(Looking) Back to the Future: A reconstruction of historic land use and its application for global change research

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Chapter 3

The HYDE 3.1 spatially explicit database of human induced global land use change over the past 12,000 years.

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Abstract

This paper presents a tool for long term global change studies; it is an update of the History Database of the Global Environment (HYDE) with estimates of some of the underlying demographic and agricultural driving factors. Historical population, cropland and pasture statistics are combined with satellite information and specific allocation algorithms (which change over time) to create spatial explicit maps, which are fully consistent on a 5 minute longitude/latitude grid resolution, and cover the period 10 000 BC to AD 2000. Cropland occupied roughly less then 1% of the global ice-free land area for a long time period until AD 1000, quite similar like the area used for pasture. In the centuries that followed the share of global cropland increased to 2% in 1700 (ca. 3 million km^2), and 11% in 2000 (15 million km^2), while the share of pasture area grew from 2% in 1700 to 24% in 2000 (34 million km^2) These profound land use changes have had, and will continue to have quite considerable consequences for global biogeochemical cycles and subsequently global climate change.

Some researchers suggest that mankind has shifted from living in the Holocene (~emergence of agriculture) into the Anthropocene (~humans capable of changing the Earth' atmosphere) since the start of the Industrial Revolution. But in the light of the sheer size and magnitude of some historical land use changes (e.g. as result of the depopulation of Europe due to the Black Plague in the 14th century and the aftermath of the colonization of the Americas in the 16th century), we believe that this point might have occurred earlier in time. While there are still many uncertainties and gaps in our knowledge about the importance of land use (change) in the global biogeochemical cycle, we hope that this database can help global (climate) change modelers to close parts of this gap.

3.1 Introduction

Imagine the evolution of the Earth in one day, then mankind is only present on this planet since a few minutes to midnight, yet still we managed to obtain dominance over the world in that short time frame. Already more than 30% of the world's landscape is currently under some sort of development (agriculture), another 30% is more or less influenced and many natural resources are already heavily used or even depleted. All these activities have led to anthropogenic emissions of greenhouse gases and have subsequently influenced global (climate) change, but it is uncertain from which point in time, and to what extent these influences have been. A key question is: How did this come so far?

As long as humans have been present on the Earth, they have been altering the global landscape. These historical changes in land use, primarily conversion (deforestation) of undisturbed ecosystems to other forms of land use (cropland, grazing land), have contributed considerably to the cumulative carbon dioxide (CO_2) increase in the atmosphere. Although estimates of historical CO_2 emissions from land use changes are uncertain (Ruddiman, 2003), most studies (DeFries *et al.*, 1999; Houghton, 1999; McGuire *et al.*, 2001; Pacala *et al.*, 2001; Houghton, 2003) indicate that land use change is an important net source of CO_2 causing global emissions of 1.4 (0.4 – 2.3) Pg yr^{-1} (Pg, petagram; 1 Pg = 10^{15}g) of carbon (C) for the 1980s and 1.6 (0.5 – 2.7) Pg yr^{-1} for the 1990s, roughly one-fifth of the total anthropogenic CO_2 emission (Le Quéré *et al*., 2009). Due to an estimated residual terrestrial sink of -1.7 Pg G yr^{-1} during the 80s and -2.6 Pg C yr^{-1} for the 90s, the terrestrial part of the Earth is currently a sink for carbon, but this has not always been the case, and probably will not continue to do so in the future (Le Quéré *et al*., 2009).

The General Circulation Models (GCM's) which are used to study the global climate, are too complex to do transient runs with a fully coupled land-atmosphere system. Therefore, a new class of Earth system models (ESM's) and ESM's of intermediate complexity (EMICs, see Brovkin *et al* (2006)) emerged. These EMIC's are able to investigate the transient response of the climate system to different climate forcings on a much longer time scale than GCM's are capable of, by being more computational efficient without losing critical land-climate interactions. Simulations with historical land cover forcing by several studies suggested that the bio-geophysical effect of historical land cover changes indeed helped to clarify the observed changes in carbon and global temperature during the last centuries. Most studies indicated global bio-geophysical cooling as a result of a land-cover change of 0.13-0.25 ^{o}C since pre-industrial times. One of the major uncertainties in these results turned out to be the historical land-cover distribution (Chase *et al.*, 2000; Bertrand & Van Ypersele, 2002; Matthews *et al.*, 2003; Matthews *et al.*, 2004; Feddema *et al.*, 2005; Brovkin *et al.*, 2006; Betts *et al.*, 2007; Findell *et al.*, 2007; Strassmann *et al.*, 2008; Vavrus *et al.*, 2008; Van Minnen *et al.*, 2009).

Historical land use/land cover information is also becoming more and more important in other studies, which for example examine different ways of looking at land use systems, e.g. the Anthromes approach (Ellis *et al.*, 2010) or the global fire/biomass burning project (Marlon *et al.*, 2008). Furthermore, it could serve as input for different disciplines such as macroecologists, helping them to understand the past dynamics of geographical ranges and species specific niches (Nogues-Bravo, 2009), determine the gain or loss in global biodiversity (Gaston *et al.*, 2003; Gaston, 2006), or explore the human impact on several biodiversity issues (Cincotta *et al.*, 2000; Goudie, 2006). It is critical that the land use/cover information is available at a sufficient level, spatially as well as temporarily.

In general there can be two approaches distinguished for global historical land-use/cover inventories. (i) modeling with so-called Dynamic Global Vegetation Models (DGVMs), which explicitly represent the interaction between ecosystem C and water exchange and vegetation dynamics to compute long historical transient time series of land cover. Cramer *et al* (2001) compared six DGVMs and demonstrated that simulated historical land-cover distribution varied strongly among the models. Most DGVMs are based on biomes representing an envelope of plant functional types. These biomes are generalized ecosystem representations and they lack fragmentation or human influences. (ii) historical land-cover datasets based on statistical information. A number of historical land-use datasets were prepared on the basis of statistics at the sub-national and national scale, for example for Burgundy in France (Crumley, 2000), the Ardennes in Belgium (Petit & Lambin, 2002), Colombia (Etter & Van Wyngaarden, 2000; Etter *et al.*, 2008) and the USA (Maizel, 1998). Other historical land-cover inventories were made at the regional and continental scale, for example for Australia (AUSLIG, 1990), for China (Ge *et al.*, 2008), for Southeast Asia (Flint & Richards, 1991) and Europe (Williams, 2000; Kaplan *et al.*, 2009).

Global estimates of the historical areas of cropland and grassland are rare and rather uncertain (see Table 1). Different approaches were used in the available global estimates Ramankutty & Foley (1998) calibrated the IGBP 1 km-resolution Global Land Cover Classification (GLCC) data set against cropland inventory data for 1992 to create a global map of cultivated land for 1992 (Ramankutty & Foley, 1998). Subsequently, they used a 'hindcast' modeling technique to extrapolate these data, using a compilation of historical cropland inventory data to create a spatial data set of croplands for the period 1700 to 1992 AD (Ramankutty & Foley, 1999). Others used a bookkeeping model with conversion rates of different land-cover types (including cropland and pasture) to estimate C fluxes (Houghton *et al.*, 1983; Richards, 1990; Houghton, 1999; Houghton & Hackler, 2002). Pongratz *et al* (2008) reconstructed agricultural areas for the last millennium from AD 800 to 1992, see supplementary table ST1 for details on the different approaches.

The original HYDE 2 database (Klein Goldewijk, 2001) was a consistent data set of historical land-use and land-cover data of the 20th century on a spatial resolution of 0.5 by 0.5 degree. HYDE 2 includes both general topics such as land use and land cover, population, livestock, gross domestic product (along with value added generated in industry and the service sector), and specific data on energy, the economy, atmosphere, oceans and the terrestrial environment. Most data were organized on the national scale for the period 1890 – 1990, and where available, for the period 1700 – 2000.

An update of HYDE 2 was presented in Klein Goldewijk & van Drecht (2006). HYDE 3.0 included several improvements compared to its predecessor: (i) the HYDE 2 version used a Boolean approach with a 30 minute degree resolution, while HYDE 3.0 used fractional land use on a 5 minute resolution; (ii) more and better sub-national (population) data (Klein Goldewijk, 2005) to improve the historical (urban and rural) population maps as one of the major driving forces for allocation of land cover; (iii) updated historical land-cover data for the period 1700 – 2000; (iv) implementation of different allocation algorithms with time-dependent weighting maps for cropland and grassland used for livestock.

This study presents a revision and extension of the HYDE 3.0 version. This HYDE 3.1 is an updated and internally consistent combination of historical population estimates and also the implementation of improved allocation algorithms with time-dependent weighting maps for cropland and grassland, while the period covered now is extended to the period from 10 000 BC to AD 2000.

3.2 Methodology and data

Input data for population

Human population growth can be regarded as the main driving force of global change over time. Therefore, it is crucial to get a good insight of the demographic developments of the past. Historical population numbers of McEvedy & Jones (1978), Livi-Bacci (2007), and Maddison (2001) form the basis of our national historical population estimates. Supplemented with the sub-national population numbers of Populstat (Lahmeyer, 2004) and many other sources, time series were constructed for each province or state of every country of the world. For simplicity reasons, current administrative units were kept constant over time, and every historical source was adjusted to match the current boundaries of HYDE 3.1 (i.e. by taking fractions of former larger administrative units). Spatial patterns were obtained by using weighing maps based on the population density map patterns of Landscan (2006) for current time periods, and gradually replacing them with weighing maps based on proxies such as distance to water and soil suitability when going back in time. See for a full description of the methodology in Klein Goldewijk *et al* (2010).

Global population increased from 2 to 6,145 million people from 10 000 BC to AD 2000, resulting in a global population density increase of < 0.1 cap km^{-2} to almost 46 cap km^{-2} and a urban built-up area evolving from almost zero to 0.5 million km^{2}, still only <0.5% of the total global land surface (Klein Goldewijk *et al.*, 2010) It is clear that this demand of food, services, and building materials has had profound impact on the Earth's environment through deforestation and conversion of land cover.

Input data for land use from historical statistics

Country totals for cropland and pasture

Starting point are the country totals for cropland and pasture from the FAO (2008), who present data for the post-1961 period on a country basis. Divided by the country population it yields a per capita use of cropland and pasture. For the pre-1960 period a following approach was used. We assumed that the per capita values for cropland and pasture are not constant, but slightly increase or decrease over time. The 1960 value is rather on the low side for many countries since population numbers have exploded after 1950 and have lowered the per capita numbers considerable. However, when going further back in time, population numbers were lower which increased the cropland and pasture areas per capita again, but they are ceiled by the lack of technology and thus limited the maximum amount of land that a subsistent farmer could handle. By estimating country by country the per capita use of cropland and pasture we derived the historical pathways of agricultural areas, see table 2 for the totals, and Supplementary material tables ST2 and ST3 for the per capita estimates.

Satellite maps

For a representation of current land cover we use the 5 by 5 minute resolution current global cropland and grassland maps developed by Klein Goldewijk *et al.* (2006). These maps were based on satellite data from the DISCover version 2 data using the IGBP classification map (Loveland *et al.*, 2000) and the Global Land Cover (GLC) based on the Global Land Cover 2000 VEGA2000 data (Bartholome *et al.*, 2002), combined with national land-use statistics (FAO, 2007) and sub-national land-use data for U.S.A. (USDA, 2006) and China (China National Bureau of Statistics, 2006a; China National Bureau of Statistics, 2006b). This current land cover map is used as an weighing map (*Wcrop_satellite).*

Allocation of land use

Cropland

The method to allocate historical cropland is carried out for each grid cell of 5' by 5' grid cell (ca 85 km^2 around the equator). For allocating historical cropland six major assumptions were made: (i) in urban builtup areas (*Uarea*) no allocation was allowed (no space left for agriculture); (ii) in areas with population density (*Wpopd*) lower than 0.1 cap km^{-2} no allocation was allowed (no need for agriculture); (iii) land with highest soil suitability for crops is colonized first (*Wsuit*); we used the Global Agro-Ecological Zones map (GAEZ) of FAO-IIASA for this (GAEZ, 2000) (iv) coastal areas and river plains are more favorable for early settlement as being easily accessible (*Wriver*); (v) steep terrain with high slopes are less attractive for settlement and agriculture (*Wslope*); (vi) below the threshold an annual mean temperature of 0 ^{o}C no agricultural activity is assumed (*Wtemp_crop*). These assumptions result in weighing maps that were normalized between 0 and 1 and multiplied to construct a final, unique weighing map for each time step.

(Sub-)national crop area statistics are allocated to grid cells according to a mix of two weighing maps; a current one which was constructed from a satellite map of the year 2000 for cropland (*Wcrop_satellite)* (Klein Goldewijk *et al.*, 2006), and a historical one, which is constructed according to the six rules as described in the former paragraph. The influence of the satellite map increases gradually from 10 000 BC to AD 2000 until it completely dominated the historical weighing map, i.e. until the cropland distribution equals the satellite map distribution (present situation).

Cropland is allocated by combining historical cropland area statistics from HYDE with the various weighing maps:

Current weighing map for allocation:

$$Wcrop_{2000} = Wsatellite_{2000} \tag{1}$$

Historical weighing maps for allocation:

$$Wcrop_{t} = Warea_{t}\ Wpop_{,t}\ Wsuit\ Wriver\ Wslope\ Wtemp\_crop \tag{2}$$

where

$$Warea_{t} = [Garea - Uarea_{t}] / Garea_{max} \tag{3}$$

Garea is the total land area (no ice and snow), $Uarea_t$ the urban builtup area for year *t*, $GAREA_{max}$ is the maximum area of a 5' grid cell. See Supplementary Figure SF1 for the cropland allocation scheme. Note that only *Warea* and *Wpopd* is changing over time.

Pasture

The method to allocate historical pasture is similar to the procedure for cropland, except that on top of area and population, other weighing maps were used (natural herbaceous areas as defined by the BIOME model (Prentice *et al.*, 1992) are more attractive for use of livestock/pastoral activities then other land cover classes (*Wbiome*); and a different temperature map below of -10° C, *Wtemp_pasture*).

Allocation is as follows:

$$Wpasture_t = Warea_t \; Wpopd_t \; Wbiome \; Wtemp\_pasture \qquad (4)$$

where

$$Warea_t = [Garea_t - Uarea_t - Carea_t] / Garea_{max} \qquad (5)$$

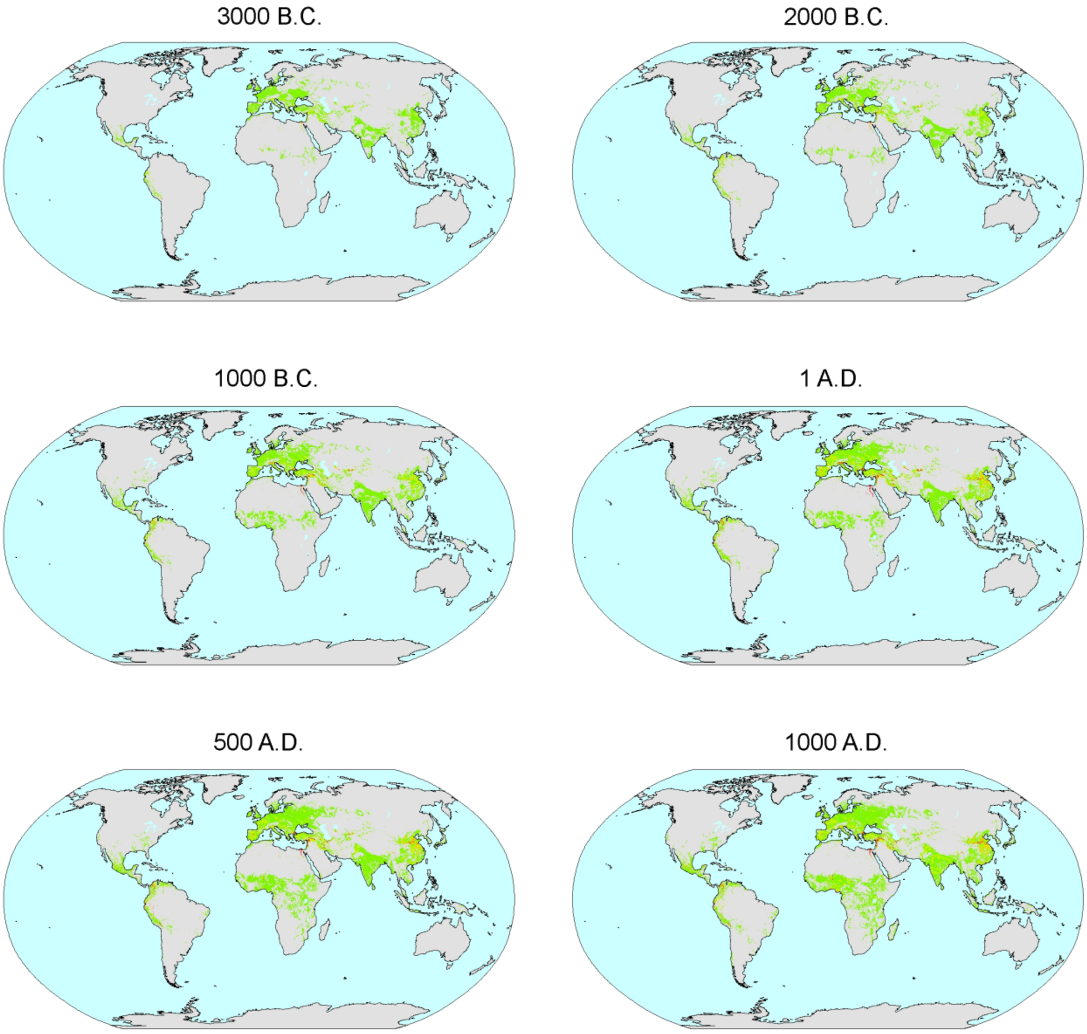
$Carea_t$, is the area occupied by cropland on year *t*. See Supplementary Figure SF2 for the pasture allocation scheme.

3.3 Results

We have constructed historical maps cropland and pasture for a 12 000 year period, on a 5 by 5 minute grid resolution. The development of agriculture was rather limited at the start of the Holocene. From the early hunters/gatherers stage, agriculture slowly emerged after the domestication of plants and animals. Sedentary agriculture was almost non-existent during that time. During that period humans began to domesticate plants and animals, at various places around the world and over different times (Vavilov, 1926).

During the Neolithic Era – Stone/Iron/Bronze Era population numbers were very low, the HYDE 3.1 estimate for 10 000 BC of 2 million is within the range found in literature of 1-20 million with most estimates below 6 million (Klein Goldewijk *et al.*, 2010). Population numbers then slowly increased to 18 (range 5-24) million in 5000 BC We estimate the global cropland area at 5000 BC at a very modest 0.03 million km^2 and pasture to be around 0.003 million km^2. This yields a 0.24 ha cropland cap^{-1} and 0.02 ha cap^{-1} of pasture (table 2). Due to a lack of technology, agriculture was sensitive to climate (change). See figures 1 and 2 for a spatial representation of the spread of agriculture over time.

Agriculture became more developed towards the Greek and Roman Era's. It was already more widespread throughout the Mediterranean, Northern India and in Eastern China, where highly developed irrigation schemes already existed. Klein Goldewijk (2010) estimated global population in AD 1 around 188 million people (range 170-330), and very cautiously we estimate the global cropland area to be near 1.3 million km^2 during that time, while the pasture area is estimated around 1.1 million km^2 (see table 1 and 2) corresponding to 0.52 ha cropland cap^{-1} and 0.56 ha pasture cap^{-1} respectively.



3000 B.C.

2000 B.C.

1000 B.C.

1 A.D.

500 A.D.

1000 A.D.

Figure 1. Historical cropland area, 3000 BC to AD 1000.

After the rise and fall of the Greek and Roman Empires, population growth remained low and fluctuated for quite some centuries. Europe gradually faded into the Dark Middle Ages where technological developments almost came to a halt, also tempered by the invasions of the Barbarians, the Huns, and the Mongols. Large scale pandemics such as de Black Plague also reduced population numbers severely in many parts of the old world. This decimation of the population led to large scale abandonment of agricultural land and subsequently to a substantial gain of forest in Europe, see the example of Germany after the bubonic plague in early 15th century (Bork *et al.*, 1998; Bork & Lang, 2003).

This was not the case in China, where ancient rice cultivation techniques were perfected to sustain relative high population densities, but developments there did not spread widely because it became more and more an inward-looking Empire, plagued by internal warfare and famines (Liu & Hwang, 1979).

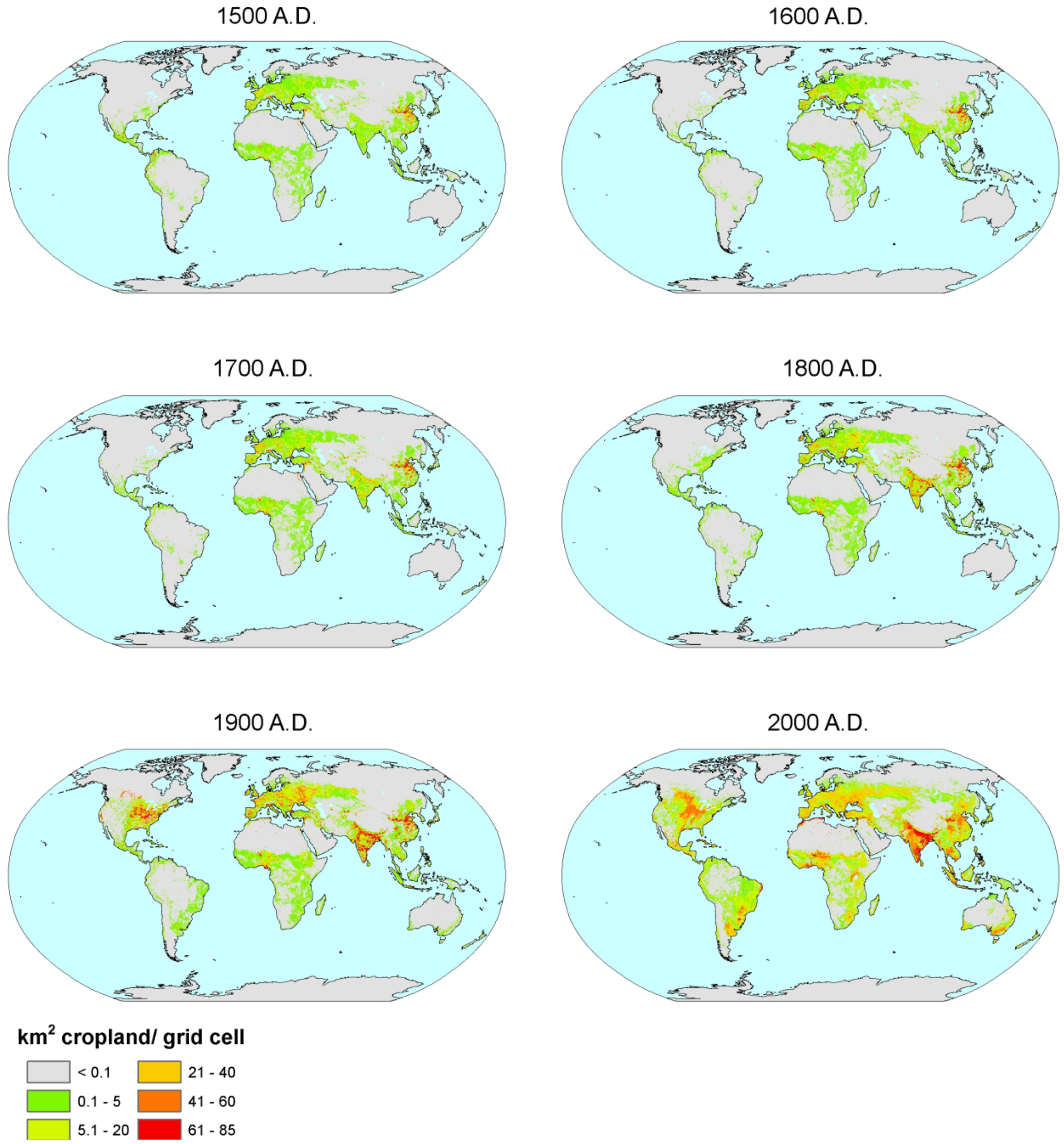


Figure 1. Historical cropland area continued, AD 1500–2000.

In contrast of Europe, the Middle and Late Middle Ages (AD 500 – AD 1600) were the peak of the Central America civilizations (the Maya's, Aztecs, Inca's), with evidence becoming available of regions with very high population densities indeed, supported with a range of agricultural activities and elaborate trade routes (Culbert, 1988; Etter & Van Wyngaarden, 2000; Nevle & Bird, 2008). This resulted in well developed agricultural systems with large supplying backcountries (DeMenocal, 2001). Remarkable is the fact that before the arrival of the Europeans late 15th century, there was no pasture in the Americas, since they were responsible for introducing horses and cattle on the continent. Supplementary figures SF3 and SF4 depict the changes over time.

All these continental differences can be summarized in a global population of 210 million in AD500, and 295 million in AD1000. Until AD 1400 numbers remained below the 400 million mark, and at the end of the Dark Ages population growth gained momentum again. Global population numbers increased to 555 million in AD 1600 (lit. range 545-578 million). The accompanying areas are estimated to be 1.2 million km^2 cropland and 1.1 million km^2 pasture in AD 500 (0.43 ha cropland cap^{-1} and 0.51 ha pasture cap^{-1}), 1.5 million km^2 cropland and 1.4 million km^2 pasture in AD 1000 (0.36 ha cropland cap^{-1} and 0.48 ha pasture cap^{-1}) and finally 2.3 million km^2 cropland in AD 1500 and 2.2 million km^2 pasture (0.33 ha cropland cap^{-1} and 0.49 ha pasture cap^{-1}). Our cropland and pasture estimates for AD 1100 are 0.2 million km^2 and 0.3 million km^2 lower resp. than Pongratz *et al* (2008), but our AD 1500 estimates are similar, due to a different, more conservative per capita approach in this study. See table 1 and for the spatial distribution patterns in figure 1 and 2, and summary tables 2 and 3, and for a graphical presentation supplementary figure SF3 and SF4.

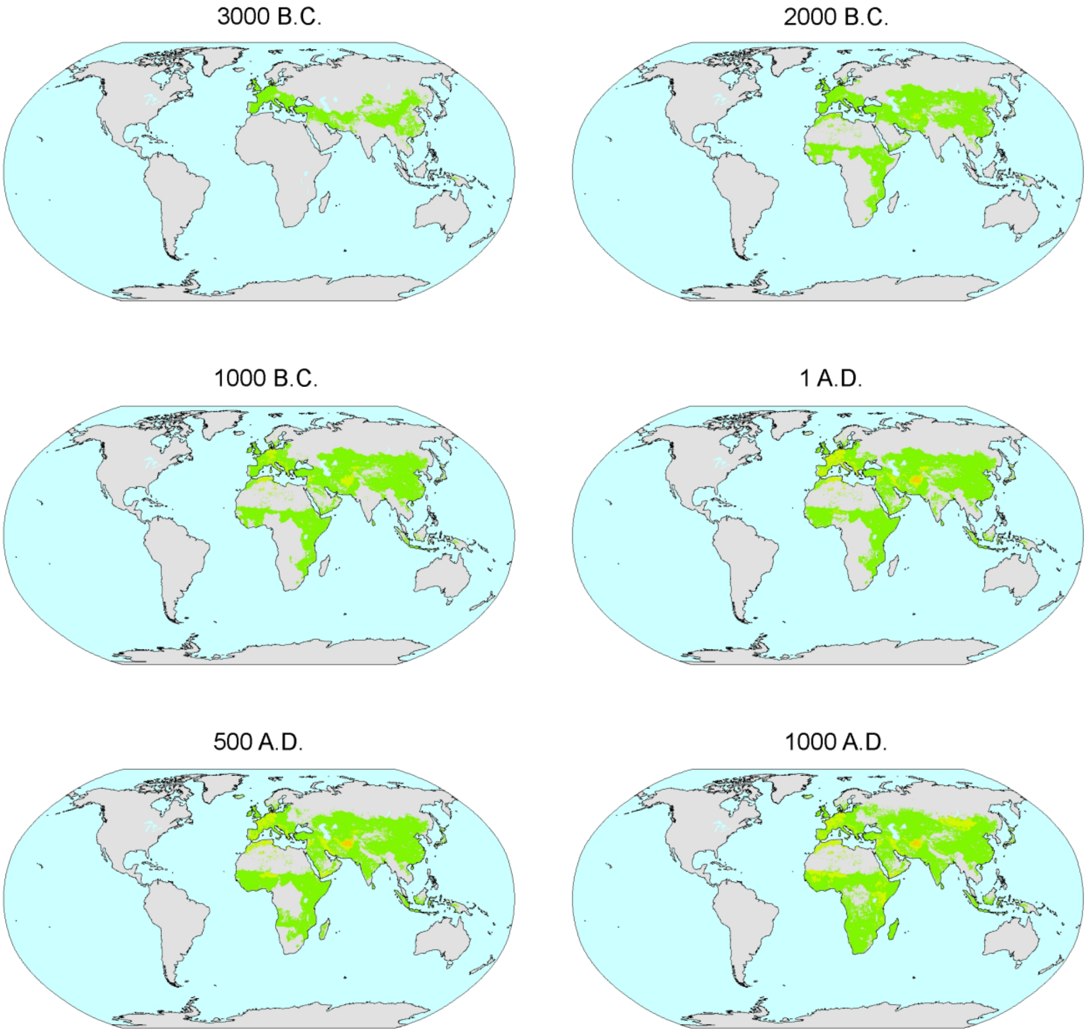


Figure 2. Historical pasture area, 3000 BC to AD 1000.

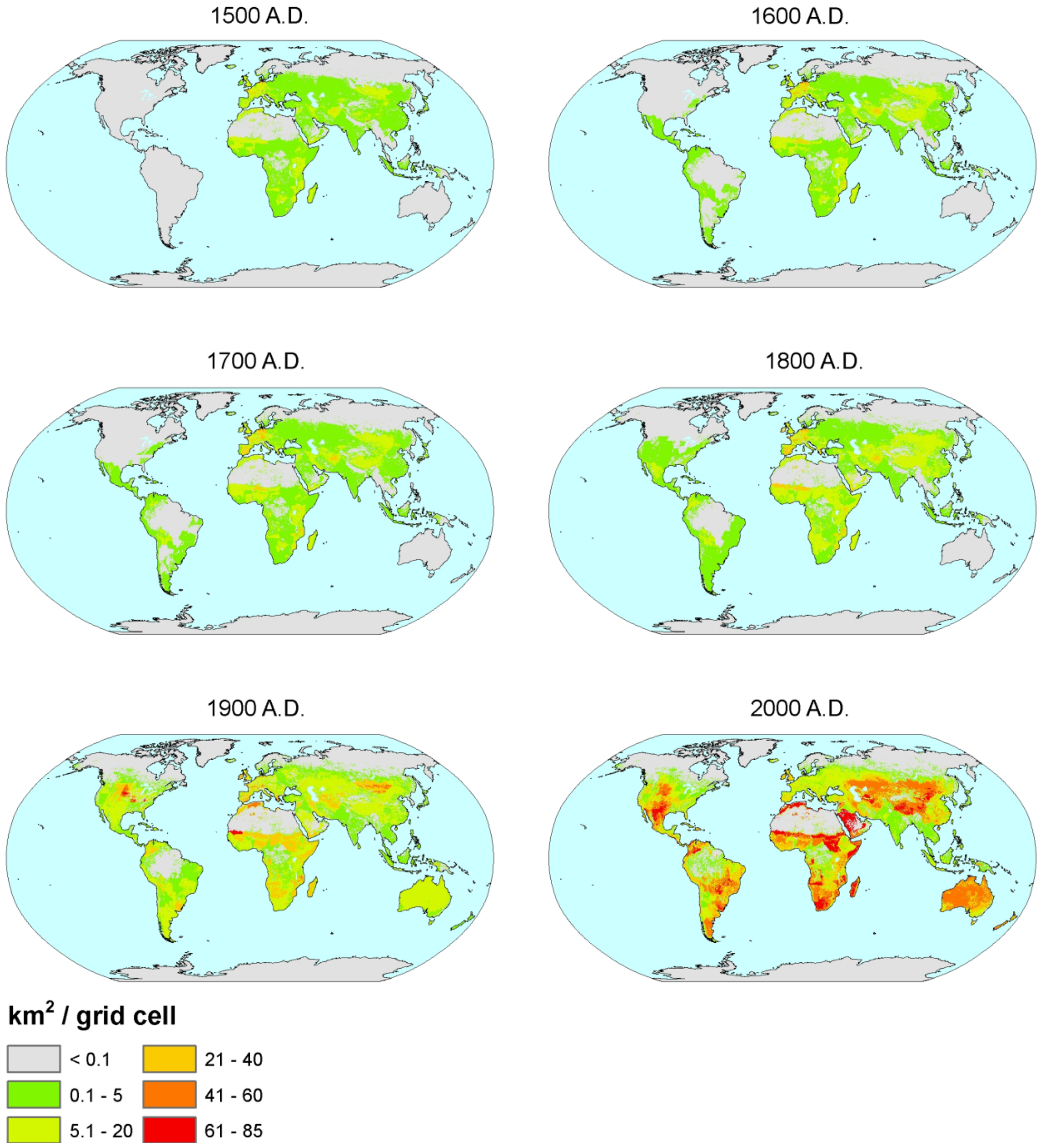


Figure 2. Historical pasture area continued, AD 1500–2000.

An important point in history was the decisive increase in world population took place after AD 1600. The start of the Industrial Revolution resulted in the colonization by Europeans of the Americas, Australia, and later Africa. This was accompanied by a rigorous agricultural expansion, first in the temperate hemisphere, later in the tropics as well (see figures 3 and 4). In 1800 global population reached the 1 billion point, 1,658 million in 1900 and 2,520 in 1950. Population numbers really exploded after WWII to 3,681 million in 1970 and 6,096 million in 2000 (Klein Goldewijk, 2005; Klein Goldewijk *et al.*, 2010). Technology also leaped, needed to feed all these people by means of agricultural optimalisation such as the use of artificial fertilizer, mechanization, the green revolution, irrigation, etc.

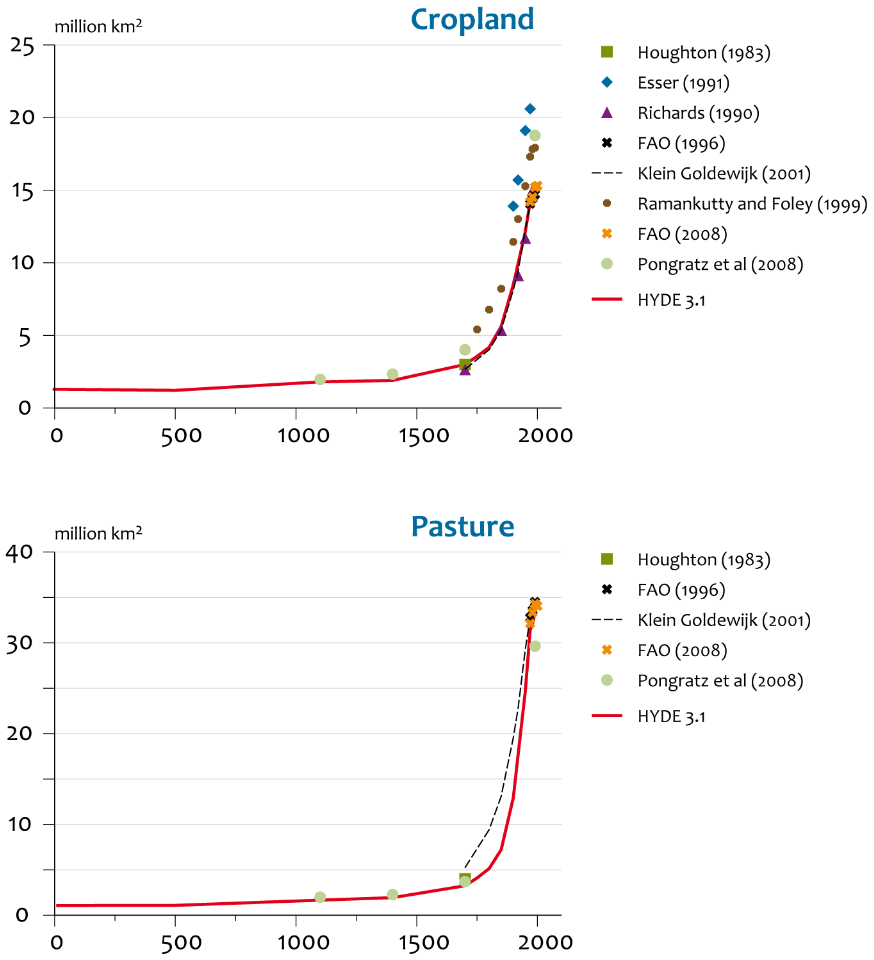


Figure 3 Overview of historical land-use estimates.

As result of this enormous population and technology growth the total global area of cropland area almost doubled every century after the 16th century from 3.0 million km^2 in 1700, to 4.2 million km^2 in 1800, 8.5 million km^2 in 1900 and 15.3 million km^2 in 2000. Pongratz (2008) and Ramankutty and Foley (1999) estimated a higher value of 4 million km^2 for 1700, probably due to the fact that their starting point for hind-casting in 1990 was already higher than the FAO, due to the implementation of non-FAO national statistics (Pongratz *et al.*, 2008). See also table 1 for comparison with other estimates and figure 3 for a graphical representation.

Our computed global pastured area increased from 3.2 million km^2 in 1700, to 5.1 million km^2 in 1800, then accelerated to 12.9 million km^2 in 1900 and finally reached 34.1 million km^2 in 2000. Although Pongratz (2008) adopted a different approach, they estimated for 1700 3.7 million km^2 , similar to this study. One has to be careful when comparing our results with other studies, because several studies have used (partly) HYDE data as input and rely also on the same population data from McEvedy and Jones (1978).

Globally, the area of cropland per capita increased until AD 1 to a maximum of 0.52 ha cap^{-1}, then it slowly decreased, with a temporarily increase in the 19th century due to a large global agricultural expansion but after 1950 it decreases again, because of a huge population growth, to 0.16 ha cap^{-1} in 2000. Technology apparently could simply not compensate entirely for this explosive population growth, and since the best suited soils are already in use, it continues to decrease. A similar trend can be detected for pasture, although the trend for pasture area per capita first increased until 1960 (a peak of almost 0.90 ha cap^{-1}) and, then decreasing to 0.55 ha cap^{-1} in 2000 (Table 2).

Uncertainties

Obviously, there are large and many uncertainties attached to hindcast attempts such as this study. We heavily leaned on historical population sources such as McEvedy and Jones (1978) and Livi-Bacci (2007) and especially for the pre-1700 period the numbers have to be treated with care. However, when looking at the growth rates it seems not to be unfair and rather acceptable as a reasonable reconstruction of historical population trends (Klein Goldewijk *et al.*, 2010).

The same (and indeed with much more uncertainties) applies to the different land use estimates. Starting with FAO numbers, although regarded as authorative but yet disputed for some countries even for the present day, the hindcasting technique by using per capita numbers seems a reasonable assumption. The magnitude of those per capita numbers however, is rather uncertain and will differ quite a lot per country and over time. The only thing we can assume when going back in time is that there is an absolute minimum (zero, people die) and a maximum area per capita which can be regarded as being feasible of what could one person handle without hardly any technology, “there only so much a man can do in a day’s hard work” (Williams, 2000).

We have estimated also a lower and upper land use scenario on the basis of an uncertainty range applied on top on the ‘baseline’ cropland and pasture per capita estimates. The uncertainty ranges were based on literature and our own judgment, and should be treated with care. The uncertainty is roughly estimated at being 5% in 2000, 10% in 1900, 25% in AD 1800, 50% in AD 1 and 75% in 10 000 BC The years in between were linear interpolated. See supplementary tables ST2 and ST3 for a original input data for the baseline variant. A global summary of the resulting cropland and pasture areas is presented in table 2 and 3. A regional summary of cropland, pasture, population, per capita cropland area and per capita pasture area is presented in supplementary table ST4, and table ST5 presents the resulting cropland areas for the different per capita scenarios, and table ST6 for pasture.

Furthermore, by absence of transient Holocene climate and vegetation maps we simplified it by using weighing maps for current climate and biome. Although the climate in 10 000 BC was certainly not the same then in the present day (Bertrand & Van Ypersele, 2002; Verschuren *et al.*, 2002; Tett *et al.*, 2005; Kropelin *et al.*, 2008; Armesto *et al.*, 2009), we believe that the lower temperature thresholds we used are still valid, especially because we use them only as one of the factors for allocation, not *the* factor. A similar reason can be given for the biome map. We acknowledge that the Sahara was a savanna type region in the pre 5 000 BC era (Verschuren *et al.*, 2000), and rapidly changed towards the current desert state ever since, but since it was hardly populated and thus there was ample agriculture in that region, we decided to let our allocation procedure unchanged during that era.

Please note that this study is not computing deforestation rates, but only expansion of agricultural land. Overlaying these rates with different natural land cover datasets will yield different deforestation rates, while processes such as logging and shifting cultivation are not considered here.

3.4 Concluding remarks

With a growing need for policymakers to gain more insight in the global change debate, there is a huge pressure for researchers to provide answers. Although the latest Intergovernmental Panel on Climate Change (IPCC) reports revealed lots of new insights and facts about the Earth system, there are still many uncertainties and gaps in our knowledge. We hope that this study can help modelers to close parts of this gap.

The internally consistent HYDE 3.1 database may support studies which investigate the long term relationships between the global environment and the atmosphere. The global (climate) change community already use results of the combined HYDE - IMAGE framework (Bouwman *et al.*, 2006) which provides consistent land use times series on a 0.5 degree lat/lon grid for AD 1500 till 2100. Combined with other assumptions it serves as input for global change modeling exercises for the 5th Assessment Report of the IPCC (Hurtt *et al.*, 2006; Hurtt *et al.*, 2009), demonstrating the usefulness of such a database.

Human impact across space and time is acknowledged by ecologists and macroecologists as an important factor by disturbing ecological processes and creating new biodiversity patterns. Nogues-Bravo (2008) for example, suggests the huge impact of avoiding humans in ecological research. However, in general it is still not properly implemented in Macroecological research, which on its turn influences the scientific debate and understanding of biodiversity patterns/processes. In potential this database could help to assess the driving factors of biodiversity patterns.

It will be interesting to see whether the proposed theories as stated by (Crutzen, 2002) and (Ruddiman, 2003; Ruddiman, 2006) can be tested by the latest state-of-the-art Earth System Models. The start of the Anthropocene (defined here as the first signal of mankind changing the atmosphere) and the magnitude of the change are crucial for further understanding of the complex climate system of the world. Arguably, the start of the Anthropocene period was much earlier than the start of the Industrial Revolution, but future experiments with HYDE 3.1 and EMICs will have to make clear whether and when this could have been the case.

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Supporting information

Additional information may be found in the online version of the article, and see also ftp://ftp.pbl.nl/hyde/supplementary/landuse

Supplementary Table ST1	Temporal and spatial overview different historical land cover/land use studies (Excel file)
Supplementary Table ST2	Historical total and per capita estimates for cropland (baseline, lower and upper variant) (Excel file)
Supplementary Table ST3	Historical total and per capita estimates for pasture (baseline, lower and upper variant) (Excel file)
Supplementary Table ST4	Regional summary HYDE 3.1 land use estimates for 10000 BC - 2000 (or 10k BC – 2k AD) Excel file)
Supplementary Table ST5	Regional cropland areas 10k BC - 2k AD (this study, different scenarios, in million km^2) (Excel file)
Supplementary Table ST6	Regional pasture areas 10k BC - 2k AD (this study, different scenarios, in million km^2) (Excel file)
Supplementary Table ST7	Lower, baseline and upper land use variants of HYDE 3.1 (this study, baseline, in million km^2) (Excel file)

Supplementary Figure SF1	Cropland allocation scheme (Acrobat file)
Supplementary Figure SF2	Pasture allocation scheme (Acrobat file)
Supplementary Figure SF3	Global estimates of cropland, different scenarios
Supplementary Figure SF4	Global estimates of pasture, different scenarios

Biosketch

This research was conducted by members of the Netherlands Environmental Assessment Agency, as part of an attempt to create a consistent database of long term historical global land use for integrated modeling of global change. The team was lead by K.K.G, who conceived the initial idea and lead the writing, G.v.D and M.d.V helped with the technical setup of the database, A.B helped with the analysis. All authors contributed to the analysis and to the revision of the manuscript.
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