pg C) up to large C sinks (e.g. Russia, sequestering 32 Pg C) over the past three centuries.

Overall, these results show that land use has had a significant effect on the C cycle in many world regions.

3.3 Sensitivity analysis

In order to assess the robustness of the preceding results, we varied input data and settings of some important processes in the C cycle (see Section 2 and Table 1), and analyzed the effect of these changes on CO_2 concentration, land-use emissions and the terrestrial carbon cycle (Table 4).

Using FAO land-use information on historical pasture instead of satellite-based information resulted in considerably higher land-use emissions (e.g. 27 Pg C for the period 1700 to 2000, Table 4), especially in tropical regions (Table 3, Fig. 6c). In Africa, for example, the emissions in 2000 were found to have been 42% higher due to the larger deforestation rates. For many temperate regions the effect was small because of the smaller uncertainty of land-use changes (Klein Goldewijk et al. 2007). The substantial effect of different assumptions related to historical land-use changes (i.e. default, NoLUC and FAOpasture) shows that an accurate land-use pattern is essential for estimating land-use emissions, especially in tropical regions. This supports the findings of Hurtt et al. (2006) and Ramankutty et al. (2007). Using FAO information for historical pasture land has a rather small effect on the atmospheric CO_2 concentration (i.e. +4 ppm in 2000, Table 4), despite the higher land-use emissions. This small effect is caused by a higher terrestrial carbon uptake (11 Pg C over entire period, Table 4) and higher ocean uptake (7 Pg over the entire period).

Varying parameter settings within the C-cycle model hardly influences land-use emissions, but can have a considerable effect on the historic carbon cycle via the carbon dynamics of natural vegetation (Table 4). Large effects have especially

Table 4 Effects of different historical land-use pattern and parameter settings on the C cycle

	Default	Input uncertainty	Model uncertainty		
	simulation	FAOpasture	NoAddGrowth	NoFert	ShortLifetime
CO_2 conc. (in 2000) (ppm)	370	374	395	378	375
Land-use emissions (1700–2000) (in Pg C)	140	167	140	143	169
Land-use emissions 1990s (in Pg C year^{-1})	1.3	1.6	1.3	1.3	1.6
Res. terrestrial sink (1700–2000) (in Pg C)	−105	−117	−22	−114	−112
Res. terrestrial sink 1990s (Pg C year^{-1})	−2.1	−2.3	−1.3	−0.9	−2.2

been found in the NoAddGrowth experiment (i.e. the experiment excluding the autonomous NPP increase that accounts for nitrogen fertilization and changes in forest management) and the NoFert experiment (i.e. the experiment keeping the CO_2 effect on NPP at its 1970 level throughout the entire simulation period). Excluding the autonomous NPP increase resulted in an additional 25 ppm CO_2 in the atmosphere up to 2000. This was due to a lower terrestrial C uptake and lower terrestrial biomass pools. Keeping the CO_2 feedback constant also increased the atmospheric CO_2 concentration compared to the default simulation, but less than when removing the autonomous growth factor (Table 4). The smaller effect was due to the overall large terrestrial uptake over the entire three centuries, which was mainly the result of a CO_2 induced uptake already in the early stages of the experiment (e.g. eighteenth century), whereas the carbon uptake became strongly reduced after 1970 (even more than in the NoAddGrowth experiment). Reducing the lifetimes of wood products by factor of 10 mainly had an effect on the historical land-use emissions as more timber was needed to compensate for the faster decay. But the effect on the terrestrial sink and consequently on the atmospheric CO_2 concentration was small (Table 4). These experiments show the need to accurately quantify the CO_2 fertilization of natural vegetation, and to study the historically observed carbon sink in forests due to management and nitrogen fertilization in a more detailed and process-based approach.

Next to the effect of these uncertainties, it should be kept in mind that the C-cycle model used in this study does not include changes in biophysical conditions such as albedo. Although such changes have a considerable effect on the climate system (e.g. shown by Brovkin et al. 2006; Schaeffer et al. 2006; Bala et al. 2007), biophysical conditions are less relevant here, since the objective of this study is to study the effects of changes in land-use, climate and CO_2 concentration feedbacks on the historical carbon cycle. Climate information has been taken directly from exogenous data sources (see Section 2).

4 Conclusions

In this study, we evaluated the role of land use and natural terrestrial ecosystems in the global and regional C cycle for the period from 1700 to 2000 by combining an integrated modeling framework (i.e. IMAGE 2) with a database on long-term historical land-use data (i.e. HYDE). The resulting estimates of land-use related and natural C fluxes (as affected by environmental changes) contribute to reducing some of the pertinent uncertainties in the historical C cycle dynamics. The strength of the methodology presented is the simultaneous consideration of multiple anthropogenic and biophysical processes in a geographically explicit and transparent manner. For example, we considered explicitly the abandonment of agricultural land use, resulting in a recovery of natural C pools. Likewise, we looked explicitly at the direct effect on the carbon cycle of deforestation, wood harvest (for timber and fuel wood) and reforestation, as well as the indirect feedback effects through CO_2 fertilization, climate change and nitrogen deposition. In our opinion, this integration is essential because of the closely interlinked processes of the terrestrial C cycle, and their complex temporal and spatial dynamics.

The historical atmospheric CO_2 concentration profile was well reproduced in our study and global and regional terrestrial C fluxes were in line with many other studies. Globally, we calculated that historical land use led to 177 Pg less carbon stored in the terrestrial biosphere compared to a case with no land-use changes. This is more than half the historical fossil fuel-related emissions of 308 Pg C for the period from 1700 to 2000. Up to 1900 land-use emissions were higher than fossil-fuel related emissions, mainly due to considerable land-use emissions in the US and Europe, and fossil fuel use that was still low. During the twentieth century the carbon uptake of natural ecosystems increased due to re-growing vegetation, changes in climate and management, and CO_2 and nitrogen fertilization.

Overall, we found that land-use change played a more important role in the global and regional C cycle over the past centuries than the biosphere response to environmental changes (such as climate, CO_2 effects and nitrogen deposition). In past decades, however, this has changed because environmental change is rapidly changing ecosystems and their C fluxes. The global and regional land-use and natural fluxes also differed significantly between the two different data sources of historical land use. This illustrates the need to improve the accuracy of historical patterns of land use and land cover.

The role of land use and natural processes also varies geographically. In temperate regions such as Europe and especially the US, land-use change played an important role at the end of nineteenth and early twentieth century. This led to considerable carbon emissions and decreased natural uptake rates. This trend has changed after 1950 because agricultural abandonment resulted in afforestation. Remaining land-use change emissions came mainly from timber. In tropical Asia, Africa, and South America, the role of land-use changes increased during the twentieth century, resulting in considerable losses of natural ecosystems, and associated carbon emissions and lower uptake rates. Most of the estimated historical land-use emissions in tropical regions result from land conversion for additional cropland and pastures. Avoiding future land-use changes in these regions may contribute significantly to limiting the further increase in CO_2 concentration and should, therefore, be part of international mitigation strategies. But climate policies that focus solely on slowing deforestation or enhancing afforestation will not be sufficient for mitigating climate change, because historical fossil fuel emissions are nearly twice as high as all the land emissions taken together. Nowadays, the share of fossil-fuel emissions remains dominant.

The sensitivity experiments showed that using different land-use patterns and/or changed parameter settings can result in higher land-use emissions. But these emissions are still significantly lower than the emission figures as given by Houghton (2003). Changing parameter settings within the C-cycle model had a considerable effect on the terrestrial carbon uptake of the past three centuries and consequently the atmospheric CO_2 concentration. Giving the fact that in the default experiment the historical CO_2 profile was reproduced well, we conclude that there had been autonomous factors in the terrestrial C cycle as such nitrogen fertilization and management. Also CO_2 feedbacks on the terrestrial carbon uptake are important, especially over recent decades. Developing a robust parameterization of these feedbacks will improve the robustness of projecting the future C cycle.

Given the considerable role of land-use and natural processes in the historical and current terrestrial C cycle, as well as their geographical and temporal variation, there is a need for integrated approaches for energy, the natural environment and land use. This is also valid in projecting the future C cycle and in assessments of mitigation efforts needed to cope with climate change.

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