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ORIGINAL ARTICLE

Effects of human land-use on the global carbon cycle during the last 6,000 years

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Abstract Humanity has become a major player within the Earth system, particularly by transforming large parts of the land surface and by altering the gaseous composition of the atmosphere. Deforestation for agricultural purposes started thousands of years ago and might have resulted in a detectable human influence on climate much earlier than the industrial revolution. This study presents a first attempt to estimate the impact of human land-use on the global carbon cycle over the last 6,000 years. A global gridded data set for the spread of permanent and non-permanent agriculture over this time period was developed and integrated within the Lund-Potsdam-Jena Dynamic Global Vegetation Model (LPJ-DGVM). The model was run with and without human land-use, and the difference in terrestrial carbon storage was calculated as an estimate of anthropogenic carbon release to the atmosphere. The modelled total carbon release during the industrial period (A.D. 1850–1990) was 148 gigatons of carbon (GtC), of which 33 GtC originated from non-permanent agriculture. For pre-industrial times (4000 B.C.–A.D. 1850), the net carbon release was 79 GtC from permanent agriculture with an additional 35 GtC from non-permanent agriculture. The modelled pre-industrial carbon release was considerably lower than would be required for a substantial influence on the climate system.

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Introduction

Human activity has altered between a third and a half of Earth's land surface through cropping, pasture, forestry and urbanisation (Vitousek et al. 1997). This has had consequences for key biogeochemical cycles, changing the atmospheric composition and resulting in considerable modification of ecosystems (Foley et al. 2005). Land-use changes result in biogeophysical climatic effects through modifications of surface albedo and roughness (Brovkin et al. 2006) and biogeochemical effects through, for example, alterations in vegetation and soil carbon pools (Houghton and Goodale 2004), which influence atmospheric greenhouse gas levels and global climate (Foley et al. 2003).

Deforestation for agriculture and pasture has been a major driver of accelerating land transformation (Williams 2000), and the reduction in Earth's forests has followed the rise of human history since the beginning of agricultural and pastoral development (Turner et al. 1990). An increasing human population and civilization making advances in technology in agriculture, forestry, mining and trade have caused massive changes in forest vegetation (Williams 2000). This resulted in an estimated loss of natural forest/woodland area of 6% by A.D. 1700, 14% by 1850 and 34% by 1990 (Klein Goldewijk 2001). Today, most natural temperate forests in Europe and China, as well as the monsoon and dry forests in India, have disappeared (Williams 2003). Clearance of tropical rain forests has accelerated since the 1950s and accounts for most of the present land-use-related emissions (Malhi et al. 2002), while Europe and North America, as a result of a stabilised population size and increased crop returns, currently experience a small net re-expansion of forests following a farmland reduction (Williams 2000).

Agricultural practice is believed to have started 10,000 years ago in the Fertile Crescent around the Tigris and Euphrates rivers as well as along the Nile Valley in Egypt, from whence it gradually spread into Europe, North Africa and western Asia (Roberts 1998). Early agriculture evolved independently in other regions, notably around the Yellow River in China, the Indus valley in India, regions in Central America and in the Andes (Simmons 1996). Together with agricultural development the first permanent settlements and societal systems were established (Gupta 2004). Flood plains cleared of trees were used for intensive cultivation and pasture of cattle, sheep and pigs, which supported stable settlements for long periods (Williams 2000). Fire was often used for clearing forested land, and is therefore seen as an indicator of early human activity in several charcoal records in Europe, America and Southeast Asia (Clark et al. 1989; Carcaillet et al. 2002). Increasing charcoal levels are often accompanied by decreasing tree pollen and increasing cereal and weed pollen, indicating human cultivation and grazing of domesticated animals (Roberts 1998; Williams 2000).

When nutrient conditions are too poor for permanent agriculture, an alternative cultivation method is shifting cultivation or "slash-and-burn", characterised by a cycle of regularly alternating farming and fallow periods (Metzger 2003). Initially forested land is cleared by man aided by fire, enriching the soil with nutrients from the ashes (Giardina et al. 2000). The cleared land is usually cultivated for 2–4 years before the nutrient level is too low to give an acceptable return (Lanly 1985; Crutzen and Andreae 1990). The land is abandoned, allowing re-growth of secondary vegetation, typically for a 10–20 year fallow period (Brady 1996), or up to 50 years (Crutzen and Andreae 1990). A farmer often has several plots at different stages in the shifting cultivation cycle, before returning to re-clear the initial plot. Today slash-and-burn is practised mainly in the tropics by 300 to 500 million people (Brady 1996). As forest ecosystems contain a large proportion of the biospheric carbon, a major change in forest cover results in modifications to the global carbon cycle (Houghton and Goodale 2004), making accumulated land-use change the second most important source of atmospheric carbon after fossil fuel use (Prentice et al. 2001). Apart from the reduction in vegetation carbon, 25–30% of the soil carbon in the upper metre of soil is released when clearing forests for permanent cultivation (Houghton and Goodale 2004). When fallow periods in slash-and-burn systems are short, as is currently the case in large parts of the tropics where population pressure is increasing (Crutzen and Andreae 1990), shifting cultivation also results in a soil carbon source (Fearnside 2000). For these reasons, widespread use of fire for land opening throughout the second part of the Holocene could have had a considerable impact on atmospheric CO_2 concentration (Carcaillet et al. 2002). Ruddiman (2003) went further in linking early human land-use to a strong modification of the atmosphere and climate long before any large-scale burning of fossil fuel. According to this hypothesis, human interference with the climate system has prevented a marked cooling that would have otherwise naturally occurred during the last 8,000 years. Humans would have increased atmospheric greenhouse gas forcing by releasing CO_2 through deforestation, and methane (CH_4) from irrigated rice fields (Ruddiman and Thomson 2001). On the other hand natural cooling would have been associated with falling levels of atmospheric CO_2 and CH_4 as seen in the ice-core records from the three previous interglacials (Indermühle et al. 1999; Petit et al. 1999; Ruddiman 2003).

Global land use-related carbon emissions with a focus on the past 300 years have been estimated by various methods. Using the "book-keeping" model (Houghton et al. 1983), which is based on deforestation statistics combined with vegetation and soil carbon approximations, Houghton (1999) estimated a net release of 124 GtC between A.D. 1850 and 1990, later revised to 134 GtC (Houghton 2003). Another approach is to use ecosystem models that represent global patterns of land cover and the terrestrial carbon cycle in combination with data sets on human land-use at different times. The models can then be driven with data on existing or historical land-use and with potential natural vegetation cover and carbon dynamics. The difference between the modelled total terrestrial carbon storage with land-use and the results obtained with natural vegetation provides an estimate of the carbon release that has been caused by that land-use. Different combinations of ecosystem models and land-use data have suggested a range of carbon releases, summarised in Table 2 below.

The objective of the present study is to estimate the development of carbon emissions from human land-use through time. We have developed a global land-use data set with permanent and non-permanent agriculture over the past 6,000 years. Non-permanent agricultural practices, such as repeated slash-and-burn, can result in a decrease of mean vegetation and soil carbon over the combined farming and fallow period, and thus cause release of carbon to the atmosphere without showing a permanent "fingerprint" on land cover, but the global impacts have, to our knowledge, not been assessed in any other study. The data set was used to run the Lund-Potsdam-Jena Dynamic Global Vegetation Model, LPJ-DGVM (Sitch et al. 2003), and the result was compared to a model run with potential natural vegetation in order to estimate the anthropogenic impact on the carbon cycle and greenhouse gas forcing through land-use during the last 6,000 years.

Materials and methods

The Lund-Potsdam-Jena Dynamic Global Vegetation Model (LPJ-DGVM)

LPJ-DGVM is a coupled biogeography–biogeochemistry model which incorporates process-based representations of terrestrial vegetation dynamics and biogeochemical cycling. The model is used by a large group of scientists. LPJ-DGVM has been shown to reproduce the interannual global exchange of CO_2 with the atmosphere (Sitch et al. 2003), together with global patterns of vegetation distribution (Sitch et al. 2003; Hickler et al. 2006) and the observed high-latitude vegetation greening trend in the 1980s and 1990s (Lucht et al. 2002). We used the model version described in Sitch et al. (2003), with updated hydrological processes by Gerten et al. (2004), and minor parameter updates given in Hickler et al. (2006; supplementary material S2).

The structure of LPJ-DGVM is based on modules, each mechanistically representing a well-defined set of ecosystem processes, linked together by a central framework (Fig. 1). Ecophysiological processes, such as photosynthesis, soil water dynamics, stomatal regulation and exchanges of carbon and water between the soil, vegetation and the atmosphere are implemented on a daily time step. Changes in vegetation structure through growth, population dynamics and fire-disturbance are implemented at the end of each simulation year. Global vegetation is commonly represented by ten plant functional types (PFTs), which are differentiated by bioclimatic limits and by physiological, morphological and life history characteristics, which govern competition for resources. As the PFT specifically representing Siberian larch (*Larix sibirica*) is not mechanistically distinguished in the model it was excluded, while the other nine standard PFTs were implemented as in Sitch et al. (2003). Leaf fall and dead biomass from mortality and root turnover are added to the litter pool, which is divided into both a highly labile fraction respired directly into the atmosphere and two soil carbon pools with different turnover times. Soil decomposition depends on soil temperature and moisture. LPJ-DGVM is driven by data on climate (temperature, precipitation and solar insolation), atmospheric CO_2 and soil texture.

Incorporating human land-use within LPJ-DGVM

Two modes of agriculture were implemented within the model:

1. *Permanent agriculture* was implemented by forest clearance, followed by natural vegetation without allowing tree establishment. The cleared forest biomass was added to the litter pool for decomposition. Without trees, the vegetation in the model is composed of two herbaceous PFTs (with C3 or C4 photosynthesis, see Sitch et al. 2003). These PFTs share fundamental physiological and growth characteristics with crops (Bondeau et al. 2007).
2. *Non-permanent agriculture* was implemented as a rotating scheme between humans setting fire to the natural vegetation, facilitating productive agriculture for a few years (farming time) during which tree establishment was not allowed, followed by a longer fallow period when tree establishment and growth was permitted. After the fallow period, another agriculture cycle was started by fire.

Harvest was implemented by releasing a larger litter fraction (80%) directly into the atmosphere than that without agriculture (70%). Only the remainder, 20 or 30% respectively, was entering the soil carbon pools. Note that, in LPJ-DGVM, all aboveground grass biomass is transferred to the litter pool within one year.

The land-use data set was divided into seven time-slices to cover the simulation period from 4000 B.C. until the present (1998) (Table 1). During each time-slice, the land-use mode in an individual grid-cell was kept constant, though the land-use mode could change between time-slices. The spatial extent of the two modes of agriculture through time is shown in Fig. 3.

Land-use data

A gridded global data set at $0.5° \times 0.5°$ resolution with seven time-slices of human civilization and land-use development during the last 6,000 years was derived from the literature (e.g. Sherratt 1980; Turner et al. 1990; Simmons 1996; Roberts 1998). The first four time-slices were based on maps from Lewthwaite and Sherratt (1980), representing the spread of human civilization by: (a) 4000 B.C., (b) 2000 B.C., (c) A.D. 1 and (d) A.D. 1000. These maps were manually digitised to facilitate further computer-based processing. Another three time-slices were taken from the digital HYDE database (Klein Goldewijk 2001): (e) A.D. 1700, (f) A.D. 1850 and (g) A.D. 1990 (Fig. 2; Table 1).

Permanent agriculture

For the last three time-slices (1500–1998), the spatial distribution of areas under permanent agriculture was taken as that for the land-use classes "intensive cropland" and

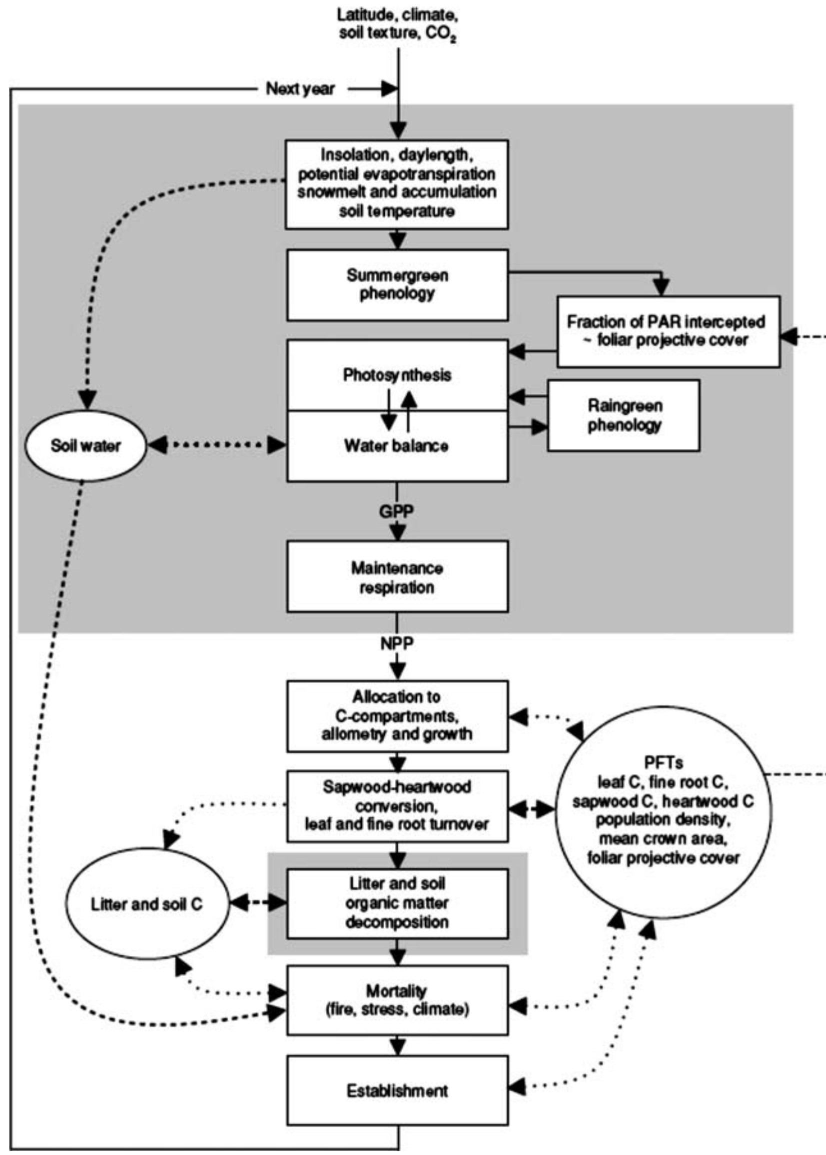

Fig. 1 Structure of LPJ-DGVM represented as a flow chart for one simulation year. Modules with *shaded background* are called on a daily time step while the other modules are called annually. (From Sitch et al. 2003)

Table 1 Time-slices used to construct the land-use data set

Time-slice	First year	Last year	Population	Non-permanent agriculture	
				Fraction %	Fallow period + farming time
4000 B.C.	4000 B.C.	3001 B.C.	7	75	250
2000 B.C.	3000 B.C.	1001 B.C.	27	50	200
A.D. 1	1000 B.C.	A.D. 499	170	25	150
A.D. 1000	A.D. 500	A.D. 1499	265	22	100
A.D. 1700	A.D. 1500	A.D. 1774	610	20	80
A.D. 1850	A.D. 1775	A.D. 1920	1,200	15	60
A.D. 1990	A.D. 1921	A.D. 1998	5,300	11	30

Population data (in millions) for 1990 from Klein Goldewijk (2001), other years from McEvedy and Jones (1978). Estimated fraction of the world population living under non-permanent agriculture during the respective time-slice (%). The total number of people depending on non-permanent agriculture, together with cultivation area required per person and farming time (4 years), was used to derive an estimate of the global average fallow period (years) in non-permanent agricultural systems

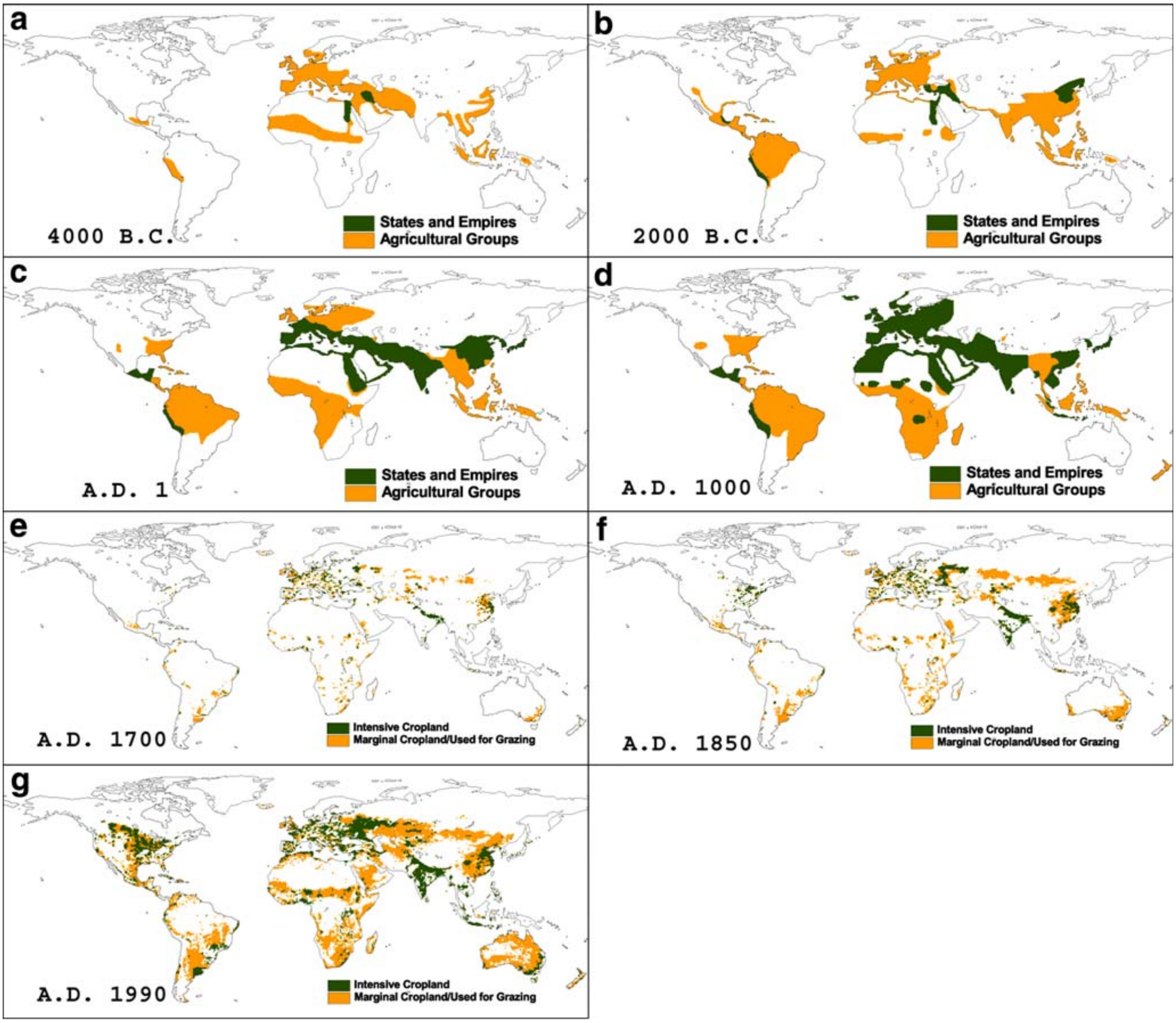

Fig. 2 **a**–**d** "States and Empires" and "Agricultural Groups" (From Lewthwaite and Sherratt 1980); **e**–**g** "Intensive Cropland" and "Marginal Cropland/Used for grazing" (From Klein Goldewijk 2001)

"marginal cropland/used for grazing" in the HYDE-database. Before 1500, only areas referred to as "states and empires" in Lewthwaite and Sherratt (1980) were assumed to be possibly covered by permanent agriculture (following Roberts 1998; Ruddiman 2003). On this basis grid cells assigned permanent agriculture during time-slice (e) were used to constrain the maximum extent of permanent agriculture during the four preceding time-slices (a–d), with the exception of Egypt and the Fertile Crescent, for which the extent of farmland was taken from the individual time-slices. Permanent agriculture has been a prerequisite for the development of state- or empire-like societies (Diamond 1997), which explains why the spread of complex societies has been strongly associated with the spread of permanent agriculture (Roberts 1998). Ten percent of each grid cell was considered inappropriate for agriculture and therefore left for natural vegetation (Ruddiman 2003). This accounted for landscape heterogeneity in that some areas are always covered by ridges, streams, etc. and are therefore not suitable for agricultural use.

Non-permanent agriculture

For the earliest four time slices (a–d), "suitable" areas within the categories "states and empires" and "agricultural groups" from Lewthwaite and Sherratt (1980) that were not already assigned permanent agriculture (see above) were assumed in this study to be under non-permanent agriculture (Fig. 3). For the three last time-slices

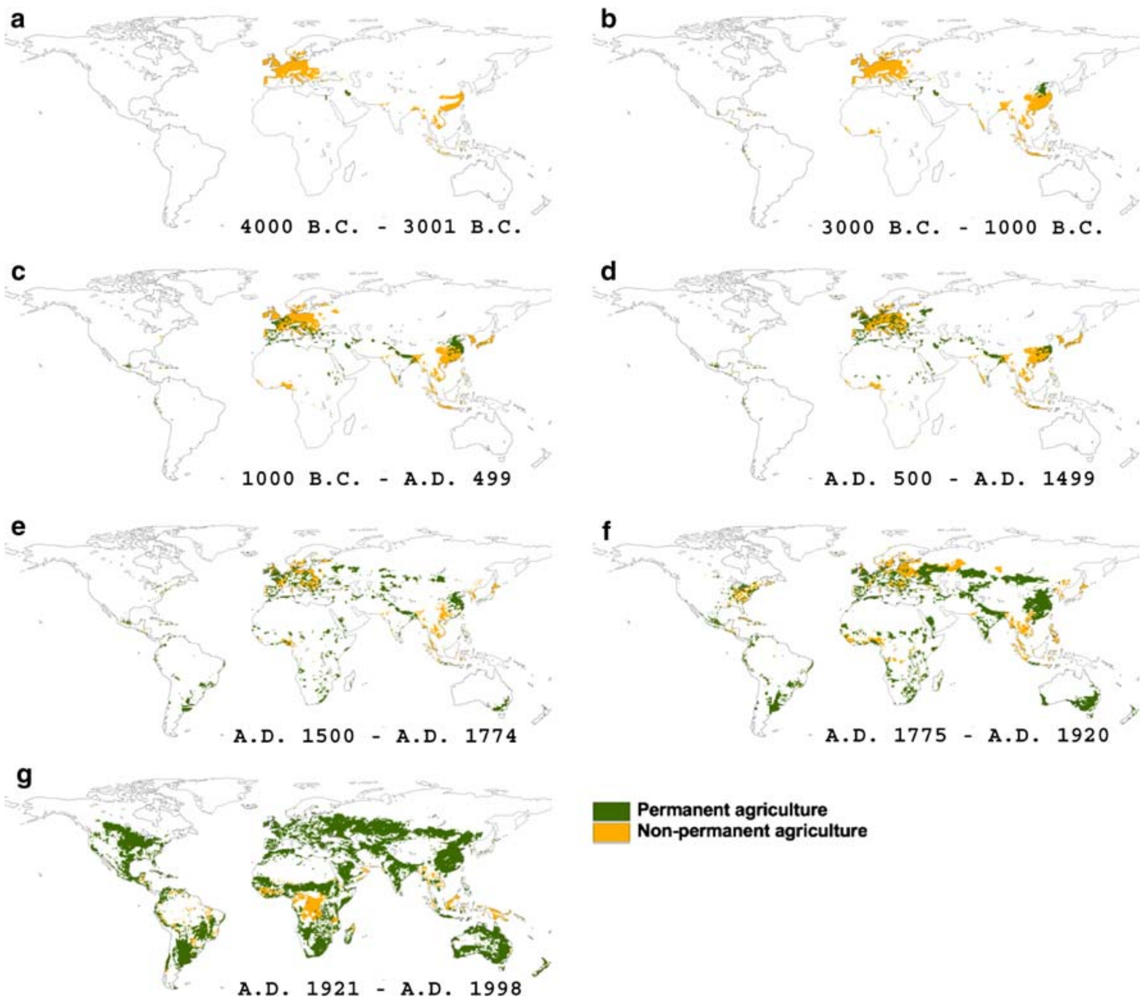

Fig. 3 Spatial extent of permanent and non-permanent agriculture used in this study during seven time-slices (Table 1)

(e–g), non-permanent agriculture was assumed to occur in all suitable areas on the globe not already assigned permanent agriculture. Suitable areas were distinguished from unsuitable land as follows: only grid cells with a maximum average elevation of 1,000 m were considered for farming in order to exclude less accessible forested areas (Ruddiman 2003). As for permanent agriculture, 10% of each grid cell was left for natural vegetation. Areas with limited potential natural vegetation, set to less than 2 kg C/m^2, were regarded as unproductive and therefore excluded from non-permanent agriculture. Regions with a sparse population of less than five inhabitants/km^2 in 1700, the earliest HYDE population data available, were regarded as unsuitable areas for non-permanent agriculture during the four earliest time-slices (a–d). Furthermore, densely populated regions with more than 25 inhabitants/km^2, as well as sparsely populated areas as above, based on HYDE for the respective time-slice, were regarded inappropriate for non-permanent agriculture during the last three time-slices (e–g). For the final time-slice (g), non-permanent agriculture was restricted to areas south of latitude 25°N. (Fig. 3)

The farming period t_{farm} was set to 4 years (Lanly 1985). The required farming area under crops per person a_{person} was set to 1/6 ha (Lanly 1985; based on current global non-permanent farming practices, mainly in the tropics) and to 4/6 ha for the first two time-slices, when non-permanent farming was less technically advanced and more widespread in less favourable climatic zones. a_{person} and data on global population p_{global} (McEvedy and Jones 1978; Klein Goldewijk 2001; Table 1) were used to derive the fallow period t_{fallow} (average period between the end of one farming period and the start of the next one). For this purpose, the fraction of the global population depending on non-permanent agriculture f_{non_perm} had to be estimated (Table 1). By multiplying p_{global} with f_{non_perm} and a_{person}, the area required for farming at a given time was derived. Together with numbers of the areas categorized as suitable for non-permanent agriculture a_{suit} (see above), the farming area requirement was used to calibrate an approximate global average fallow period for each time-slice to be applied in this simulation study (Table 1):

$$t_{\text{fallow}} \approx \frac{a_{\text{suit}}}{p_{\text{global}} \times f_{\text{non\_perm}} \times a_{\text{person}} \times \frac{1}{t_{\text{farm}}}} - t_{\text{farm}} \quad (1)$$

Modelling protocol

Monthly mean surface climate data for temperature, precipitation and percentage sunshine hours were taken from the CRU05 (1901–1998) data set on a 0.5° × 0.5° global land grid provided courtesy by the Climate Research Unit (CRU), University of East Anglia (New et al. 1999, 2000). The atmospheric CO_2 concentration was held constant at 275 ppmv until 1900, which is approximately the average level for the 6,000 years before the industrial revolution (Indermühle et al. 1999; Monnin et al. 2004). For the last 98 years (1901–1998), historical annual mean CO_2 values from the Carbon Cycle Model Linkage Project (McGuire et al. 2001) were applied. Soil texture data were as in Sitch et al. (2003), based on the FAO soil data set (Zobler 1986; FAO 1991).

The simulation process started from bare ground, and the model was spun up for 1,000 years to allow vegetation, soil and litter carbon pools to reach equilibrium status with the long-term climate. During the spin-up detrended climate data from the first 30 years (1901–1930) of the CRU05 climate data set, was used repetitively. Following the spin-up, the model was run continuously from one time-slice to the next one (Table 1; Fig. 3), using repetitively the same 30 years of climate data as during the spin-up throughout the entire simulation period, except for the period 1901 until 1998, when historical CRU05 and CO_2 data were used. In one run the model was used to simulate potential natural vegetation and carbon pools, while in a second the model was run with the developed land-use data set. The difference between the simulated carbon pools in both runs was taken as an estimate of the carbon emissions caused by land-use. For the period before the 20th century, we thus distinguished land-use-driven carbon fluxes and excluded carbon dynamics that were caused by changes in climate and atmospheric CO_2. The climate-driven signal has been addressed in other studies, but with contrasting results. Joos et al. (2004) and Kaplan et al. (2002) suggested a terrestrial carbon uptake of 28–75 GtC and 100–120 GtC, respectively, while Brovkin et al. (2002) suggested a decrease in terrestrial carbon storage of 90 GtC.

Results

The simulated potential natural, pre-industrial vegetation carbon stock, 744 GtC, was in the middle of the "most realistic range" of 622–908 GtC from the global studies reviewed in Köhler and Fischer (2004). The accumulated carbon flux related to the developed land-use data set until 1990 was 262 GtC (Fig. 4). During pre-industrial times, until 1850, human land-use resulted in an accumulated carbon release of 114 GtC, while 148 GtC was emitted during the industrial time-period, from 1850 until 1990. Ninety percent of the total carbon release occurred after A.D. 1 (Fig. 4).

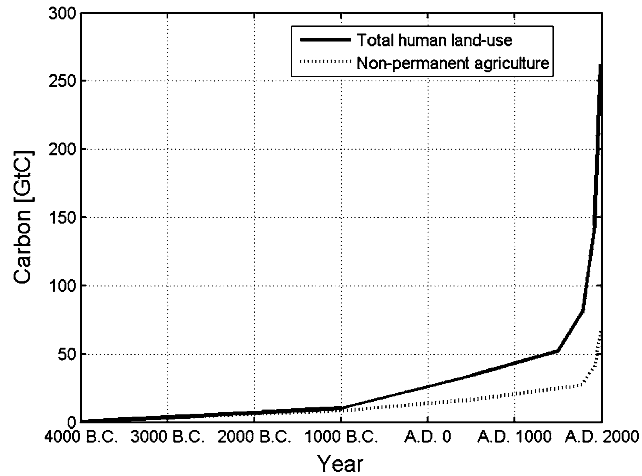

Fig. 4 Simulated accumulated carbon release from human land-use during the last 6,000 years (GtC)

Over the full simulation period until 1990, the accumulated carbon release from permanent agriculture was 194 GtC. Carbon fluxes originating from non-permanent agriculture contributed an additional 68 GtC, corresponding to 26% of the total flux to the atmosphere. Until A.D. 1500, non-permanent agriculture contributed 47% of the released carbon. A decrease in vegetation carbon of 207 GtC accounted for 79% of the accumulated carbon emissions over the entire simulation period. Over the same time period, the soil carbon pool decreased by 61 GtC, while the litter pool increased by 6 GtC.

With less forested land and more land being used for cultivation and pasture, there was an increase in vegetation openness induced by human land-use (Fig. 5). At A.D. 1, a strong human impact on vegetation openness was only obvious in some regions of Europe and Southeast Asia. However, by 1990, modelled anthropogenic landscape openness was pronounced in several areas all over the world. For interpretation it has to be kept in mind that the impacts of non-permanent agriculture were averaged over the whole area where this farming method was assumed to occur. This explains why the openness maps do not depict more localised effects of early humans. When modelling global total carbon releases, small averaged carbon releases over large areas can still add up to considerable magnitudes.

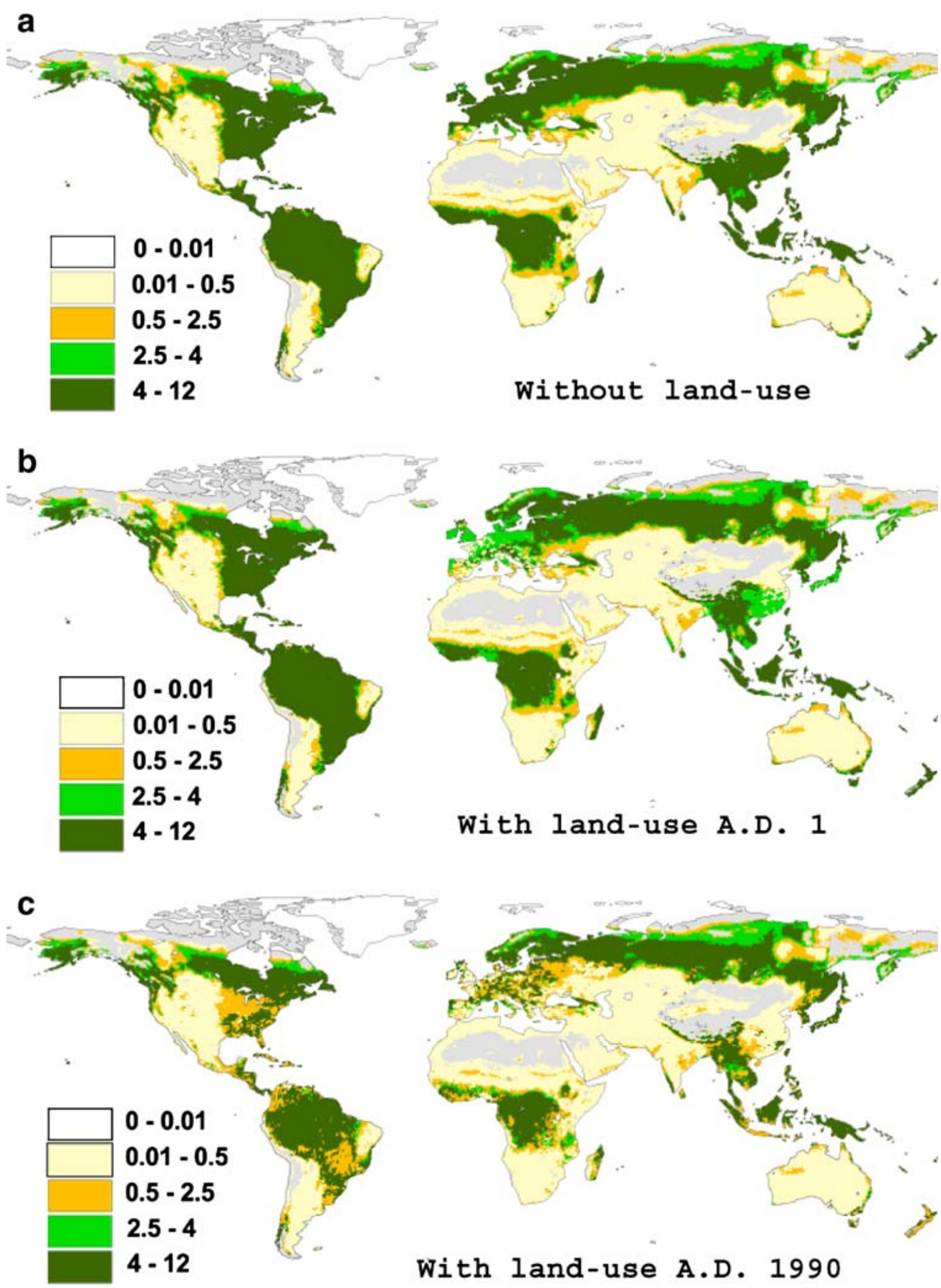

Fig. 5 Modelled landscape openness expressed as averaged forest Leaf Area Index (LAI): **a** without human land-use; **b** with human land-use at A.D. 1; **c** with human land-use at A.D. 1990

Table 2 shows a comparison with other land-use studies. For most time periods the estimated carbon release from permanent agriculture was within the range reported in these studies. At A.D. 1, the modelled carbon release was, however, an order of magnitude lower than the estimate from Ruddiman (2003). He assumed a larger area of deforestation by A.D. 1, as well as higher standing vegetation biomass per area cleared from forests. Compared with the estimate up to 1850 by DeFries et al. (1999), the modelled carbon release from permanent agriculture was approximately 50% higher. Carbon fluxes from non-permanent agriculture added considerably to the carbon releases originating from permanent agriculture during the entire simulated time period, especially before A.D. 1.

Discussion

This study presents a first estimate of transient changes in carbon emissions caused by land-use during the last 6,000 years, including non-permanent agriculture. Our results suggest the same magnitude of carbon release from

Table 2 Comparison of the modelled total land-use-change-related global carbon release with estimates by other authors (GtC)

Study	–A.D. 1	1700–1990	–1850	1850–1990	–1990	1920–1992
DeFries et al. (1999)			48–57		182–199	
McGuire et al. (2001)						56–91
Houghton (2003)				134		
Ruddiman (2003)	250		320			
Levy et al. (2004)		222		173		
Campos et al. (2005)		139		98		
This study total	26	189	114	148	262	121
Permanent	12	148	79	115	194	94
Non-permanent	14	41	35	33	68	27

permanent agriculture during industrial times as presented in other studies based on process models, but indicate a considerable additional role for non-permanent agriculture. Fourty-four percent of the carbon release over the entire study period originated before the industrial revolution, showing that the pre-industrial period is also important for assessing land-use-change-driven carbon releases.

Our estimates of carbon releases caused by land-use are generally consistent with results from other studies which mostly addressed the last 300 years. The modelled fractional decrease in soil carbon as a result of farming was similar in magnitude to that suggested by Houghton and Goodale (2004). The long calculated fallow periods (Table 1) during the initial time-slices correspond with the theory of Iversen's landnám phases of forest clearance (Iversen 1941 in Roberts 1998). These may have lasted up to 600 years (Smith 1981 in Roberts 1998) although a repetition of the clearance cycle is seldom seen in Neolithic pollen diagrams (Roberts 1998). However, when discussing the simulated fallow periods, one has to consider that we developed an approach to derive an objective estimate of global total carbon releases, including considerable averaging of human impacts over large areas. When zooming in on a particular area, for example by analysing the modelled spatial pattern of landscape openness, the model may not adequately represent the human fingerprint on the landscape. As spatial data on global human population densities from before 1700 are not yet available, it might be difficult to account for this real-world heterogeneity when using a global, quantitative modelling approach. The trend of shortening fallow periods over time is consistent with an increase in food production because of growing population pressure, as observed during Medieval times in Europe (Williams 2000) and in modern non-permanent agriculture societies (e.g. Fearnside 2000; Metzger 2003).

We acknowledge that some of the parameter values used to implement non-permanent human land-use might be subject to considerable uncertainty. After carrying out a number of alternative simulations, with slight modifications in the land-use implementation, we are nevertheless confident that our results are generally robust, and we plan to carry out more-detailed sensitivity tests in a forthcoming study. At this stage, we would like to emphasize that we did not include human effects on ecosystems that are not directly related to agriculture. Native North American Indians have, for example, used fire to open up the forest for thousands of years to provide better opportunities for hunting, thereby potentially maintaining an open prairie instead of partly forested woodlands (Anderson 1987). Logging for fuel and livestock grazing were not included either, but the collection of firewood has probably mainly been carried out on a small scale, allowing fast vegetation re-growth, and livestock densities are difficult to estimate for the last thousands of years. Furthermore, the spatial pre-industrial land-use assignment could be improved by integrating more detailed information about the human population density from, for example, archaeology, pollen sediments and recorded historical sources, which are available in many regions of the world, but not in the form of a global data set. Finally, we have not included any estimate of carbon losses from anthropogenic soil erosion, which could play an important role in the global carbon cycle (Lal 2003). In spite of these uncertainties, we think that the land-use effects implemented in our model account for a major fraction of the total anthropogenic carbon releases before the fossil fuel era.

By A.D. 1, the present study indicates an accumulated total carbon release from land-use of 26 GtC, which is an order of magnitude lower than the 250 GtC originally suggested by Ruddiman (2003). However, Joos et al. (2004) concluded that much larger anthropogenic emissions (710 GtC until present) would have been necessary for the strong influence on atmospheric CO_2 and climate that Ruddiman suggested, because on a millennium timescale the oceans would remove 85% of the emitted carbon. In response to Joos et al. (2004), Ruddiman (2005) has modified his hypothesis by stating that "perhaps a third" of the total CO_2 anomaly compared with earlier interglacials could have originated directly from human land-use, while indirect effects (changing ice sheets influencing ocean biogeochemistry) could account for the remaining two-thirds. However, our results are also an order of magnitude lower than this modified hypothesis. If the estimate by Joos et al. (2004) is accurate, our results suggest that a strong atmospheric effect from land-use-related carbon emissions before A.D. 1 as well as for the entire pre-industrial period is unlikely (see also Fig. 4). These findings call for an alternative explanation for the current relatively long interglacial as compared with the previous three warm periods. The current low eccentricity of the Earths' orbit might be the reason for this long warm period (Broecker and Stocker 2006). When a similar eccentricity to that of today prevailed around 400,000 years ago [Marine Isotope Stage (MIS) 11], atmospheric CO_2 levels stayed at interglacial levels, above 270 ppmv, for 28,000 years (Siegenthaler et al. 2005; Broecker and Stocker 2006).

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