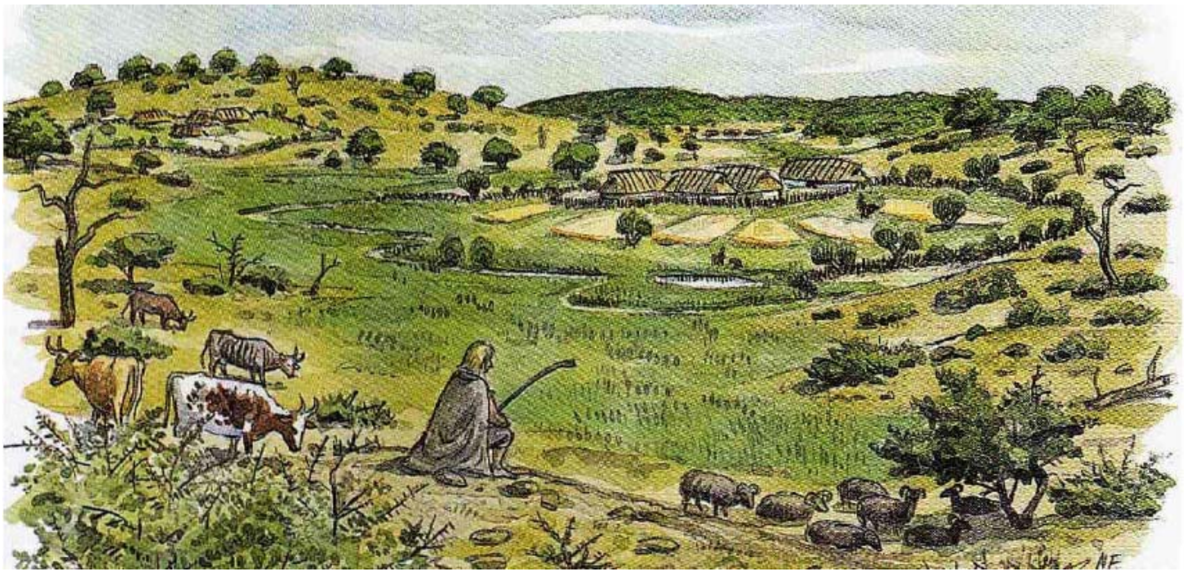
Seminar series nr 129

Effects of human land-use on the global carbon cycle during the last 6000 years



Scania landscape by AD 1000 (aquarelle by Nils Forshed)

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Effects of human land-use on the global carbon cycle during the last 6000 years

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ABSTRACT

Humanity has become a major actor within the Earth system, particularly through 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, which might have resulted in a detectable human influence on climate much earlier than the industrial revolution.

This study presents a first attempt to estimate dynamic changes in anthropogenic carbon fluxes over the last 6000 years. A global gridded data set on 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 differences in terrestrial carbon pools were calculated as an estimate of anthropogenic carbon release to the atmosphere.

The modelled total carbon release during the industrial period (1850-1998) was 162 gigatons of carbon (GtC), of which 36 GtC originated from non-permanent agriculture. For pre-industrial times (6000 BP until AD 1850), human-related carbon release was 79 GtC from permanent agriculture and an additional 35 GtC as a result of non-permanent agriculture. The modelled total carbon release was considerably lower than would be required for a substantial influence on the climate system.

Keywords: human land-use, dynamic global vegetation model (DGVM), deforestation, agriculture, carbon cycle, Holocene

POPULÄRVETENSKAPLIG SAMMANFATTNING

Människan har blivit en viktig aktör inom systemet jorden, bland annat genom en betydande omvandling av stora landarealer och en stor påverkan på atmosfärens sammansättning. En omfattande avskogning för jordbruksändamål inleddes redan för tusentals år sedan vilket bland annat har medfört ett kolflöde till atmosfären. Enligt en nyligen framlagd hypotes skulle mänsklighetens markanvändning därmed troligen ha orsakat en märkbar klimatpåverkan långt tidigare än med den storskaliga förbränningen av fossila bränslen med resulterande koldioxidutsläpp som inleddes vid industrialiseringens begynnelse för 200 år sedan.

Studien är ett första försök att uppskatta förändringar i antropogena (orsakade av människan) kolflöden på grund av markanvändning under de senaste 6000 åren. En global rutnätsbaserad databas över utvecklingen av permanent och icke-permanent jordbruk för tidsperioden har tagits fram och integrerats i Lund-Potsdam-Jena Dynamic Global Vegetation Model (LPJ-DGVM), som med klimatdata (temperatur, nederbörd, solinstrålning, koldioxidhalt) mekanistiskt simulerar växtlivet uppdelat i vegetationstyper. Modellen kördes under 6000 år såväl med som utan den globala databasen över markanvändning. Skillnaden i vegetations- och markkollager mellan de två körningarna beräknades som en uppskattning av nettokolflödet till atmosfären på grund av mänsklig markanvändning.

Det modellerade nettokolflödet orsakat av markanvändning under industrialiseringen (1850-1998) var 162 gigaton kol (GtC), av vilka 36 GtC var ett resultat av icke-permanent jordbruk. Som jämförelse uppskattas kolflödet från förbränning av fossila bränslen under samma tid till 262 GtC. Under förindustriell tid (6000 år före nutid till år 1850) var det modellerade nettokolflödet 79 GtC från permanent jordbruk och ytterligare 35 GtC från icke-permanent jordbruk. Nettokolflödet orsakat av förindustriell markanvändning var betydligt lägre än vad som skulle ha krävts för att ha en märkbar inverkan på det globala klimatsystemet.

Nyckelord: markanvändning, dynamisk global vegetationsmodell (DGVM), avskogning, jordbruk, kolcykeln, holocen

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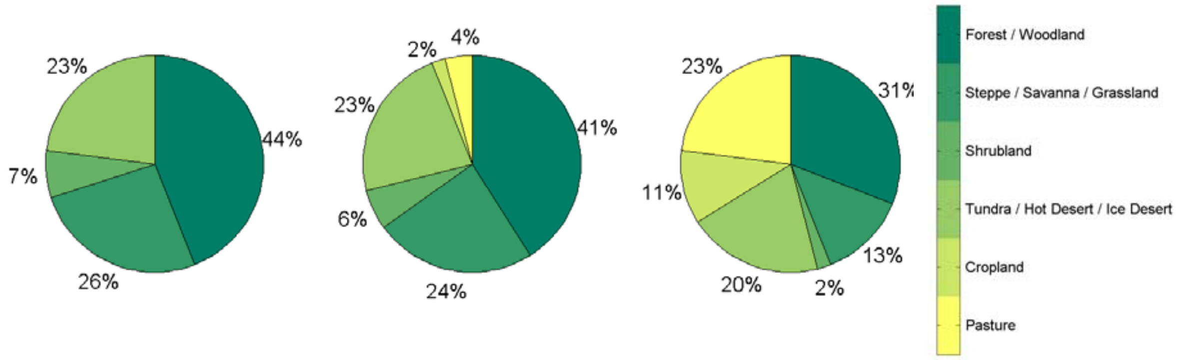
1. INTRODUCTION

Earth's climate during the past two million years has been dominated by a cyclic development of long glacial periods interrupted by short warmer interglacials, but also influenced by natural climate fluctuations on shorter time-scales (Bonan 2002). The latest glacial period ended about 11,500 years BP[1] and the current interglacial, which has seen an advancement of human beings and civilization all over Earth, is usually named the Holocene (Roberts 1998).

Until today, human activity has altered between a third and a half of Earth's land surface by especially cropping, pasture, forestry and urbanisation (Vitousek *et al.* 1997), with consequences for key biogeochemistry cycles, changing the atmospheric composition and resulting in considerable modifications 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, *e.g.*, altering the vegetation and soil carbon pools (Houghton & Goodale 2004), as well as modifying the hydrological cycle (Gordon *et al.* 2005), which influences atmospheric greenhouse gas levels and the global climate (Foley *et al.* 2003).

Deforestation for agriculture and pasture is a major driver of the 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 thousands of years ago (Turner *et al.* 1990). Domestic fuel need, shipbuilding and charcoal consuming metal melting are additional driving forces behind the increased forest clearing over the centuries (Williams 2000). An increasing human population and a civilization with technology advances within agriculture, forestry, mining and trade have caused substantial changes in forest vegetation (Williams 2000). Klein Goldewijk (2001) estimated a loss of natural forest/woodland areas as a result of human activity of 6% by 1700, 14% by 1850 and 34% by 1990 of the natural land cover (Figure 1).



a.) Undisturbed b.) 1700 c.) 1990

Figure 1. Estimated shares of global land cover classes; a.) undisturbed land cover (modelled potential natural vegetation simulated with a modified version of the BIOME model [original version described by Prentice *et al.* 1992]), b.) land-use by 1700, c.) land-use by 1990. Adapted from Klein Goldewijk (2001).

Today, most 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 have accelerated

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[1] BP means Before Present, which relates to the year 1950, established as the benchmark year for scientific dating as this was when the calibration curves for the well-known carbon-14 dating were established.

since the 1950s and accounts for most of the present land-use-related emissions (Malhi *et al.* 2002), while Europe and North America currently experience a small net-expansion of forests following a farmland reduction as a result of a stabilised population size and increased crop returns (Williams 2000).

There is a growing concern regarding human-induced climate change as a result of the rapidly increasing levels of atmospheric greenhouse gases such as carbon dioxide (CO_2) and methane (CH_4), primarily caused by fossil fuel use (Prentice *et al.* 2001), and to a lesser but important degree by human land-use, especially deforestation (Houghton 2003a). The consequences of changing temperatures along with shifting wind and precipitation patterns (Trenberth *et al.* 2003) as well as more sever weather extremes (Easterling *et al.* 2000) are difficult to estimate, but are likely to result in considerable impacts on global ecosystems and human society (McCarthy *et al.* 2001; Karl & Trenberth 2003). The starting point for anthropogenic influence on climate is usually said to be the onset of large-scale fossil fuel burning by the industrial revolution 200 years ago, and the present era has been named the *Anthropocene* (Crutzen & Stoermer 2000).

1.1 Early human impact on the carbon cycle?

Ruddiman (2003) recently raised a sharply contrasting idea: the *Anthropocene* actually begun much earlier, with forest clearing for cultivation in Eurasia starting 8000 BP resulting in CO_2 emissions, and rice irrigation in Asia 5000 BP causing increasing CH_4 levels (Ruddiman & Thomson 2001). This thought thus links early human land-use to a pre-industrial change in the atmospheric composition. Consequently, according to Ruddiman, this should explain the Holocene anomaly compared to trends of atmospheric greenhouse gases for the three previous interglacials, observed in ice core measurements (Figure 2).

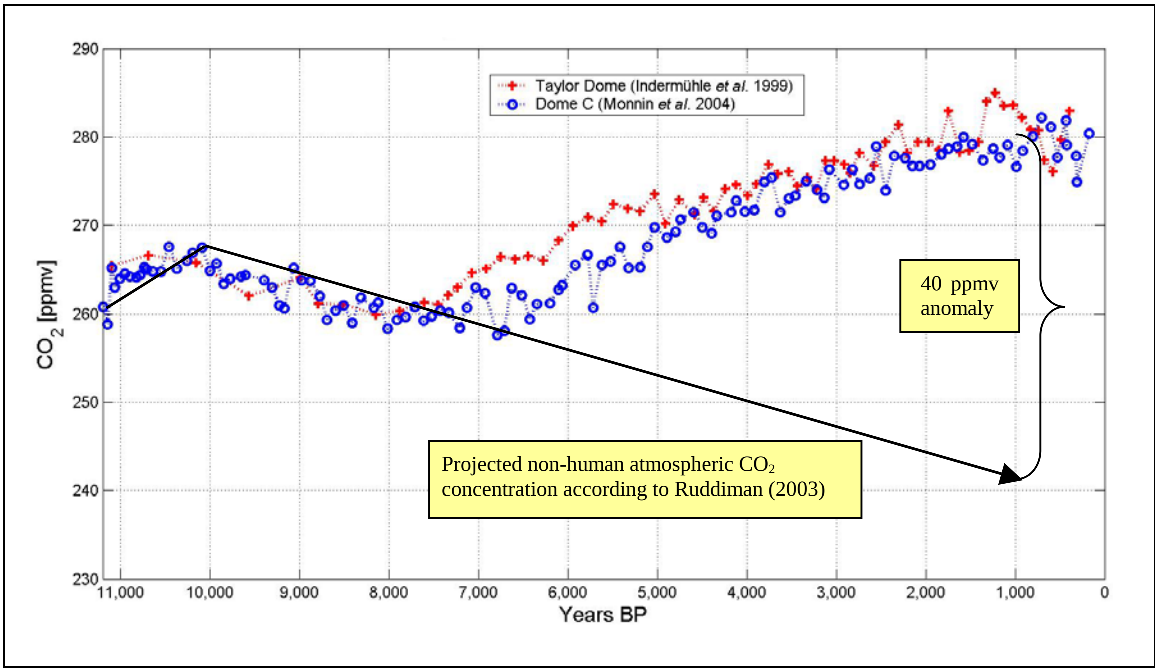

Figure 2. Atmospheric CO_2 level from 11,200 BP until 170 years BP. Ice core measurements adapted from Indermühle *et al.* (1999) and Monnin *et al.* (2004), compared with the projected, non-human influenced atmospheric CO_2 development according to Ruddiman (2003). [ppmv]

According to Ruddiman, the anomaly consists of a CO_2 increase of 40 parts per million volume (ppmv) until pre-industrial times (Figure 2), as well as a CH_4 rise of 250 parts per billion volume (not shown), which could have prevented a glaciation at high northern latitudes. The 40 ppmv CO_2 corresponds to 250 gigatons of carbon (GtC) of direct human emissions until 2000 BP (Ruddiman 2003), based on calculations[2] from Indermühle *et al.* (1999). Human influence on climate would thus have been going on for thousands of years and not, as commonly believed, only since the start of industrialisation two centuries ago.

This novel thought has received considerable attention, including rather critical views, and is being lively debated (*e.g.*, Mason 2004). Joos *et al.* (2004) performed simulations of terrestrial and atmospheric carbon development during the Holocene, and suggested that a series of natural processes could explain the CO_2 rise starting 8000 years ago. They estimated that Ruddiman's hypothesis would mean an early anthropogenic emission of 710 GtC to explain the 40 ppmv CO_2 anomaly, as oceans would remove 85% of the emitted carbon on a millennium timescale. A carbon release of this magnitude is three to four times above previous estimates of land-use emissions during the entire Holocene, including the industrial period (DeFries *et al.* 1999) and is not consistent with observed ice core $\delta^{13}C$ records[3] (Indermühle *et al.* 1999). Joos *et al.* (2004) concluded that human-induced land-use emissions might have contributed a maximum of 4-6 ppmv of the pre-industrial CO_2 increase.

Other modelling studies also discuss Ruddiman's hypothesis. In one commentary, Crucifix *et al.* (2005) noted that integration of paleoclimate so-called proxy data (Section 2.1.1) within climate models would be an important way to test early human influence. Claussen *et al.* (2005) suggested that the three latest interglacials are not an accurate equivalent for the Holocene and concluded that a strong human forcing is not needed to explain the observed Holocene CO_2 development. As older ice-core CO_2 archives are now available (Siegenthaler *et al.* 2005), even more doubt has been raised against the uniqueness in the Holocene anomaly; suggesting that natural causes would be sufficient to explain the CO_2 development (O'Hare *et al.* 2005; Broecker & Stocker 2006).

In response to the critics, Ruddiman (2005a; 2005b; 2005c) has slightly modified the original hypothesis and is now claiming that direct anthropogenic emissions would explain only 14 ppmv (Ruddiman 2005c) of the Holocene CO_2 anomaly, corresponding to an emission of slightly less than 200 GtC based on the relationship in Joos *et al.* (2004). Instead, indirect effects such as preventing northern ice sheet formation, which would cool the climate through positive feedback mechanisms, would explain a major part of the anomaly. Another indirect effect would be a restriction in southern sea-ice advance, which would cut off the carbon exchange between the surface ocean and the atmosphere. Thus, a number of indirect effects would have constrained the CO_2 drop seen during the three previous interglaciations.

Thus, the underlying causes for the Holocene atmospheric CO_2 development are not fully understood, though several explanations have been presented (*e.g.*, Joos *et al.* 2004; Wang *et al.* 2005). Modelling studies of the entire Holocene excluding human land-use show a wide variation in results. Indermühle *et al.* (1999) estimated a terrestrial release of 195 ± 40 GtC from 7000 BP to 1000 BP, possibly resulting from a colder and drier climate compared to mid-Holocene conditions. Wang *et al.* (2005) used a model with vegetation-precipitation feedback, applying actual variable solar forcings and atmospheric CO_2 forcing. Without land-

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[2] Indermühle *et al.* (1999): 195 GtC <> 25 ppmv; 195 * 40/25 * 80% = 250 (for details, see Ruddiman 2003)

[3] Ice core $\delta^{13}C$ records are used to trace the carbon source from different carbon reservoirs.

use they found a global terrestrial carbon release from 6000 BP until the end of the pre-industrial period of 68-95 GtC. Simulations without land-use by Joos *et al.* (2004) yielded a terrestrial carbon *uptake* of 28-75 GtC during the past 6000 years, contradicting the carbon release found in most recent studies (see, *e.g.*, Wang *et al.* 2005).

1.2 Estimating carbon release from human land-use

A variety of methods have been used to estimate the carbon release caused by land-use. The methodology and investigated time period influence the result (see Table 1 for a summary of recent land-use-related studies). One approach is the "book-keeping" method, based on deforestation statistics combined with vegetation and soil carbon approximations (Houghton *et al.* 1983). Land-use changes are represented as vegetation disturbances with corresponding response curves for each ecosystem. By using this approach, Houghton (1999) estimated a net release of 124 GtC between 1850 and 1990 caused by human land-use, later revised to 134 GtC for the same time period (Houghton 2003a).

Table 1. Recent land-use-change-related studies covering different time periods, with resulting estimates of global carbon release. [GtC]

Study	Time period	Carbon release
DeFries *et al.* (1999)	-1850	48-57
	-1990	182-199
McGuire *et al.* (2001)	1920-1992	56-91
Houghton (2003a)	1850-1990	134
Ruddiman (2003)	-2000 BP	250
	-1850	320
Levy *et al.* (2004)	1700-1990	222
	1850-1990	173
Campos *et al.* (2005)	1700-1990	139
	1850-1990	98

DeFries *et al.* (1999) used a global terrestrial carbon cycle model to estimate carbon emissions caused by human-induced land cover change. Existing vegetation cover was derived from satellite NDVI[4]-data while pre-industrial natural vegetation was simulated based on maps derived from ground-based information or climate-driven models. By comparing the resulting maps the difference in terrestrial carbon was recognized as human-induced land cover change, estimated to have caused an accumulated net carbon loss of 182-199 GtC until 1990. Carbon release from agricultural expansion before 1850 was estimated to 48-57 GtC, based on areas cleared for agriculture by 1850 from Houghton *et al.* (1983). (Table 1)

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 (*e.g.*, Prentice *et al.* 2000). The difference between the modelled total terrestrial carbon storage with land-use and the results

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[4] Normalized Difference Vegetation Index (NDVI) = (NIR-VIS)/(NIR+VIS)
NIR = Near Infra-red Radiation, wavelength > 0.7 µm and VIS = Visible Radiation, wavelength 0.4-0.7 µm
Higher positive NDVI-values indicate a more productive vegetation absorbing more VIS (Section 2.2)

obtained with natural vegetation provides an estimate of the carbon release that has been caused by that land-use.

Ramankutty & Foley (R&F 1999) estimated fractional cropland on a continuous scale (0-100%) based on permanent global cropland areas in 1992, derived from remotely sensed land cover classification and inventory data. Fractional cropland maps back to 1700 were thereafter reconstructed through a land cover change model based on historical population data. Klein Goldewijk (2001) developed a historical global environment database (HYDE) with grid cells influenced by agriculture classified either as cropland or pasture from 1700 until 1990, based on population density as a proxy for agricultural activity, assuming that areas with high population densities have remained so over the investigated time-period.

Several modelling studies based on R&F or HYDE have been carried out to estimate terrestrial carbon fluxes caused by land-use changes. Applying the R&F data set, McGuire *et al.* (2001) included biogeochemical effects in a simulation with four ecosystem models. For land-use alone, the modelled carbon release ranged from 56 to 91 GtC between 1920 and 1992. The large range indicates that fluxes associated with agricultural activity represent a major uncertainty between the models. Levy *et al*. (2004) applied the R&F data set into a dynamic global vegetation model together with simulated historical climate (HadCM3, Gordon *et al.* 2000) and estimated the flux from land-use to 222 GtC for 1700 until 1990, and 173 GtC for 1850 until 1990. Campos *et al.* (2005) used the HYDE data with cropland and pasture, resulting in a simulated net emission of 98 GtC (1850-1990) and 139 GtC (1700-1990). (Table 1; see also Section 4.2 and Table 7)

1.3 Scope of this study

The objective with the present study is to estimate the development of carbon emissions in the form of CO_2 from human land-use through time. In contrast to DeFries *et al.* (1999), dynamic land-use was considered in the present study. A dynamic global land-use data set with permanent and non-permanent agriculture over the past 6000 years was developed from the literature. Non-permanent agricultural practices, such as slash-and-burn or shifting cultivation, can repeatedly result in release of carbon to the atmosphere without showing a permanent “fingerprint” on the land cover, but the global impact is not known to have been assessed in any other study. The developed land-use data set was used to run the Lund-Potsdam-Jena Dynamic Global Vegetation Model, LPJ-DGVM (Sitch *et al.* 2003). The model was run with and without land-use, and the differences in terrestrial carbon pools were calculated to quantify an estimate of anthropogenic impact and greenhouse forcings through land-use during the last 6000 years.

1.4 Overview

After these introductory pages, a more detailed background is given for the climate and carbon systems, followed by an overview of the development of humanity, land-use and resulting consequences. The applied method with modifications of the vegetation model and the derivation of the land-use data set is then described in detail. The modelling results are presented with graphs and tables, together with an overview of previous land-use studies. Results and uncertainties are thereafter discussed, followed by a final section where the main conclusions are noted and a few recommendations for future research are given.

2. BACKGROUND

2.1 Climate

Earth's climate has varied greatly during the 4.55 billion years of age, with changes occurring on timescales from years up to billions of years (Ruddiman 2001). Global climate has fluctuated also during the Holocene, sometimes rapidly (Mayewski *et al.* 2004), occasionally abruptly as the so-called 8k-event (Alley & Ágústsdóttir 2005), with severe consequences for ecosystems and human societies (Berglund 2003). Understanding the historical climate development is crucial in research regarding likely consequences of the expected near-future climate change caused by human activities (Bradley 2000; Jones & Mann 2004).

During the past two million years there has been a cyclic advance and retreat of glaciers in the Northern Hemisphere with a periodicity of 100,000 years, dominated by long glacial periods interrupted by short warmer interglacials (Bonan 2002). At the Last Glacial Maximum about 21,000 years BP, Earth was on average approximately 5ºC colder and significantly drier than present climate (Roberts 1998). Thick ice sheets covered an area twice that of the current glaciers and the sea level was about 100 meters lower, resulting in 10% more continental landmass than today. Terrestrial carbon was considerably lower (931 GtC, 35% of present potential) and forests covered only one third of the area compared to late Holocene excluding human clearance (Adams & Faure 1998), as Northern boreal-forested areas were ice covered, while regions south of the ice-cover were mostly steppes and savannas.

2.1.1 Sources of past climate

Global instrumental meteorological records are available only for the last 100-150 years (Jones & Mann 2004). As this is a very short glimpse in Earth's long history, several paleoclimatic so-called proxy-data sources have been developed, including sediments, pollen, ice cores, corals, tree rings and historical archives (Roberts 1998; Brázdil *et al.* 2005). Combinations of these climate archives have facilitated the reconstruction of historical climate series (*e.g.,* Mann *et al.* 1998; Jones & Mann 2004; Moberg *et al.* 2005).

Pollen preserved in lake mud or peat bogs constitute one source used to reconstruct past vegetation and to determine the underlying controlling factors, such as precipitation and temperature (Bonan 2002). Determination of human activities from pollen diagrams usually involves a combination of evidences, including changes in vegetation composition and grassland indicator species (Ren 2000; Berglund 2003). From vegetation modelling based on pollen data, studies of past landscape openness have been performed, *e.g.*, for southern Sweden (Sugita *et al.* 1999), for China north of the Yangtze River (Ren & Beug 2002) and recently on a European level (Mitchell 2005).

Analysing deposited charcoal in stratified sediments from lake and wetlands facilitates temporal studies of past biomass fires (Carcaillet *et al.* 2002). Vegetation response to past fire events can be identified by combining charcoal records with pollen taxa studies. Relationship changes between fire-adapted and fire-sensitive taxa with fire frequency trends throughout the Holocene have been identified. Through a combination of charcoal and fire reconstruction studies from several locations, an estimate of past regional and global climate change and variability can be realised (Whitlock & Bartlein 2004).

2.1.2 Climate forcings

Several mechanisms influence Earth's climate: plate tectonics (continental drift), orbital changes, the greenhouse house effect (water vapour, CO_2, CH_4, nitrous oxide as well as ozone, halocarbons and carbon compounds with fluorine, chlorine, bromine or iodine), freshwater runoff and thermohaline circulation, solar variability and aerosols (Bonan 2002). Incoming solar radiation is the main driver, controlling temperature, pressure, precipitation, wind and the global weather systems. Received radiation at the surface fluctuates as a result of variations in the precession and tilting angle of Earth's rotational axis, spatially with latitude and temporally with seasons, affecting local, regional and global climate, essential for the cyclic dynamics of global ecosystems (Bonan 2002).

Milankovitch (Hays *et al.* 1976) identified three main astronomical cycles, *eccentricity* (100,000/413,000 years cycle), *axial tilt* (41,000 years) and *precession* (21,000 years). Combining these cycles produces a complex configuration, amplifying or reducing seasonal and latitudinal differences in solar radiation, which is believed to control the glacial-interglacial cycle (Roberts 1998) together with physical, chemical and biological feedback mechanisms within the climate system (Bonan 2002). According to the Milankovitch theory, weak summer insolation at high latitudes, resulting in reduced summer melting and thus allowing snow and ice sheet accumulation, would increase climate cooling and lead to glacial periods, and the opposite to warmer interglacial periods (Ruddiman 2001).

Variations in volcanism and concentration of sulphate aerosols in the atmosphere (Zielinski 2000), solar irradiance (Beer *et al.* 2000), greenhouse gases and vegetation cover are additional factors controlling climate. Feedback mechanisms including changes in water vapour content, cloud formation, ocean circulation and ice-albedo also have an important influence on climate (Houghton 2005a). The interrelationships between these forcings and mechanisms are far from being completely understood. Moreover, during the Holocene a human factor has emerged, with increasing agricultural and industrial activities through time. The results are a transformed land cover and a change in the atmospheric composition including rising levels of greenhouse gases, sulphate and soot particles. Thus, humanity has further complicated the research of understanding past, current and future climate (Sagan *et al*. 1979; Ruddiman 2001).

Land cover and albedo

Surface properties and land cover, especially vegetation, influence local and regional climates (Bonan 2002). An important parameter is the albedo, the proportion of incoming radiation reflected by the surface. High albedo means that less solar radiation is absorbed resulting in a cooler surface, while a low albedo results in a warmer surface. Snow, deserts and glaciers have the highest albedo values, while vegetation, water and urban surfaces all have low albedo. Land cover changes from forest to agriculture increase the albedo (Vitousek *et al.* 1997) and reduce the evapotranspiration, which affect local and regional precipitation patterns (Bonan 2002), and by so alters local and regional climate conditions. On a global level, large-scale human-induced land cover changes are today believed to influence the global climate system (*e.g.*, Pielke *et al.* 2002; Pielke 2005).

Greenhouse gases

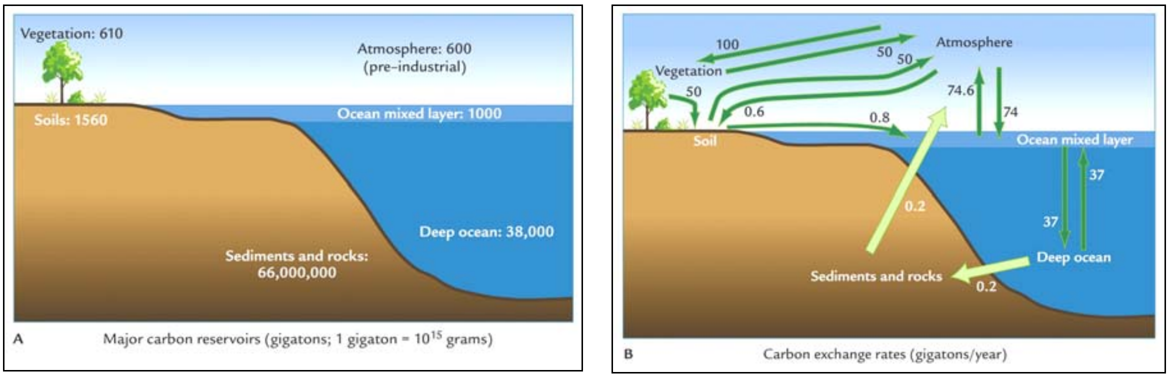
Atmospheric greenhouse gases, notably water vapour, CO_2 and CH_4, absorb 95% of the long-wave radiation emitted from the surface, resulting in a global average net-heating of 31°C compared to a situation with no greenhouse gases, making Earth an inhabitable, non-frozen planet (Ruddiman 2001). From climate archives it is known that greenhouse gas levels and climate conditions have varied considerably throughout time (Petit *et al.* 1999). However, it is also recognised that the present CO_2 concentration is at a higher level than in at least 650,000 years (Siegenthaler *et al.* 2005), and today possibly higher than during the last 20 million years (Pearson & Palmer 2000). Furthermore, the current rapid increase is at least ten times faster than during any period during the last 20,000 years (Prentice *et al.* 2001).

2.2 The carbon cycle

Carbon is a fundamental element for life. Atmospheric CO_2 is essential for photosynthesis in plants, where incoming radiation energy is absorbed, and allowing the conversion of CO_2 to carbohydrates, providing energy and structural material as well as building blocks for necessary molecules. Through photosynthesis the plants produce oxygen, vital for humans, animals and most living organisms. Moreover, only plants are able to directly convert incoming radiation energy into carbohydrates that through metabolism (respiration) constitute essential energy sources for a majority of all other life forms. Via this energy release and decomposition (respiration of organic matter primarily by fungi and bacteria), carbohydrates are reconverted to CO_2, which when released back to the atmosphere closes the biological carbon cycle. (Bonan 2002)

2.2.1 The natural carbon cycle

The main pre-human carbon reservoirs and yearly exchange rates are presented in Figure 3.



a.) b.)

Figure 3. The natural carbon cycle; a.) major natural carbon reservoirs [GtC], b.) yearly natural carbon exchange rates [GtC/yr]. (From Ruddiman 2001)

Sediments and rocks contain by far most of the carbon, followed by the deep ocean. However, the main yearly carbon exchange paths connect the relatively smaller pools of vegetation, soil, ocean mixed layer and the atmosphere, making these carbon reservoirs and exchanges the most important to understand on shorter time scales. Noteworthy is that the soil contains more than twice the amount of carbon found in living vegetation biomass, while the atmosphere approximately holds as much carbon as the vegetation during the pre-human interglacial time. During glacial times considerably less carbon has been present in both the biosphere (vegetation and soil) and in the atmosphere. The ocean is believed to be the main carbon regulator on this glacial-interglacial timescale, through a transfer of carbon via the exchange between the ocean surface and the atmosphere into the deep ocean. (Ruddiman 2001)

2.2.2 Human disturbance of the carbon cycle

Today the carbon cycle is not natural as a result of extensive human activity. Carbon trapped by the biosphere in pre-historical times and then transferred to the geological reserves is now being quickly returned to the atmosphere through fossil fuel combustion, resulting in a rapidly increasing CO_2 level (Prentice *et al.* 2001). Furthermore, clearing of forests for agricultural purposes results in a reduction in vegetation and soil carbon (Houghton 1999; Paul *et al.* 2002) and an increase in atmospheric CO_2 (Houghton 2003a). On the other hand, abandoning agricultural land allows forest re-growth and a re-accumulation of carbon in biomass and soil, which reduces atmospheric CO_2 (see also Section 2.5.5).

Carbon budget 1850-2000

Human activities such as fossil fuel burning and land-use have disturbed the natural carbon balance. For the last 150 years the carbon pool changes are relatively well known (Figure 4).

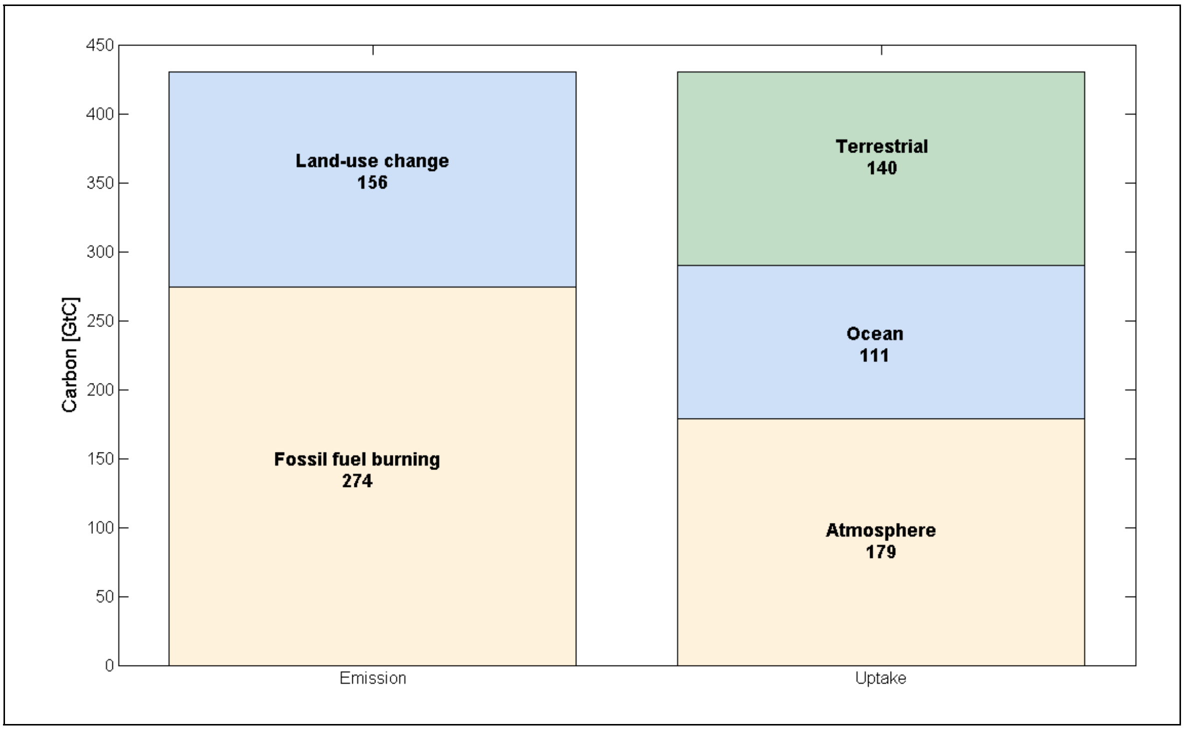


Figure 4. Estimated balance between carbon emissions and uptake from 1850 until 2000. [GtC]

Stored fossil fuel has decreased by 274[5] GtC (Marland *et al.* 2006), while the estimated loss related directly to human land-use is 156 GtC (Houghton 2003a). Atmospheric carbon has increased with 179[6] GtC based on Etheridge *et al.* (1996) and Keeling & Whorf (2005), and ocean carbon by 111[7] GtC based on House *et al.* (2002), all numbers for the period 1850 until 2000. The remaining 140 GtC is believed to have been absorbed by the terrestrial biosphere through a mixture of processes such as vegetation re-growth on abandoned farmland, land management practises, fertilizing effects caused by increased atmospheric CO_2 levels and nitrogen deposits, and climate change effects such as increasing growing seasons at higher latitudes (House *et al.* 2002).

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[5] 1850-1998: 262 GtC (Marland *et al.* 2006)

[6] 1850: 285.2 ppmv (Etheridge *et al.* 1996) and 2000: 369.5 ppmv (Keeling & Whorf 2005). Difference 84.3 ppmv, corresponding to 178.97 GtC based on 2.123 GtC/ppmv (Joos *et al.* 2004)

[7] 25.8% (124/480) of total emissions (274+156=430 GtC) (see House *et al.* 2002)

Carbon budget before 1850

The carbon budget prior to 1850 is considerably less well known, especially regarding land-use estimates. The use of fossil fuel before 1850 was rather insignificant and estimated to a total of 1.25 GtC (Marland *et al.* 2006). Deforestation on the other hand was already by 1850 substantial in temperate regions (Prentice *et al.* 2001), contributing to an accumulated human-related carbon release until 1850 of 48-57 GtC estimated by DeFries *et al.* (1999).

2.3 Atmospheric CO_2 concentration

Direct measurements of atmospheric CO_2 concentration has been performed since 1958 at Mauna Loa in Hawaii. Currently (2004), the yearly averaged CO_2 level is 377 ppmv, with an annual increase of 1.9 ppmv, averaged from 1995 until 2004 (Keeling & Whorf 2005). The present CO_2 concentration corresponds to 800 GtC with an approximate 4 GtC annual increase based on the well-established conversion rate 2.123 GtC/ppmv CO_2 (Joos *et al.* 2004). The pre-industrial CO_2 level is commonly referred to as 280 ± 10 ppmv (Prentice *et al.* 2001), implying an atmospheric increase of approximately 200 GtC since the start of the industrial revolution about 200 years ago. (Figure 5)

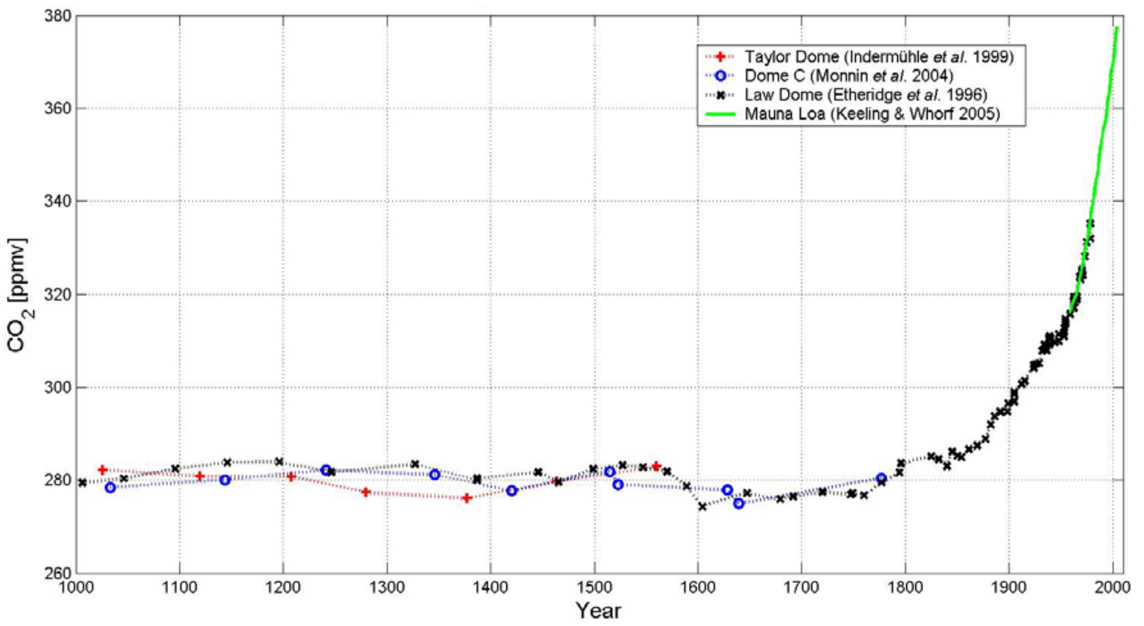

Figure 5. Atmospheric CO_2 concentration during the last 1000 years, adapted from Indermühle *et al.* (1999), Monnin *et al.* (2004), Etheridge *et al.* (1996) and Keeling & Whorf (2005). [ppmv]

For comparison, Köhler & Fischer (2004) estimated global pre-industrial vegetation and soil carbon to 622-908 GtC and 1150-1700 GtC, respectively, while present-known fossil fuel reserves and resources are approximately 4000-5000 GtC (Sundquist 1993; Falkowski *et al.* 2000). However, estimates of historical and even present carbon stocks and changes in the global terrestrial ecosystem, especially for the tropical forests, are all associated with large uncertainties, as further discussed in Houghton (2003b; 2005b) and House *et al.* (2003).

2.3.1 Past atmospheric CO_2 concentration

Extracted ice cores with enclosed air bubbles from accumulated snow provide excellent opportunities for direct studies of past atmospheric composition (Petit *et al.* 1999; Wolff 2005). Ice cores from Antarctica with a slow accumulation rate provide the longest time records, though precise time resolution is limited to about 200 to 550 years (Monnin *et al.* 2001). Faster accumulating ice from Greenland (Andersen *et al.* 2004) provides higher temporal resolution but lacks the extensive time records of the Antarctica. Ice cores from other glacial regions such as the Andes, the Himalayas and Kilimanjaro (Thompson *et al.* 2003) provide additional direct recordings of past greenhouse gas levels.

An alternative CO_2 proxy is the stomatal frequency method, based on the fact that the atmospheric CO_2 level determines the number of leaf cells developing into stomata (Woodward 1987), and the latter can be used to calculate a proxy for atmospheric CO_2. Using this method, Rundgren *et al.* (2005) reconstructed atmospheric CO_2 during the last interglacial from Danish lake sediments, with results showing agreement with ice core reconstructions but with a larger variability, probably as a result of a higher temporal resolution, about 100 years.

Analysis of the Vostok ice core in Antarctica by Petit *et al.* (1999) show a similar trend in atmospheric CO_2 for all four glacial cycles in the last 420,000 years. A peak-level of 280-300 ppmv was found at the warm but short interglacial period followed by a slow decrease to values of 180-200 ppmv at the glacial maximum before a rapid increase to the higher level at a new interglacial. Each cycle is about 100,000 years, thus showing a variance on equal time-scale as the eccentricity variation according to the Milankovitch theory. Ice core records covering the last 740,000 years and eight glacial cycles is now available (Augustin *et al.* 2004), and recently atmospheric CO_2 concentrations back to 650,000 BP (Siegenthaler *et al.* 2005), the latter confirming the cyclic CO_2 behaviour found by Petit *et al.* (1999). (Figure 6)

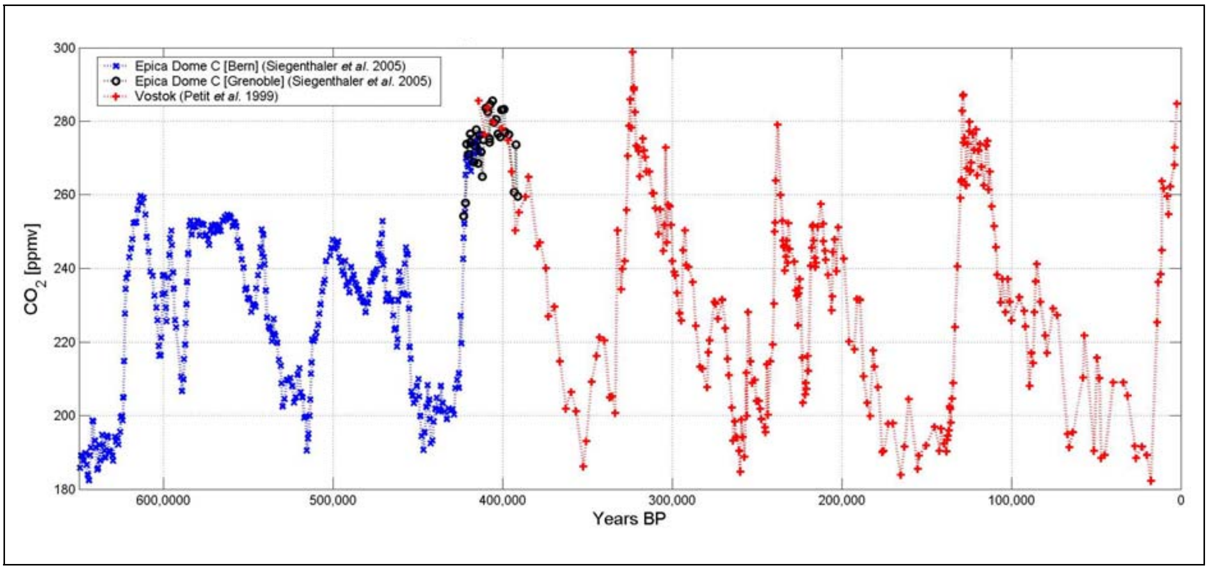

Figure 6. Atmospheric CO_2 levels during the last 650,000 years, adapted from Siegenthaler *et al.* (2005) and Petit *et al.* (1999). [ppmv]

Indermühle *et al.* (1999) and Monnin *et al.* (2004) performed detailed ice core analysis from the Holocene (Figure 2). Observations from ice core records based on deuterium[8]

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[8] Measurements of ice core deuterium are used to derive corresponding past temperatures (*e.g.*, Petit *et al.* 1999)

measurements indicate that CO_2 changes usually lag behind temperature changes by between 800 and 1900 years (Siegenthaler *et al.* 2005). However, the causes for the glacial-interglacial CO_2 variation are not yet completely understood (Archer *et al.* 2000; Sigman & Boyle 2000).

2.4 Human population

Modern *homo sapiens* is believed to have originated in central Africa about 200,000 years ago, and spread first to the Middle East region followed by Asia and Europe, and then Australia 40,000 years ago (Simmons 1996; Roberts 1998). America was the last continent to be inhabited by human beings, starting with migration through the land connection over Bering Sound at the end of the latest glacial. By this time, 10,000 years ago, only about 4 million humans populated the entire planet (McEvedy & Jones 1978).

Since the end of the latest glacial the world population has increased greatly, and is today estimated to exceed 6.5 billion people (U.S. Census Bureau 2006). For most of the Holocene, the population growth was rather modest and occasionally even negative as a result of major diseases or warfare (Ruddiman 2003). The development of the human population during the Holocene has been estimated by McEvedy & Jones (1978), see Figure 7.

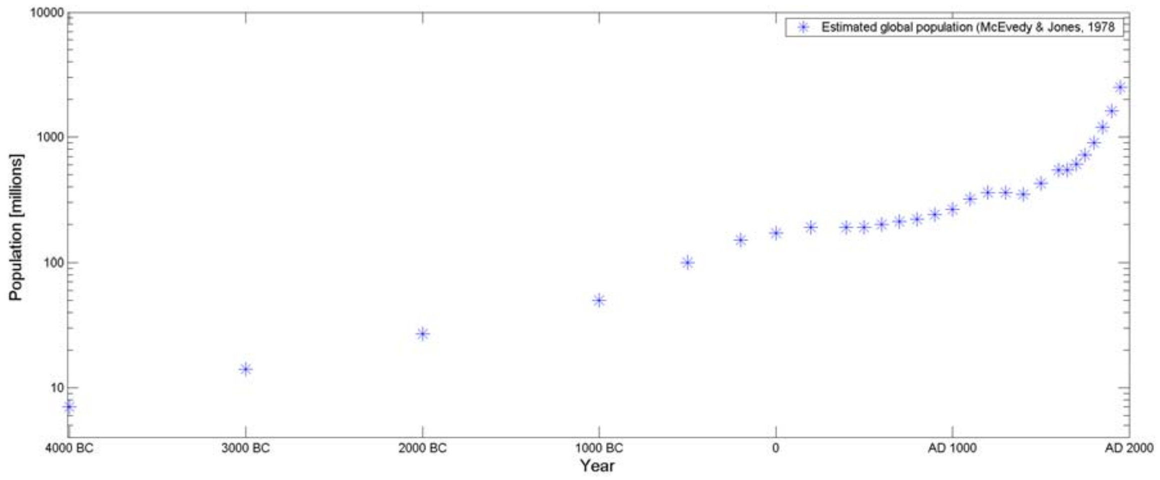

Figure 7. Global human population during the last 6000 years in logarithmic scale, derived from McEvedy & Jones (1978). [million]

Thus, the human population at the beginning of the Holocene was rather limited. By this time, humans are thought to have been mainly hunters and gatherers, relying on what nature provided through fruits, nuts and hunted game (Simmons 1996). Being completely dependent on the surrounding environment for survival, populations are believed to have had to move their camps frequently in response to season and climate changes and hence did not establish any permanent settlements prior to the development of agriculture (Gupta 2004).

2.5 Land-use

Changed climatic conditions after the latest glacial brought higher temperatures, more precipitation and an increasing atmospheric CO_2 level, which possibly initiated domestication of animals and plants in tropical and subtropical regions (Gupta 2004). Grazing animals such as goats and sheep were likely domesticated before agriculture commenced (Simmons 1996), contributing to the transformation from hunting to herding and later agricultural practice.

2.5.1 Origin of agriculture

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 where 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, which supported stable settlements for long periods (Williams 2000).

In Europe, human impact on forest vegetation by clearing, cultivation and grazing is believed to have been "significant for at least 6000 years" (Williams 2000), together with the establishment of the first permanent settlements. In Central and South America human-induced forest fires were used for expanding agriculture during the middle Holocene by Maya and Inca cultures (Carcaillet *et al.* 2002), with a distinct decrease 500 years ago associated with the dramatic human population decline caused by the diseases following the first European contact. Major human transformation of the forests in eastern North America started only after the introduction of steel axes by the European settlers (Doolittle 2004). In China, anthropogenic disturbance by early agriculture and settlement is suggested to explain the observed forest pollen decline in the middle and lower Yangtze regions by 5000 years BP (Ren 2000; Ren & Beug 2002).

2.5.2 Fire

Natural fires have always occurred, depending on climate, volcanic activity and vegetation (Carcaillet *et al.* 2002). Fire is essential in numerous plant communities, where tree, grass and shrub species have developed in response to frequent fires. Nutrients are rapidly mobilized by fire, encouraging establishment of early succession vegetation in newly burnt areas (Bonan 2002). In addition, biomass burning is important for atmospheric chemistry through release of trace gases and aerosols, as well as for the global carbon cycle (Thonicke *et al.* 2001).

Fire has often been used by man 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 with decreasing tree pollen and increasing cereal and weed pollen, indicating human cultivation and domesticated grazing animals (Roberts 1998; Williams 2000). In addition to agriculture, fire has commonly been used to open up forestland for pasture, after which browsing sheep and goats often prevent natural tree regeneration (Ruddiman 2003). Furthermore, the development of seemingly "natural" ecosystems such as the African savannas, the Brazilian cerrado, several Mediterranean-type ecosystems and prairie grasslands are all believed to have evolved as a result of human burning activities (Thonicke *et al.* 2001).

2.5.3 Non-permanent agriculture

When nutrient conditions are too poor for permanent agriculture, an alternative farming method is shifting cultivation or "slash-and-burn", characterized by a cycle of regular alternating short farming and longer 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 2-3 years before the nutrient level becomes too low to give an acceptable return (Crutzen & Andreae 1990). The land is abandoned, allowing re-growth of secondary vegetation, typically for a 10-20 year fallow period before returning to re-clear and re-cultivate the initial plot (Brady 1996). A farmer typically has several plots at different stages in the shifting cultivation cycle.

According to Carcaillet *et al.* (2002), the increased biomass burning in Europe since 6000 years ago are best explained by agricultural development, probably at least initially applying a slash-and-burn agricultural system as suggested by Clark *et al.* (1989) and Ruddiman (2003), indicating that non-permanent agriculture might have been in use for thousands of years. Farming communities have practised traditional small-scale and sustainable slash-and-burn agriculture with long fallow periods and large areas of undisturbed forests (Tinker *et al.* 1996). Because of an increased population pressure, fallow periods in general have shortened significantly and are currently often too short for the land to recover its previous productivity between farming periods (Crutzen & Andreae 1990). Current shifting cultivation practises therefore often result in reduced harvests, soil degradation, aerosol release as well as a net emission of carbon (Fearnside 2000).

2.5.4 Land requirements for agricultural purposes

By 1700 the global permanent cropland area was 266 million ha[9], as estimated by Klein Goldewijk (2001), and the world population 610 million according to McEvedy & Jones (1978), which gives an average of 0.44 ha cropland per capita while an area twice this size was used for pasture. Corresponding values for 1990 are 0.28 ha cropland per capita and 0.65 ha pasture per person (Klein Goldewijk 2001), indicating an increased crop return per unit area as a result of increased efficiency in agricultural practices.

The size of land area per person for non-permanent agriculture is more uncertain and varies according to soil fertility, population density and length of the fallow season (Grigg 1974). Grigg (1974) estimated average land area with crops in modern shifting cultivation at 0.44 ha per person in Africa while in India, South East Asia and southern China the corresponding area was 0.28 ha per person, though by including fallow areas the total land requirement was higher, in Asia 2 ha per person. A more recent estimate by Lanly (1985) based on current global shifting cultivation practices in the tropics by about 500 million people, gave an average of 0.17 ha under active cultivation per person, while the total land requirement including fallow areas was about 1 ha per person (see also Brady 1996).

Other food and nutrient sources for the human population are obviously possible, such as fishing and hunting. However, these sources were not included in the estimates of land requirements, neither was human-managed forestry and related potential carbon release taken into account in the present study, being focused only on agricultural land-use.

2.5.5 Reforestation

Forests have a remarkable power to regenerate and re-expand once human pressure declines, which is seen since the last century in parts of North America and Europe as marginal agriculture land has been abandoned as a result of intensified farming on more productive soils (Bonan 2002; Malhi *et al.* 2002). Plague and warfare are other powerful factors resulting in reduced land pressure and advancement of reforested areas (Ruddiman 2003), for instance during the Black Death (van Hoof *et al.* 2006) and major European conflicts as well as when new pathogens were introduced in America by the first European contact (Williams 2000).

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[9] 1 ha = 0.01 km^2 (1 km^2 = 100 ha)

2.6 Consequences of land-use

As forest ecosystems contain a large proportion of the biospheric carbon in living biomass and soil organic matter, a major change in forest cover results in modifications of the global carbon cycle (Houghton & 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 reducing vegetation carbon, 25-30% of the soil carbon in the upper meter of soil is released when clearing forests for permanent cultivation, as less crop production accumulates as litter and decomposes to soil compared to the higher forest litter fall (Guo & Gifford 2002; Houghton & 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 & Andreae 1990), shifting cultivation also results in a net soil carbon source, as less forest litter fall between the farming periods have time to be decomposed to soil (Fearnside 2000). For these reasons, widespread use of fire for land opening throughout the second part of the Holocene might explain the development of the observed atmospheric CO_2 concentration during this period (Carcaillet *et al.* 2002). Ruddiman (2003) went further in linking early human land-use to a strong modification of the atmosphere and climate far prior to any large-scale fossil fuel burning (Section 1.1).

Deforestation followed by agriculture also causes aerosol releases that affects the atmospheric composition, increases soil erosion and causes a loss of soil organic matter (Tinker *et al.* 1996). Additional consequences are changes in water infiltration and the hydrological cycle (Tinker *et al.* 1996), as well as an increased eutrophication of rivers and lakes from the currently extensive use of fertilizers (Matson *et al.* 1997). By opening up the forest canopy, early succession species such as fir, birch and spruce flourish in human-influenced landscapes, while later succession species with a later maturity age, such as elm and oak, decline (Williams 2000; Bonan 2002). A fragmented mosaic of natural ecosystems in agriculture-dominated landscapes affects functions and composition for the remaining natural flora and fauna negatively (Saunders *et al.* 1991), and results in a decreased biodiversity (Pimm & Raven 2000).

3. MATERIAL AND METHODS

3.1 The Lund-Potsdam-Jena Dynamic Global Vegetation Model

The Lund-Potsdam-Jena Dynamic Global Vegetation Model (LPJ-DGVM) is a coupled biogeography-biogeochemistry model, which incorporates process-based representations of terrestrial vegetation dynamics and biogeochemical cycling. The model, developed in Microsoft Visual C++, has become a so-called community model and is being used by a large number of scientists. LPJ-DGVM has previously been shown to, *e.g.*, successfully reproduce the interannual global exchange of CO_2 with the atmosphere (Sitch *et al.* 2003), global patterns of vegetation distribution (Sitch *et al.* 2003; Hickler *et al.* 2006), Holocene terrestrial carbon development (Kaplan *et al.* 2002), and the observed high-latitude vegetation greening trend in the 1980s' and 1990s' (Lucht *et al.* 2002).

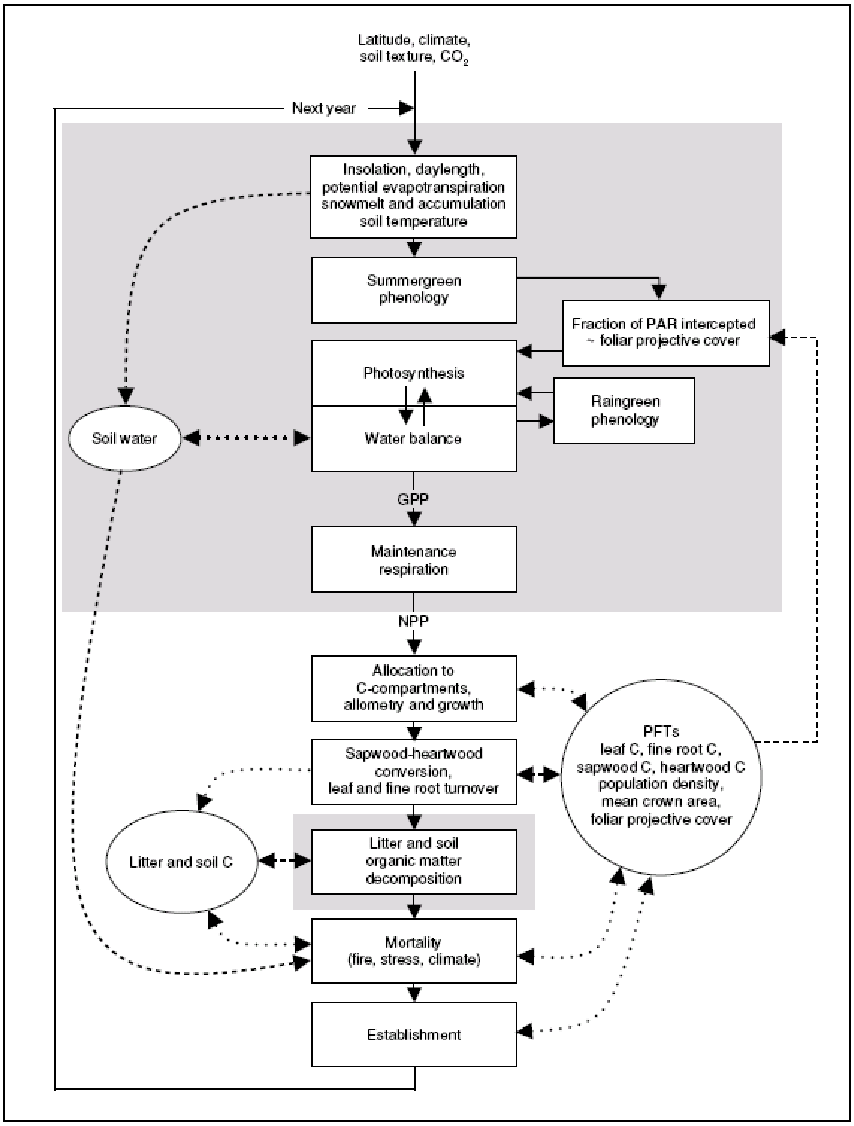


Figure 8. Structure of LPJ-DGVM represented as a flow chart for one simulation year. Modules with shaded background are called on a daily time step basis while the other modules are called annually. (From Sitch *et al.* 2003)

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 (Figure 8). Ecophysiological processes, such as photosynthesis, soil water dynamics, stomatal regulation, and exchanges of carbon and water between soil, vegetation and the atmosphere are implemented on a daily time step basis. Changes in vegetation structure through growth, population dynamics and fire-disturbance are performed at the end of each simulation year. Leaf fall and dead biomass from mortality and root turnover are on a yearly basis added to the litter pool, which is divided into a highly labile fraction respiring directly into the atmosphere and two soil carbon pools with turnover times of 33 and 1000 years, respectively. The soil decomposition rate depends on the seasonal temperature and soil moisture.

Vegetation in each simulated grid cell is described as the fractional coverage of a set of plant functional types (PFTs), broadly accounting for the diversity in plant structure and function (Bonan 2002). In LPJ-DGVM, global vegetation is commonly represented by 10 PFTs, differentiated by bioclimatic limits, and physiological, morphological and life history characteristics, which govern competition for resources (Sitch *et al.* 2003). For computational reasons, the PFT specifically representing Siberian larch (*Larix sibirica*) was excluded, while the other 9 standard PFTs were implemented as in Sitch *et al*. (2003).

LPJ-DGVM is driven by monthly data on climate (temperature, precipitation and solar insolation), atmospheric CO_2 concentration and soil texture. The computational modelling process over the entire simulation time is performed for one grid cell at the time, and thus not taken into account the vegetation development in neighbouring grid cells. In this study the model version described in Sitch *et al.* (2003), with updated hydrological processes by Gerten *et al.* (2004), the fire module explained in Thonicke *et al.* (2001), and minor parameter updates given in Hickler *et al.* (2006; supplementary material S2) was used.

3.2 Incorporating human land-use within LPJ-DGVM

Two modes of agriculture were implemented within the model:

- *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.* 2006).
- *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) 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 not explicitly implemented. Instead, when operated in agricultural mode, 80% of the grass litter was respired directly into the atmosphere compared to 70% for the standard set-up, implicitly realising harvest. This resulted in a lower addition of litter to the carbon pools than without agriculture, and thus contributed to a decrease in the soil carbon pools.

The land-use data set was divided into seven time-slices to cover the simulation period from 6000 BP until present (1998) (Table 2). 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 Figure 14.

Table 2. Time-slices and population data [millions] used to construct the land-use data set. Population data for 1990 from Klein Goldewijk (2001), other years from McEvedy & Jones (1978).

Time-slice	First year	Last year	Years	Population
a) 6000 BP	6000 BP	5001 BP	1000	7
b) 4000 BP	5000 BP	3001 BP	2000	27
c) 2000 BP	3000 BP	AD 499	1500	170
d) AD 1000	AD 500	AD 1499	1000	265
e) AD 1700	AD 1500	AD 1774	275	610
f) AD 1850	AD 1775	AD 1920	145	1 200
g) AD 1990	AD 1921	AD 1998	78	5 300

One example of a simulated development of the three carbon pools (vegetation, soil and litter) is shown in Figure 9, with applied climatic data from the grid cell corresponding to the area including and surrounding Lund in southern Sweden. Non-permanent agriculture with shorter and shorter fallow periods (Section 3.3.2) for each time-slice was applied during the four first time-slices of the simulation period, and followed by permanent agriculture during the last three time-slices (Section 3.3.1).

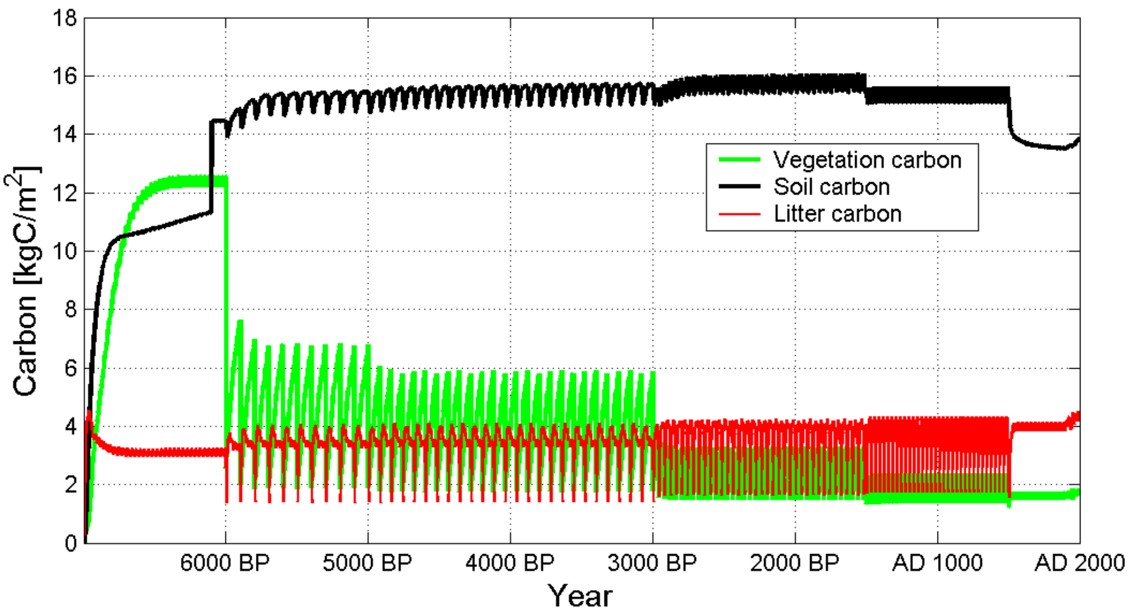
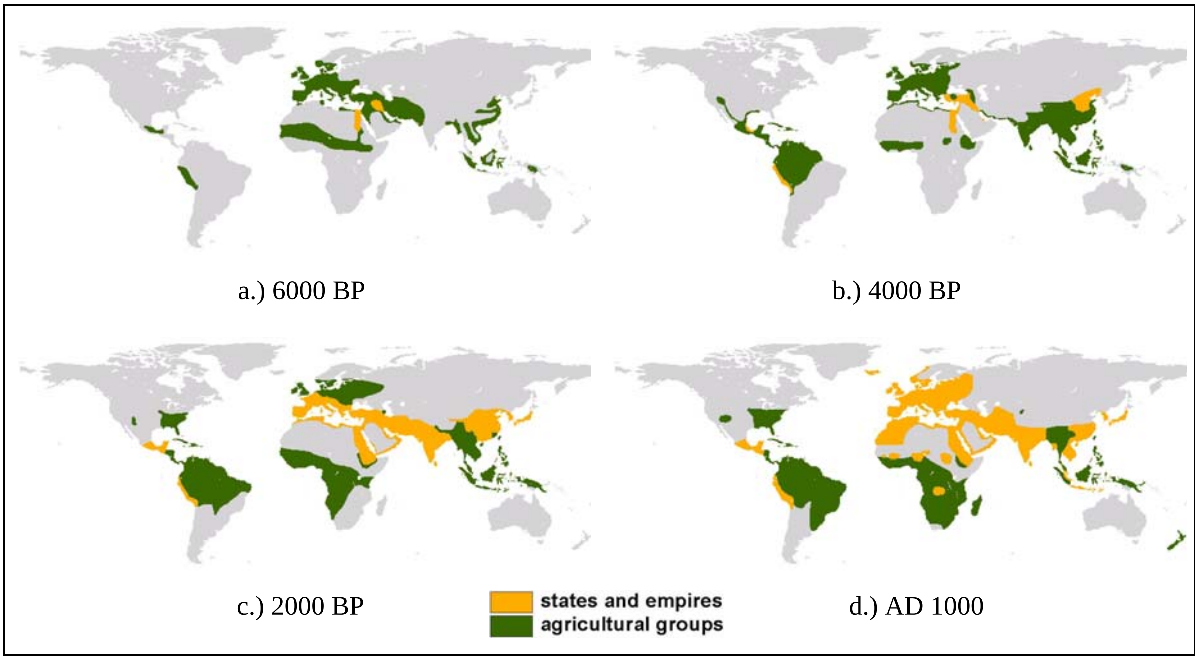


Figure 9. Example of the simulated development of the three carbon pools, with applied climatic data from the grid cell corresponding to the area including Lund in southern Sweden. The model was spun up for 1000 years, until 6000 BP, to allow the carbon pools to reach equilibrium status with the long-term climate (Section 3.4). Non-permanent agriculture was in the this example applied during the first four time-slices, until AD 1499, with shorter fallow periods for each time-period (Section 3.3.2), resulting in lower maximum vegetation the shorter the fallow period. Permanent agriculture was applied during the last three time-periods, AD 1500 until AD 1998 (Section 3.3.1). The increase in terrestrial carbon pools during the very last century was a result of changes in applied climate and atmospheric carbon dioxide concentration during this century (Section 3.4).

3.3 Land-use data set

A gridded global data set at 0.5° x 0.5° resolution (59,191 non-glacial-covered land cells), with seven time-slices of human civilization and land-use development during the last 6000 years (Table 2) 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 & Sherratt (1980), representing the spread of human civilization by: (a) 6000 BP, (b) 4000 BP, (c) 2000 BP and (d) AD 1000. The four maps were manually digitised with ArcView and IDRISI to facilitate further computer-based processing (Figure 10).


a.) 6000 BP

b.) 4000 BP

c.) 2000 BP

d.) AD 1000

Figure 10. Development of civilization represented as “states and empires” and “agricultural groups”, adapted from Lewthwaite & Sherratt (1980).

The 2000 BP map from Lewthwaite & Sherratt (1980) has been adapted by Roberts (1998) with the two civilisation levels now categorised as “complex stratified agriculture” and “simple peasant agriculture”, respectively. This interpretation of the same map was lately further developed in the hypothesis raised by Ruddiman (2003; 2005b).

An additional series of three time-slices were taken from the digital HYDE database[10] (Klein Goldewijk 2001): (e) AD 1700, (f) AD 1850 and (g) AD 1990 (Figure 11; Section 1.2).

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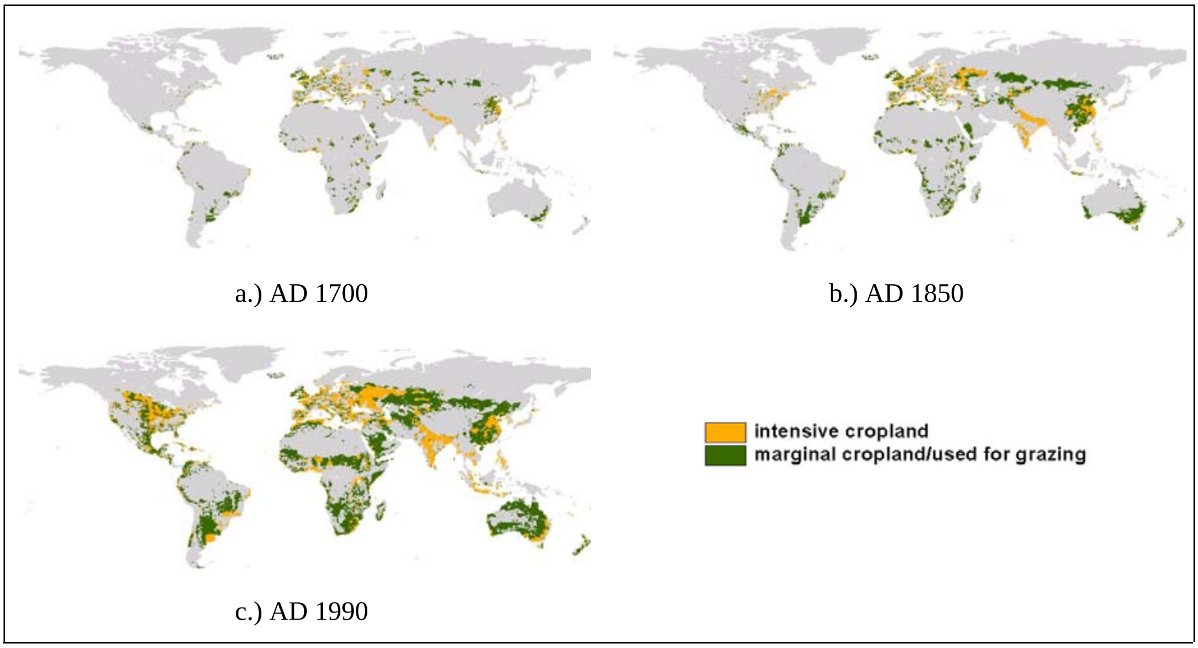
[10] The History Database of the Global Environment is available through http://www.mnp.nl/hyde/ (2006-06-13)


a.) AD 1700

b.) AD 1850

c.) AD 1990

Figure 11. Agriculture represented as “intensive cropland” and “marginal cropland/used for grazing”, adapted from the HYDE database (Klein Goldewijk 2001).

3.3.1 Permanent agriculture

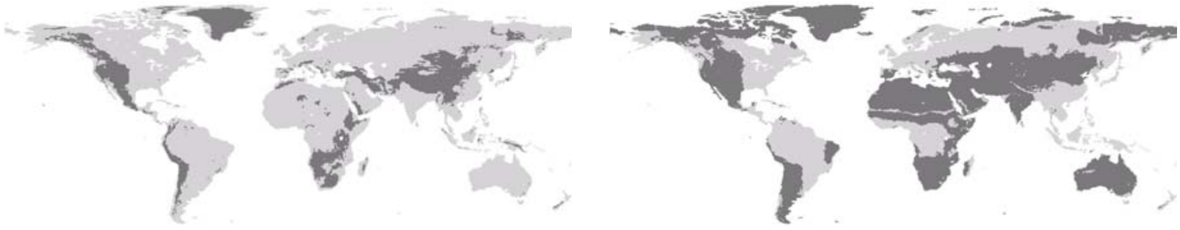
For the last three time-slices (1500-1998), the spatial distribution of areas assigned permanent agriculture was taken as the land-use classes “intensive cropland” and “marginal cropland/used for grazing” in the HYDE database (Figure 11). Before 1500, only areas referred to as “states and empires” in Lewthwaite & Sherratt (1980) (Figure 10) were assumed to be possibly covered by permanent agriculture (following Roberts 1998 and Ruddiman 2003), whereby 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); except 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). Furthermore, 10% of each grid cell was considered inappropriate for agriculture and therefore left for natural vegetation (Ruddiman 2003), accounting for landscape heterogeneity, *i.e.*, that some areas are always covered by ridges, streams etc, and therefore not suitable for agricultural use.

3.3.2 Non-permanent agriculture

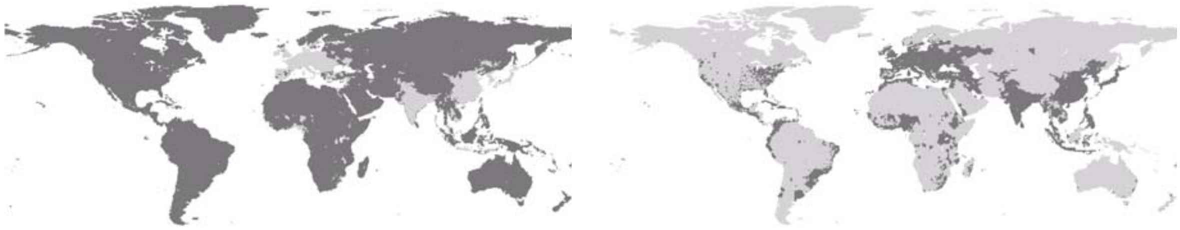
For the earliest four time slices (a-d), “suitable” areas (see below) within the categories “states and empires” and “agricultural groups” from Lewthwaite & Sherratt (1980) that were not already assigned permanent agriculture (see above) were assumed to be under non-permanent agriculture (Figure 10). For the three last time-slices (e-g), non-permanent agriculture was assumed to occur in all suitable areas on the globe not assigned by permanent agriculture.

Suitable areas were distinguished from unsuitable land as follows: only grid cells with a maximum elevation of 1000 meters were considered for farming in order to exclude less accessible forested areas (Ruddiman 2003). And just 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 kgC/m^2, were regarded as unproductive and therefore excluded from non-permanent agriculture. Regions with sparse populations of less than 5 inhabitants/km^2 in 1700, the earliest HYDE 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 defined above, based on HYDE for respective time-slice, were regarded inappropriate for non-permanent agriculture during the three last respective time-slices (e-g). In addition, for the last time-slice (g) non-permanent agriculture was restricted to areas south of latitude 25° N. (Figure 12)



a.) Elevation restriction (>1000 meters)

b.) Vegetation restriction (<2 kgC/m^2)



c.) Sparse population in 1700 (<5 inhabitants/km^2)

d.) Dense population in 1990 (>25 inhabitants/km^2)

Figure 12. Examples of applied restrictions for developing suitable areas for non-permanent agriculture (unsuitable areas marked with dark colour).

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 more widespread in less favourable climatic zones. a_{person} and data on global population p_{global} (McEvedy & Jones 1978; Klein Goldewijk 2001; Table 2) were used to derive the fallow period t_{fallow} (average period between the end of a farming period and the start of the next farming period):

$$t_{fallow} \approx \frac{a_{suit}}{p_{global} * f_{non\_perm} * a_{person} * \frac{1}{t_{farm}}} \tag{1}$$

For this purpose, the fraction of the global population depending on non-permanent agriculture f_{non_perm} had to be estimated (Table 3). 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 (Equation 1; Table 3).

Table 3. Numbers used for calibrating an approximate global average fallow period t_{fallow} [years] for non-permanent agriculture during respective time-slice. Suitable areas for non-permanent agriculture a_{suit} [million km^2] derived according to Section 3.3.2. Global population data p_{global} [million] from Table 2. Estimated fraction of the world population living from non-permanent agriculture $f_{non\text{-}perm}$ for time-slice (c) based on Ruddiman (2005b), for time-slice (g) based on Lanly (1985), while fractions for the other time-slices are best estimates. Required farming area under crops per person a_{person} [km^2/person] for time-slices (c-f) based on Lanly (1985) while a four times larger area for time-slices (a-b) were assumed because of less developed cultivation techniques and that these agricultural areas were situated in less favourable climatic zones. Farming period t_{farm} based on Lanly (1985).

Time-slice	a_{suit}	p_{global}	f_{non_perm}	a_{person}	t_{farm}	Applied t_{fallow}
a)	4.07	7	0.75	0.0067	4	246
b)	5.72	27	0.50	0.0067	4	196
c)	5.53	170	0.25	0.0017	4	146
d)	4.86	265	0.22	0.0017	4	96
e)	2.93	610	0.20	0.0017	4	76
f)	5.65	1200	0.15	0.0017	4	56
g)	5.40	5300	0.11	0.0017	4	26

3.3.3 The developed land-use data set

The land-use data set with permanent and non-permanent agriculture for the seven time-slices was derived following the procedure explained above, coarsely representing the development of human civilization and land-use expansion in order to facilitate a first estimate of changes in anthropogenic land-use-related carbon fluxes during the last 6000 years. The development over time of land areas assigned with the two modes of agriculture following this procedure is shown in numbers in Figure 13, and spatially in Figure 14. Detailed data of the assigned agricultural land areas per continent for each time-slice is given in Appendix A.

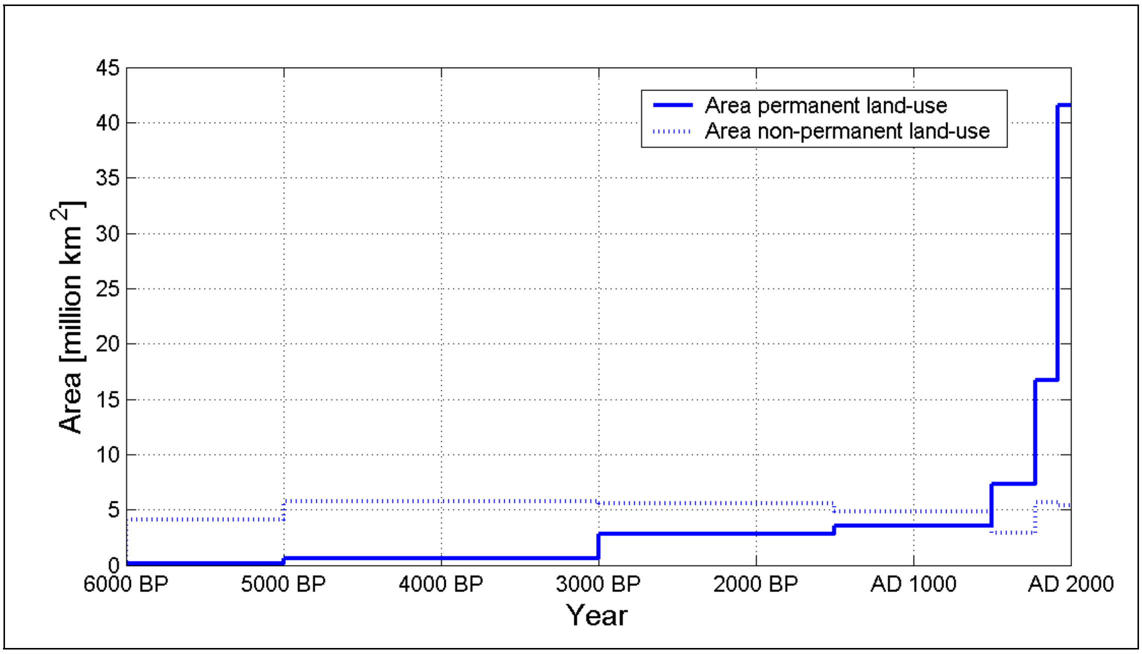
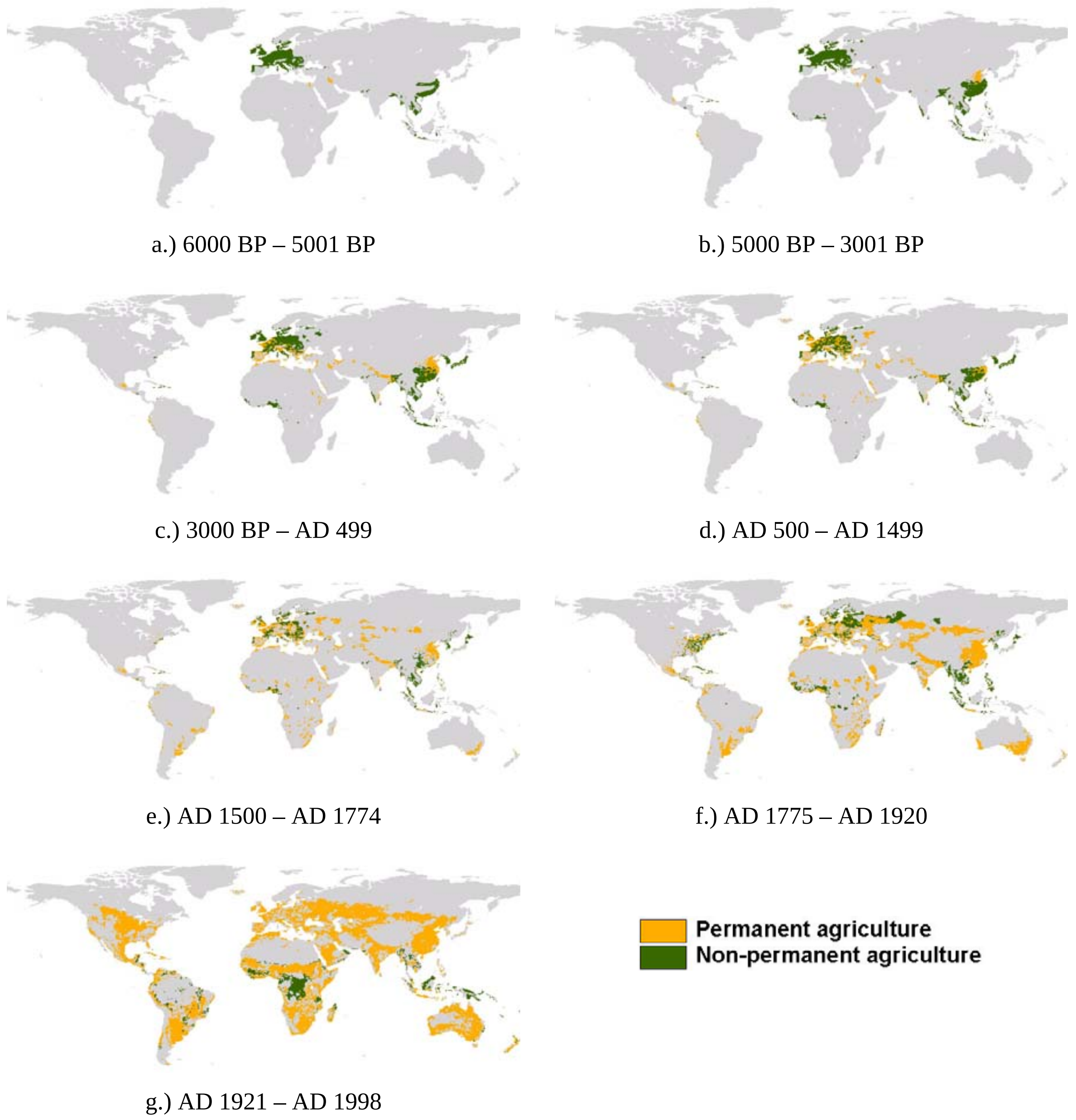


Figure 13. The development of the global land areas assigned with the two modes of agriculture with time for this simulation study. In comparison the Earth's total land area is estimated to 134 million km^2 (Klein Goldewijk 2001).



a.) 6000 BP – 5001 BP

b.) 5000 BP – 3001 BP

c.) 3000 BP – AD 499

d.) AD 500 – AD 1499

e.) AD 1500 – AD 1774

f.) AD 1775 – AD 1920

g.) AD 1921 – AD 1998

Figure 14. The developed land-use data set with spatial extent of areas assigned permanent and non-permanent agriculture during seven time-slices (6000 BP until AD 1998).

3.4 Modelling protocol

Monthly mean surface climate data of temperature, precipitation and percentage sunshine hours were taken from the CRU05 (1901-1998) data set on a 0.5° x 0.5° global land grid provided courtesy by the Climate Research Unit (CRU), University of East Anglia (New *et al.* 1999; 2000). Land elevation data was taken from New *et al.* (1999), shown in Figure 15.

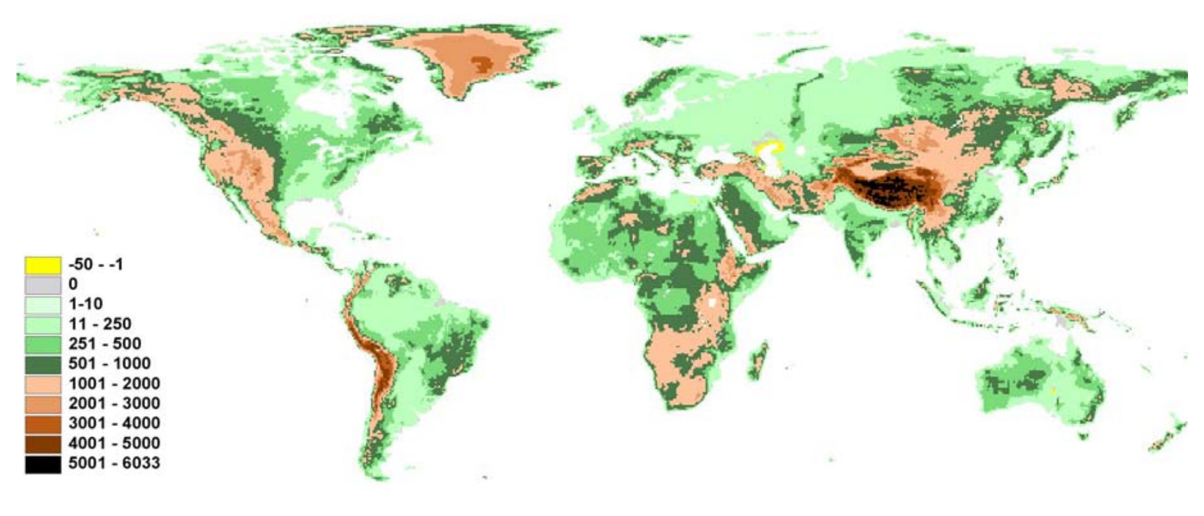


Figure 15. Elevation for all land grid cells except Antarctica, derived from New *et al.* (1999). [m]

The atmospheric CO_2 concentration was held constant at 275 ppmv, which is approximately the average level for the 6000 years before the industrial revolution based on ice core data from Indermühle *et al.* (1999) and Monnin *et al.* (2004), see Appendix B for details. 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 1000 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 to get an inter-annually varying climate to receive a variation in dryness/wetness, which is required by the fire module for a realistic vegetation representation (Thonicke *et al.* 2001). The same 30 years of climate data was further used during the entire simulation period, except for the period 1901 until 1998, when historical CRU05 and CO_2 data were used. See also Figure 9 for one simulation example.

In one run the model was used to simulate potential natural vegetation and carbon pools; and in the second run 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. This approach neglects climate variations during the study period, except for the last 98 years. These variations did, however, not play a considerable role for the global carbon cycle during the last 6000 years (Joos *et al.* 2004).

The computational modelling procedure was set up on a networked PC-cluster running with the Linux operating system (OS). With 8 high-performance computers operating in parallel mode on the cluster, one global simulation with the land-use data set took about 10 hours to execute. In comparison, the same simulation set up on a single PC with Windows OS was estimated to take at least 1,200 hours, equivalent to more than 7 weeks, figures emphasising the computational difficulties to model thousands of simulation years on a global scale.

4. RESULTS

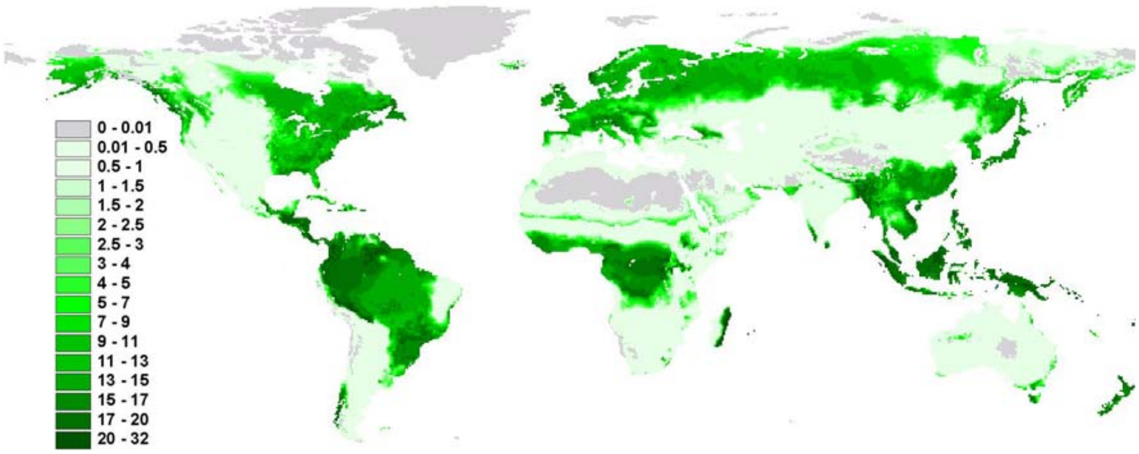
The simulated potential natural, pre-industrial vegetation carbon stock, 744 GtC, was in the middle of the “most realistic range” of 622-908 GtC from the global studies reviewed in Köhler & Fischer (2004). Simulated soil carbon and the total terrestrial carbon stock for pre-industrial times were also within the ranges in Köhler & Fischer (2004). (Table 4)

Table 4. Simulated potential natural vegetation separated by carbon pool and total terrestrial carbon (vegetation + soil + litter), compared with a few other studies. [GtC]

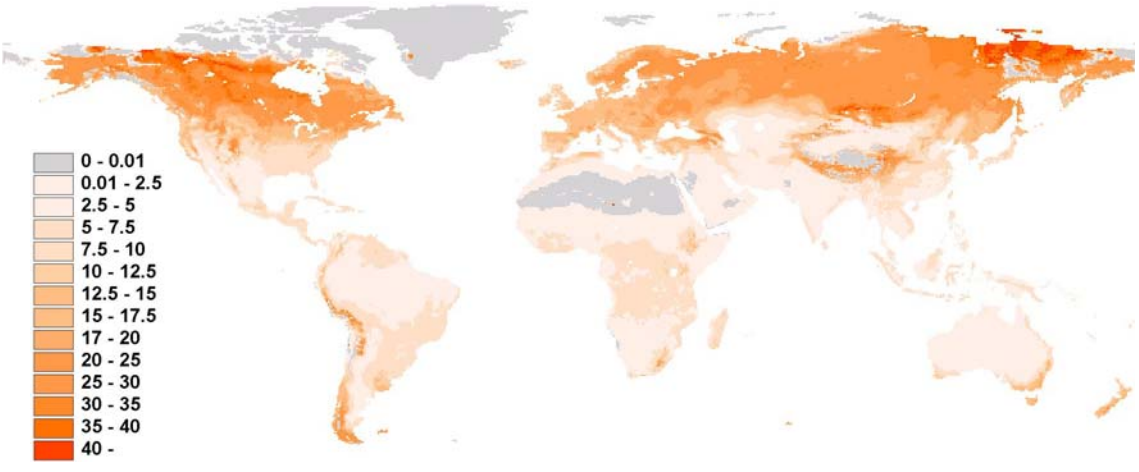
Study	$C_{Vegetation}$	C_{Soil}	C_{Litter}	$C_{Terrestrial}$
Prentice *et al.* (2001)[1]	466-654	1567-2011	x[1]	2221-2477
Sitch *et al.* (2003)	923	1670	171	2764
Köhler & Fischer (2004)[1]	622-908	1150-1700	x[1]	1911-2422
This study [275 ppmv]	744	1283	283	2311

[1] Note that neither Prentice *et al.* (2001) nor Köhler & Fischer (2004) separate the labile litter pool

Geographic allocation of potential natural vegetation and soil carbon are shown in Figure 16.



a.) vegetation carbon ($C_{Vegetation}$)



b.) soil carbon (C_{Soil})

Figure 16. Simulated potential natural areas of vegetation and soil for the 1901-1930 climate. [kgC/m^2]

The distribution of simulated natural vegetation per carbon pool and per continent is presented in numbers in Table 5. Asia together with South and Central America dominate the total vegetation carbon, though also the European continent has rather high vegetation carbon per area. For soil carbon there is a clear dominance for the higher latitudes, explained primarily by the slower decomposition rates as a result of a colder climate.

Table 5. Simulated potential natural vegetation with carbon pools divided per continent [GtC]. Average carbon stock per area given in parenthesis [kgC/m^2].

Continent	**$C_{Vegetation}$**		**C_{Soil}**		**C_{Litter}**	
Africa	105	(3.5)	102	(3.4)	26	(0.9)
Asia	226	(5.0)	526	(11.7)	113	(2.5)
Australia	11	(1.3)	29	(3.6)	7	(0.8)
Europe	91	(8.8)	172	(16.6)	37	(3.5)
North America	108	(5.5)	330	(16.9)	69	(3.5)
South and Central America	203	(9.9)	125	(6.1)	32	(1.6)

4.1 Simulated carbon release as a result of human land-use

The accumulated carbon flux related to the developed land-use data set for the entire simulation period until 1998 was 275 GtC. Until 1850, human land-use resulted in an accumulated carbon release of 114 GtC, while 148 GtC was emitted from 1850 until 1990. 91% of the total carbon release occurred after 2000 BP. (Figure 17; Table 6)

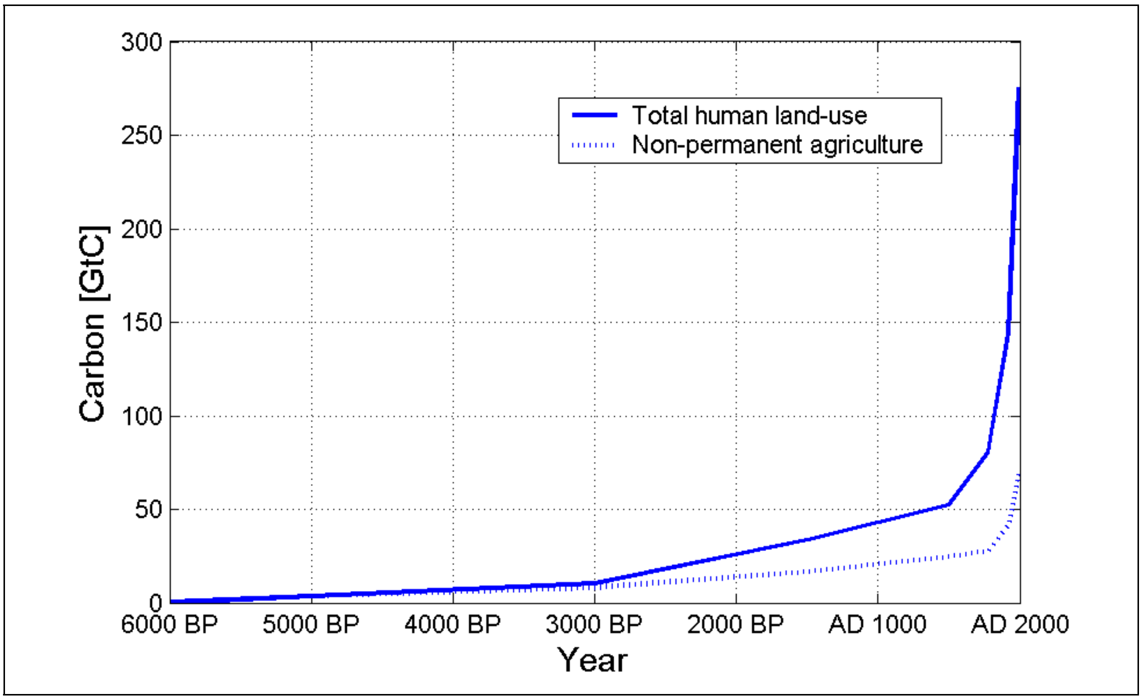


Figure 17. Simulated *accumulated* carbon release as a result of the applied human land-use during the last 6000 years. [GtC]

Over the full simulation period, the *accumulated* carbon release from permanent agriculture was 205 GtC. Carbon fluxes originating from non-permanent agriculture contributed an additional 71 GtC, corresponding to 26% of the total flux to the atmosphere. Until AD 1500, non-permanent agriculture contributed with 47% of the released carbon. The relative role of permanent agriculture increased with time and was especially noticeable during the two last time-slices. A decrease in vegetation carbon of 217 GtC accounted for 79% of the accumulated carbon emissions over the entire simulation period. At the same time, the soil carbon pool decreased by 64 GtC and the litter pool increased by 6 GtC. (Figure 17; Table 6)

Table 6. Simulated *accumulated* carbon pool changes as well as carbon flux divided per land-use mode, by the end of each time-slice, and at selected years. [GtC]

	Carbon pool			**Land-use mode (flux)**		
Time	$C_{Vegetation}$	C_{Soil}	C_{Litter}	**Permanent**	**Non-perm.**	**Total flux**
a) 5001 BP	-3.9	0.2	0.0	0.1	3.5	3.6
b) 3001 BP	-9.8	-0.5	0.0	2.0	8.3	10.3
c) AD 499	-29.0	-5.1	0.2	17.3	16.5	33.8
d) AD 1499	-46.0	-7.0	0.8	27.5	24.8	52.3
e) AD 1774	-61.5	-18.7	-0.3	52.8	27.6	80.4
f) AD 1920	-117.6	-32.6	5.7	103.4	41.1	144.5
g) AD 1998	-217.3	-63.7	5.6	204.9	70.6	275.4
2000 BP (estimated)	-22.6	-3.5	0.1	12.2	13.8	26.0
AD 1700 (est.)	-57.2	-15.5	0.0	45.9	26.9	72.7
AD 1850 (est.)	-90.5	-25.9	2.8	79.0	34.6	113.5
AD 1990 (est.)	-207.1	-60.5	5.6	194.5	67.5	262.0
AD 1992 (est.)	-209.6	-61.3	5.6	197.1	68.3	265.3

A geographical data separation of simulated carbon flux per continent for permanent and non-permanent agriculture is shown in Appendix C (see also data in Appendix A).

The geographical distribution of accumulated carbon flux per grid cell for the entire simulation period is shown in Figure 18. Areas with an accumulated net flux to the atmosphere clearly dominate the general picture. However, a few areas show a net terrestrial uptake, primarily as a result of the applied climatic changes during the 20th century in combination with abandoned agricultural areas that are currently being reforested.

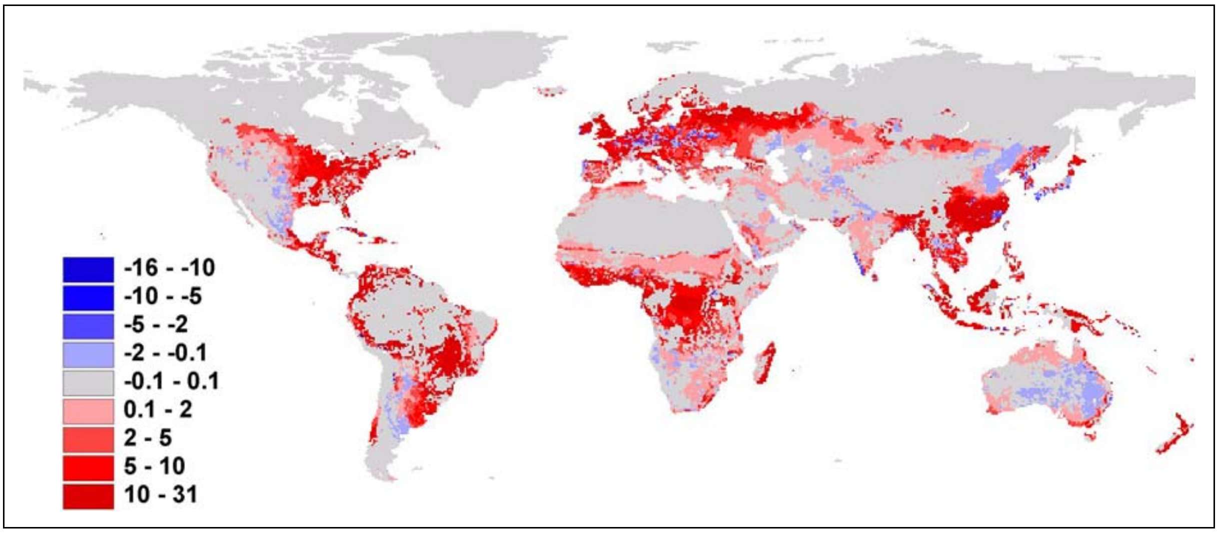


Figure 18. Simulated accumulated carbon flux from 6000 BP until 1998 as a result of the derived land-use data set. Positive values represent a net flux to the atmosphere, while negative values represent a net terrestrial uptake. [kgC/m^2]

4.2 Comparison with other land-use studies

Table 7 shows a comparison with other land-use studies (see also Section 1.2; Table 1): for most time periods, the estimated carbon release from permanent agriculture was within the range reported in other studies. At 2000 BP, the modelled carbon release was, however, an order of magnitude lower than the estimate from Ruddiman (2003), as a result of considerably smaller areas assigned with land-use by 2000 BP in the present study as well as a lower modelled estimate of carbon loss per area for the regions assigned with agriculture. Compared with the estimate until 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 2000 BP.

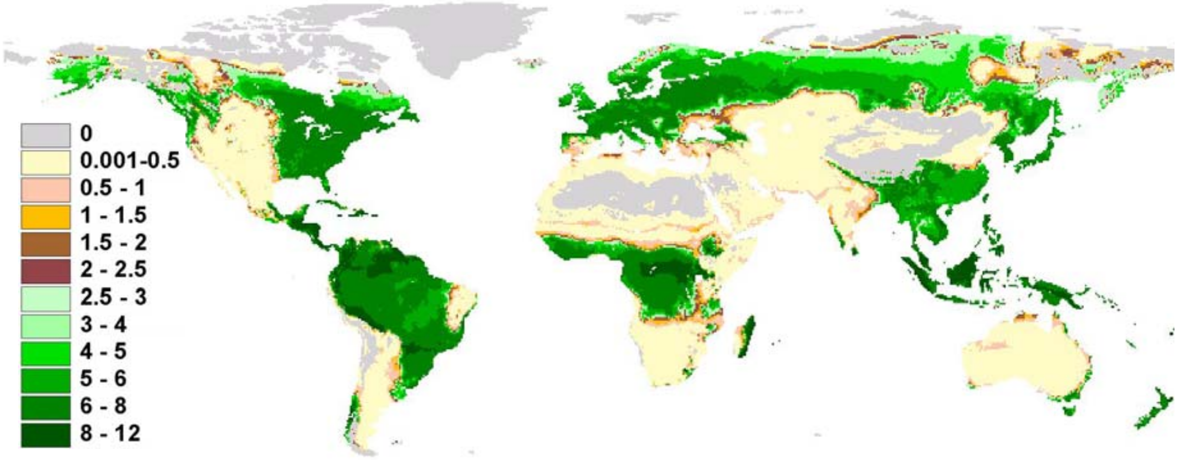
Table 7. Comparison of the modelled total land-use-change-related global carbon release with estimates from other studies (Section 1.2; Table 1). The results from this study are shown also with the separate contributions from permanent and non-permanent agriculture. [GtC]

Study	- 2000 BP	1700 - 1990	- 1850	1850 – 1990	- 1990	1920 - 1992
DeFries *et al.* (1999)			48-57		182-199	
McGuire *et al.* (2001)						56-91
Houghton (2003a)				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

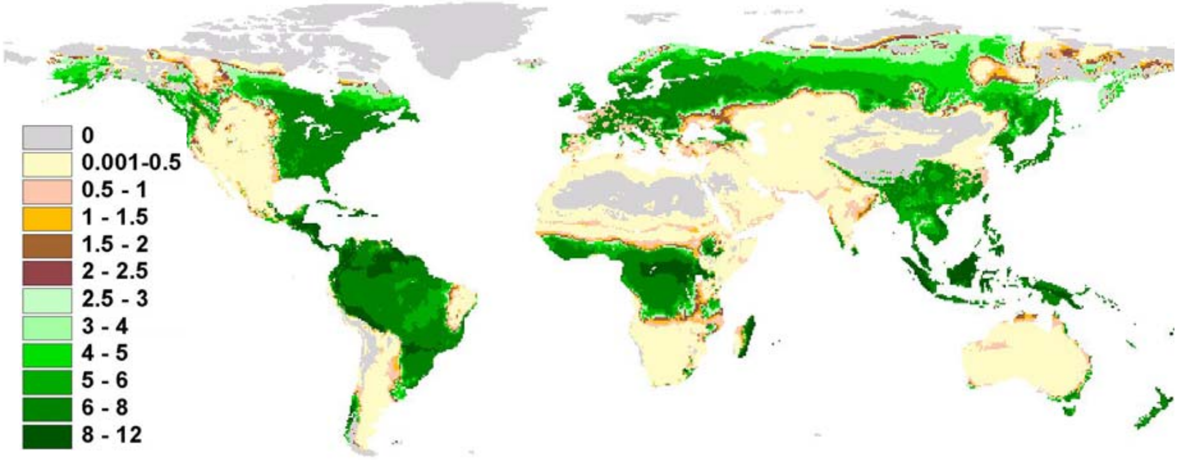
4.3 Vegetation landscape openness

With less forested land and more land areas being used for cultivation and pasture, there was an increase in vegetation openness induced by human land-use, which can be visualised as a change in forest Leaf Area Index (LAI), see Figure 19. At 2000 BP, a strong human impact on vegetation openness was only obvious in some regions in Europe and Southeast Asia. However, by AD 1990, modelled anthropogenic landscape openness was pronounced in several areas all over the world. (Figure 19)

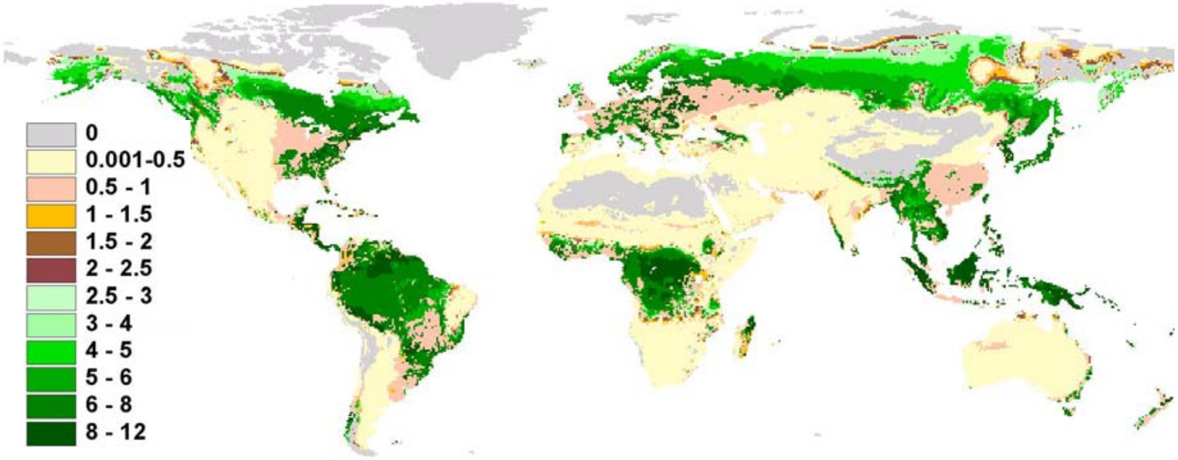
While interpreting these results, however, it has to be kept in mind that the impacts of non-permanent agriculture were averaged over the whole area where this farming method was assumed to occur. This explains why the openness maps do not depict more localised effects of early humans. When modelling global total carbon releases, small averaged carbon releases over large areas can still add up to considerable magnitudes.



a.) without human land-use



b.) with human land-use at 2000 BP



c.) with human land-use at AD 1990

Figure 19. Modelled landscape openness expressed as forest Leaf Area Index (LAI).

5. DISCUSSION

The ever-increasing human presence complicates the task of understanding the development of the Earth system since the end of the latest glacial. Foley *et al.* (2005) noted that land-use in general has been regarded as a local environmental issue but is at the present becoming a matter of global importance driven by the increasing needs of a growing human population.

The hypothesis of Ruddiman (2003) that a human impact on climate, through an extensive deforestation far prior to the industrial era, connects early land-use to global climate change. Already Sagan *et al.* (1979) related human land-use via albedo changes to climate variations and found it possible that humans have contributed considerably to induce global climate shifts in the past millennia and maybe as early as a million years ago.

Early land-use might thus be a more important parameter for understanding the climate and the global carbon cycle than has been previously thought. Land-use history is important for correctly assessing the effects of past land-use on the development of current soil carbon pools because of the slow decomposition rates involved (Houghton & Goodale 2004).

The present study using a dynamic global vegetation model including an extended land-use history should therefore be seen as a further attempt in investigating a possible early anthropogenic impact on the Earth system. As remarked already, this study has focused on land-use and related CO_2 fluxes, and thus carbon fluxes in the form of CH_4 from, *e.g.*, irrigated rice-paddies, were not included as well as other human land-uses such as forestry.

5.1 Carbon release from human land-use

This study presents a first estimate of dynamic changes in carbon emissions during the last 6000 years caused by land-use, including non-permanent agriculture, and thus goes considerably further back in time than previous global studies, which have mainly focused only on the last 300 years. The results suggest the same magnitude of carbon release from permanent agriculture as presented in other studies based on process models (Section 1.2; Table 7), but indicate a considerable additional contribution from non-permanent agriculture.

The modelled fractional decrease in soil carbon as a result of farming was similar in magnitude to the figure suggested by Houghton & Goodale (2004). The modelled average annual carbon release during 1920 until 1998 from permanent and non-permanent agriculture was 1.3 and 0.4 GtC yr^{-1}, respectively. These averages correspond relatively well with estimates from Houghton (2003a) that land-use change and management in the 1990s caused a net annual release of 2.2 GtC yr^{-1} including 0.2 GtC yr^{-1} from shifting cultivation, considering an increased land-use impact with time during the last modelled time-slice.

The long calculated fallow periods (Table 3) during the initial time-slices correspond to the theory of Iversen's *landnám phases*[11] of forest clearance (Iversen 1941 in Roberts 1998), which might 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). The trend of shortening fallow periods over time is consistent with an increasing food production because of a growing human population, as observed during medieval times in Europe

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[11] The process when man stopped being hunters/collectors and started to "take possession of the land" for pasture and agriculture, a development at least initially resembling of shifting cultivation (see p 155 in Roberts 1998).

(Williams 2000) and in modern non-permanent agriculture societies (Fearnside 2000; Metzger 2003).

5.1.1 Results relating to Ruddiman's hypothesis

By 2000 BP, the present study indicates an accumulated total carbon release from land-use of 26 GtC (Table 6), which is considerably less than the 250 GtC originally suggested by Ruddiman (2003), recently modified to "perhaps a third" of the total CO_2 anomaly compared with earlier interglacials (Ruddiman 2005a) corresponding to about 200 GtC (Ruddiman 2005c) based on Joos *et al.* (2004). According to Joos *et al.* (2004), an even higher anthropogenic emission (710 GtC until present) would have been necessary for the strong influence on atmospheric CO_2 suggested by Ruddiman (Section 1.1).

A human-induced direct release of 26 GtC would correspond to an atmospheric CO_2 increase of about 1.8 ppmv following the calculations in Joos *et al.* (2004)[12], which is a factor 20 less than Ruddiman's initial hypothesis (40 ppmv). This study therefore suggests that a strong influence of land-use-related carbon emissions before 2000 BP is unlikely (Figure 17).

These findings call for an alternative explanation for the current relatively long interglacial, compared with the last three warm periods: the current low eccentricity of the Earths' orbit might be the reason for the long warm period (Broecker & Stocker 2006). When a similar eccentricity as today prevailed about 400 thousand years BP (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 & Stocker 2006).

5.2 Uncertainties

In summary, the results are generally consistent with findings from other studies on the involved processes. However, it has to be acknowledged that some of the parameter values used to implement non-permanent human land-use are subject to some uncertainty. Zaehle *et al.* (2005) investigated general parameter uncertainties for LPJ-DGVM and found that the soil carbon pools represented the most uncertain model output as a result of their long turnover times. After carrying out a number of alternative simulations for the study presented here, with modifications in the land-use implementation such as variations in areas under non-permanent agriculture and fallow period lengths, there is a certain confidence that the presented results are generally robust.

At this stage, two shortcomings of the current study need to be emphasised: the approach was developed to derive an objective estimate of global total carbon releases, including considerable averaging of human impacts over large areas. When zooming into 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 are not yet available for the period before 1700, it might however be difficult to account for this real-world heterogeneity when using a global, quantitative modelling approach.

Secondly, human effects on ecosystems that are not directly related to agriculture were not included. Native North American Indians, for example, have used fire to open up the forest for thousands of years to provide better opportunities for hunting, thereby potentially

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[12] 0.15 * (26 [GtC] / 2.123 [GtC/ppmv]) [85% of the emitted carbon removed by the ocean (Joos *et al.* 2004)]

maintaining an open prairie instead of partly forested woodlands (Anderson 1987). Managed forestry, which currently influences large areas of the global forests, was neither considered in this study.

An additional potential factor to consider is soil erosion, which is estimated to presently cause a release 0.8-1.2 GtC yr^{-1} and thus having a strong impact on the global carbon cycle (Lal 2003). Comparing with the annual carbon release of 2.2 GtC yr^{-1} related to land-use from Houghton & Goodale (2004), soil erosion might therefore substantially increase the estimated carbon flux from human agricultural activities.

Other examples of potential factors not yet incorporated are effects of large-scale irrigation that influences crop growth and the hydrological balance, as well as fertilizers used to improve the crop yields (LPJ-DGVM does not yet include nutrient dynamics and limitations). The effect of grazing animals on the carbon balance would also be interesting to examine. However, all these potential factors need to be further investigated before they can be applied in a future re-assessment modelling study (Section 6.2).

Finally, it is important to again recall that this study has included only CO_2 fluxes caused by land-use and thus not considered carbon fluxes in the form of CH_4. However, carbon fluxes related to land-use induced CH_4 are approximated to be considerably lower than the CO_2 fluxes and would thus most likely have contributed only slightly to the global carbon development during the studied period.

6. CONCLUSIONS

6.1 Key findings

The main conclusions from the land-use modelling study covering the last 6000 years were:

- Most carbon emissions occurred after 1850, even when including accumulated early non-permanent agriculture.
- Non-permanent agriculture caused about 25% of total carbon emissions, making a significant addition to fluxes from human land-use and thus indicating the importance of including more than permanent agriculture in carbon and land-use related studies.
- Changes in the soil carbon pool contributed with 23% of the emissions, stressing the importance to include more than changes in vegetation when studying land-use as well as the importance of including land-use history because of the slow soil decomposition rates.
- No major early human-induced impact on global climate was found and consequently the results suggest that the hypothesis of Ruddiman is unlikely.

6.2 Future research

As this was a first study of estimating the global impact on the carbon cycle from early dynamic human land-use, there are several potentials for improvements in future research including detailed sensitivity tests of extreme land-use alternatives. Applying “real” climate and CO_2 data (see Appendix B) for the entire simulation period would improve the modelled estimate of growth conditions, but would probably not have a considerable effect on the results. Feedback mechanisms between changes in climate and vegetation cover through land-use requiring a fully coupled Earth system model would be another interesting investigation to perform with the developed land-use set up.

However, a further development in obtaining the land-use data set is probably more important for the modelling results. The land-use data set could be divided into more time-slices for a finer representation of the land-use development for the pre-industrial period as well as applying more already developed time-slices from the HYDE data set for the last 300 years.

A closer connection to actual spatial distribution and population density of humanity during the Holocene could be accomplished through using more detailed information about the human population density available from, *e.g.*, archaeology, pollen sediments and recorded historical sources, and would thereby certainly improve the procedure of spatial assigning the land-use modes. Additional modules of other human-related land-use, such as forestry and grazing, could also be developed and integrated into the model. Furthermore, spatial and temporal variations in farming practices and crops based on local conditions (*e.g.*, soil, topography and hydrology) could as well be integrated in a more detailed future study.

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Last but not least, I would like to thank all great fellow students at the Department of Physical Geography and Ecosystem Analysis, my friends and my family.

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APPENDIX A

Data of areas assigned agriculture per continent during each time-slice

Table A1. Area assigned permanent agriculture per continent and time-slice. [1000 km^2]

Time-slice	Africa	Asia	Australia	Europe	N Am.	S&C Am.	Total
a)	31	87	0	0	0	0	118
b)	31	516	0	0	0	87	634
c)	281	1 548	0	812	0	164	2 805
d)	392	1 366	0	1 579	0	201	3 538
e)	1 553	2 580	299	1 812	68	1 008	7 320
f)	3 151	6 744	1 398	2 746	607	2 017	16 664
g)	9 355	13 333	4 462	4 523	3 949	5 968	41 590

Table A2. Area assigned non-permanent agriculture per continent and time-slice. [1000 km^2]

Time-slice	Africa	Asia	Australia	Europe	N. Am.	S&C Am.	Total
a)	3	1 619	0	2 438	0	5	4 066
b)	185	2 815	0	2 650	0	69	5 719
c)	348	2 867	0	2 226	17	70	5 528
d)	373	2 715	0	1 674	20	82	4 864
e)	223	1 538	0	1 080	35	53	2 930
f)	870	2 331	0	1 606	600	248	5 655
g)	2 819	1 434	123	0	5	1 020	5 401

APPENDIX B

Calculation of the pre-industrial CO_2 concentration

The atmospheric CO_2 concentration was set to a constant value during the entire simulation period, except during the last 98 years (see Section 3.4). The pre-industrial value is commonly referred to be about 280 ppmv (Prentice *et al.* 2001) and is often used as this constant value in modelling studies covering the Holocene.

However, when analysing the CO_2 data measured in Antarctic ice cores from Indermühle *et al.* (1999) and Monnin *et al.* (2004) for the 6000 years before the onset of the industrial revolution, graphically displayed in Figure B1, it is noticeable that the 280-ppmv level is not a representative average value for the time-period of interest in this particular study.

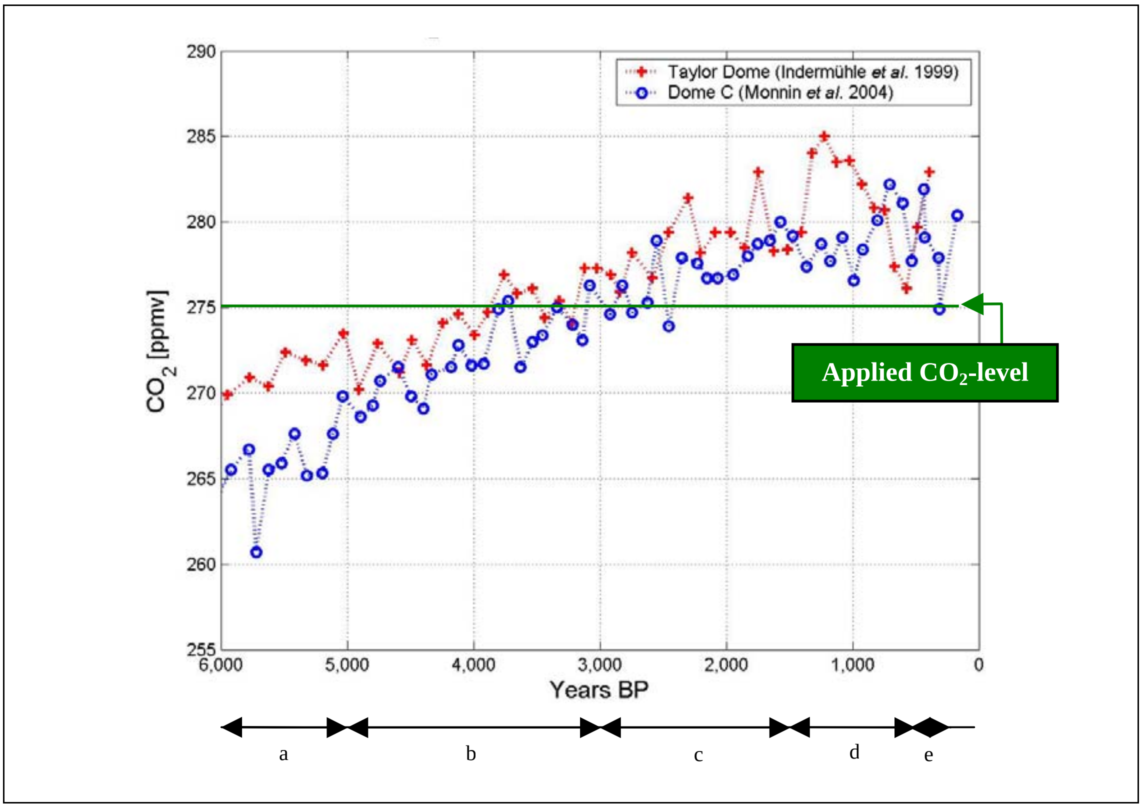

Figure B1. Atmospheric CO_2 concentration 5944 to 173 years BP, adapted from Indermühle *et al.* (1999) and Monnin *et al.* (2004) [ppmv]. The first five time-slices (a-e) are indicated below the graph.

After calculating simple as well as weighted average values for the two time-series (Table B1), a CO_2 level of 275 ppmv was applied as a representative level to be used (Figure B1).

Table B1. Average CO_2 concentration 5944 to 173 years BP. [ppmv]

	Taylor Dome	**Dome C**
Simple average	276.8	274.1
Weighted average	276.1	273.9

The data sets with measured CO_2 concentration from Indermühle *et al.* (1999) and Monnin *et al.* (2004) for the last 6000 years are displayed in Table B2.

Table B2. Measured CO_2 concentration 5944 BP – 173 years BP at Taylor Dome and Dome C.

Taylor Dome				**Dome C**					
Year BP	**CO_2 [ppmv]**	**Year BP**	**CO_2 [ppmv]**	**Year BP**	**CO_2 [ppmv]**	**Year BP**	**CO_2 [ppmv]**	**Year BP**	**CO_2 [ppmv]**
390	282.9	3021	277.3	173	280.4	2453	273.9	4895	268.6
486	279.7	3118	277.3	311	274.9	2550	278.9	5033	269.8
573	276.1	3221	274.1	322	277.9	2625	275.3	5114	267.6
670	277.4	3320	275.4	427	279.1	2743	274.7	5196	265.3
742	280.7	3435	274.4	435	281.9	2820	276.3	5318	265.2
830	280.8	3533	276.1	530	277.7	2918	274.6	5419	267.6
924	282.2	3653	275.8	604	281.1	3078	276.3	5521	265.9
1020	283.6	3758	276.9	709	282.2	3138	273.1	5621	265.5
1125	283.5	3890	274.7	806	280.1	3219	274.0	5721	260.7
1220	285.0	3990	273.4	917	278.4	3337	275.0	5780	266.7
1319	284.0	4121	274.6	991	276.6	3454	273.4	5921	265.5
1406	279.4	4243	274.1	1083	279.1	3531	273.0		
1513	278.4	4368	271.6	1175	277.7	3628	271.5		
1620	278.3	4484	273.1	1249	278.7	3724	275.4		
1745	282.9	4583	271.2	1362	277.4	3802	274.9		
1853	278.5	4757	272.9	1477	279.2	3921	271.7		
1965	279.4	4909	270.2	1574	280.0	4019	271.6		
2084	279.4	5031	273.5	1653	278.9	4117	272.8		
2203	278.2	5193	271.6	1751	278.7	4176	271.5		
2302	281.4	5327	271.9	1830	278.0	4335	271.1		
2453	279.4	5488	272.4	1948	276.9	4395	269.1		
2581	276.7	5620	270.4	2069	276.7	4496	269.8		
2742	278.2	5774	270.9	2150	276.7	4596	271.5		
2841	275.9	5944	269.9	2228	277.6	4737	270.7		
2912	276.9			2352	277.9	4797	269.3		

Data references

Taylor Dome from Indermühle *et al.* (1999)

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APPENDIX C

Resulting simulated carbon flux per continent during each time-slice

Table C1. Simulated carbon flux from permanent agriculture per continent and per time-slice. [GtC]

Time-slice	Africa	Asia	Australia	Europe	N Am	S&C Am	Total
a)	0.0	0.1	0.0	0.0	0.0	0.0	0.1
b)	0.0	1.4	0.0	0.0	0.0	0.6	1.9
c)	1.0	6.6	0.0	7.2	0.0	0.6	15.3
d)	0.2	2.1	0.0	7.4	0.0	0.4	10.1
e)	7.1	4.0	1.6	1.8	1.0	9.8	25.3
f)	6.3	20.8	2.2	5.1	6.3	9.9	50.6
g)	20.0	16.7	2.1	8.1	16.8	37.7	101.5

Table C2. Simulated carbon flux from non-permanent agriculture per continent and time-slice. [GtC]

Time-slice	Africa	Asia	Australia	Europe	N Am	S&C Am	Total
a)	0.0	0.9	0.0	2,6	0.0	0.0	3.5
b)	0.3	2.6	0.0	1.8	0.0	0.1	4.7
c)	0.7	4.8	0.0	2.6	0.0	0.1	8.2
d)	0.6	4.8	0.0	2.8	0.0	0.2	8.3
e)	0.7	-0.2	0.0	1.8	0.4	0.2	2.8
f)	1.8	5.8	-0.8	4.1	4.1	-1.6	13.4
g)	21.2	6.4	1.1	-5.4	-2.0	8.1	29.5

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