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RESEARCH PAPER

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

Aim 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.

Methods Historical population, cropland and pasture statistics are combined with satellite information and specific allocation algorithms (which change over time) to create spatially explicit maps, which are fully consistent on a 5′ longitude/latitude grid resolution, and cover the period 10,000 BC to AD 2000.

Results Cropland occupied roughly less than 1% of the global ice-free land area for a long time until AD 1000, similar to the area used for pasture. In the centuries that followed, the share of global cropland increased to 2% in AD 1700 (*c.* 3 million km^2) and 11% in AD 2000 (15 million km^2), while the share of pasture area grew from 2% in AD 1700 to 24% in AD 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.

Main conclusions Some researchers suggest that humans have shifted from living in the Holocene (emergence of agriculture) into the Anthropocene (humans capable of changing the Earth's 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 Death 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 modellers to close parts of this gap.

Keywords

Agricultural development, cropland, DGVM, EMIC, ESM, historical population, human impact, IPCC, land use, pasture.

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INTRODUCTION

Imagine the evolution of the Earth taking place in 1 day: humankind has only been present on this planet since a few minutes to midnight, yet still we managed to obtain dominance over the world in that short time. Already more than 30% of the world's landscape is under some sort of development (agriculture), another 30% is more or less influenced and many natural resources are heavily used or even depleted (Foley *et al.*, 2005). 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 occurred. A key question is: how did this come so far?

As long as humans have been present on 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 increase in carbon dioxide (CO_2) in the atmosphere. Although estimates of

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historical CO_2 emissions from land-use changes are uncertain (Ruddiman, 2003), most studies (DeFries *et al.*, 1999; Houghton, 1999, 2003; McGuire *et al.*, 2001; Pacala *et al.*, 2001) indicate that land-use change is an important net source of CO_2, causing global emissions of 1.4 (0.4–2.3) Pg C year^{-1} (Pg, petagram; 1 Pg = 10^{15} g) of carbon (C) for the 1980s and 1.6 (0.5–2.7) Pg C year^{-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 C year^{-1} during the 1980s and −2.6 Pg C year^{-1} for the 1990s, the terrestrial part of the Earth is currently a carbon sink, but this has not always been the case, and probably will not continue to be so in the future (Le Quéré *et al.*, 2009).

The general circulation models (GCMs) 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 model (ESM) and ESMs of intermediate complexity (EMICs; see Brovkin *et al.*, 2006) have emerged. These EMICs are able to investigate the transient response of the climate system to different climate forcings on a much longer time-scale than GCMs are capable of, by being more computationally efficient without losing critical land–climate interactions. Simulations with historical land-cover forcing in 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 °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, 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 macroecology, helping us to understand the past dynamics of geographical ranges and species-specific niches (Nogués-Bravo, 2009), determine the gain or loss in global biodiversity (e.g. Gaston *et al.*, 2003; Gaston, 2006) or explore the human impact on several biodiversity issues (e.g. Cincotta *et al.*, 2000; Goudie, 2006). It is critical that the land-use/land-cover information is available at a sufficient level, spatially as well as temporally.

In general two approaches can be distinguished for global historical land-use/land-cover inventories.

1. Modelling with so-called dynamic global vegetation models (DGVMs), which explicitly represent the interaction between the ecosystem carbon 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.

2. Historical land-cover datasets based on statistical information. A number of historical land-use datasets have been prepared on the basis of statistics at the subnational 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 *et al.*, 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 for 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 International Geosphere–Biosphere Programme (IGBP) 1-km resolution global land-cover classification (GLCC) dataset against cropland inventory data for 1992 to create a global map of cultivated land for 1992. Subsequently, they used a 'hindcast' modelling technique to extrapolate these data, using a compilation of historical cropland inventory data to create a spatial dataset of croplands for the period AD 1700–1992 (Ramankutty & Foley, 1999). Others used a book-keeping model with conversion rates of different land-cover types (including cropland and pasture) to estimate carbon fluxes (Houghton *et al.*, 1983; Richards, 1990; Houghton, 1999; Houghton & Hackler, 2001). Pongratz *et al.* (2008) reconstructed agricultural areas for the last millennium from AD 800 to 1992 (see Table S1 in Supporting Information for details on the different approaches).

The original HYDE 2 database (Klein Goldewijk, 2001) was a consistent dataset of historical land-use and land-cover data of the 20th century on a spatial resolution of 0.5° × 0.5°. 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 AD 1890–1990 and, where available, for AD 1700–2000.

An update of HYDE 2 was presented in Klein Goldewijk & van Drecht (2006). HYDE 3.0 included several improvements compared with its predecessor: (1) the HYDE 2 version used a Boolean approach with a 30′ resolution, while HYDE 3.0 used fractional land use on a 5′ resolution; (2) more and better subnational (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; (3) updated historical land-cover data for the period AD 1700–2000; (4) 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 HYDE 3.0. This version, HYDE 3.1, is an updated and internally consistent

Table 1 Global cropland and pasture estimates for 10,000 BC to AD 2000, different studies (in million km^2).

Cropland	10,000 BC	AD 1	AD 500	AD 1100	AD 1400	AD 1700	AD 1750	AD 1800	AD 1850	AD 1900	AD 1920	AD 1950	AD 1970	AD 1980	AD 1990	AD 2000
Houghton *et al.* (1983)						3.0										
Esser (1991)										13.9	15.7	19.1	20.6			
Richards (1990)						2.7			5.4		9.1	11.7		15.0		
FAO (1996)													14.1	14.4	14.7	
Klein Goldewijk (2001)						2.7		4.0	5.4	8.1	9.4	12.3	14.1	14.4	14.7	
Ramankutty and Foley (1999)						4.1	5.4	6.8	8.2	11.4	13.0	15.3	17.3	17.8	17.9	
FAO (2008)													14.2	14.5	15.2	15.3
Pongratz *et al.* (2008)*				2.0	2.3	4.0									18.8	
HYDE 3.1	0.0	1.3	1.2	1.8	1.9	3.0	3.6	4.2	5.6	8.5	9.9	12.1	14.2	14.5	15.2	15.3
HYDE 3.1 (% of global land area)	0.0%	0.9%	0.8%	1.2%	1.3%	2.1%	2.5%	2.9%	3.9%	5.9%	6.9%	8.4%	9.8%	10.0%	10.5%	10.6%
Pasture	**10,000 BC**	**AD 1**	**AD 500**	**AD 1100**	**AD 1400**	**AD 1700**	**AD 1750**	**AD 1800**	**AD 1850**	**AD 1900**	**AD 1920**	**AD 1950**	**AD 1970**	**AD 1980**	**AD 1990**	**AD 2000**
Houghton *et al.* (1983)						4.0										
FAO (1996)													32.8	33.6	34.5	
Klein Goldewijk (2001)						5.2		9.4	13.1	19.6	22.8	29.3	32.8	33.6	34.5	
FAO (2008)													32.1	33.4	34.3	34.1
Pongratz *et al.* (2008)*				2.0	2.3	3.7									29.6	
HYDE 3.1	0.0	1.1	1.1	1.7	1.9	3.2	4.1	5.1	7.2	12.9	17.7	24.7	31.4	32.1	33.4	34.3
HYDE 3.1 (% of global land area)	0.0%	0.8%	0.8%	1.2%	1.4%	2.3%	2.9%	3.6%	5.1%	9.2%	12.5%	17.5%	22.3%	22.8%	23.7%	24.3%

*Pongratz *et al.* presented values for AD 1100, 1400, 1700 and 1992, respectively.

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 extended to 10,000 BC to AD 2000.

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 into the demographic developments of the past. Historical population numbers from McEvedy & Jones (1978), Livi-Bacci (2007) and Maddison (2001) form the basis of our national historical population estimates. Supplemented with the subnational 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 reasons of simplicity, 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 Klein Goldewijk *et al.* (2009) for a full description of the methodology.

Global population increased from 2 to 6145 million people from 10,000 BC to AD 2000, resulting in a global population density increase of < 0.1 person km^{-2} to almost 46 persons 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.*, 2009). It is clear that this demand for food, services and building materials has had a 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 points are the country totals for cropland and pasture from FAO (2008), which presents data for the post-1961 period on a country basis. Divided by the country's population it yields a per capita use of cropland and pasture. For the pre-1960 period the 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 exploded after 1950 and have lowered the per capita numbers considerably. However, when going further back in time, population numbers were lower, which increased the cropland and pasture areas per capita again, but they are limited by the lack of technology and thus limited to the maximum amount of land that a subsistence 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 Tables S2 & S3 for the per capita estimates.

Satellite maps

For a representation of current land cover we use the 5′ × 5′ 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 (Bartholomé *et al.*, 2002), combined with national land-use statistics (FAO, 2007) and subnational land-use data for the USA (USDA, 2006) and China (China National Bureau of Statistics, 2006a,b). This current land-cover map is used as a weighing map (*Wcrop_satellite*).

Allocation of land use

Cropland

The method for allocating historical cropland is carried out for each 5′ × 5′ grid cell (*c.* 85 km^2 around the equator). For allocating historical cropland, six major assumptions were made: (1) in urban built-up areas (*Uarea*), no allocation was allowed (no space left for agriculture); (2) in areas with population density (*Wpopd*) lower than 0.1 person km^{-2}, no allocation was allowed (no need for agriculture); (3) land with the highest soil suitability for crops is colonized first (*Wsuit*) – we used the global agro-ecological zones (GAEZ) map of FAO-IIASA for this (GAEZ, 2000); (4) coastal areas and river plains are more favourable for early settlement as being easily accessible (*Wriver*); (5) steep terrain with high slopes is less attractive for settlement and agriculture (*Wslope*); (6) below the threshold of an annual mean temperature of 0 °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 map, which was constructed from a satellite map of AD 2000 for cropland (*Wcrop_satellite*) (Klein Goldewijk *et al.*, 2006), and a historical one, which was constructed according to the six rules as described in the previous paragraph. The influence of the satellite map increases gradually from 10,000 BC to AD 2000 until it completely dominates 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.

1. Current weighing map for allocation:

$$Wcrop_{2000} = Wsatellite_{2000}. \qquad (1)$$

2. Historical weighing maps for allocation:

$$Wcrop_t = Warea_t\ Wpop_{,t}\ Wsuit\ Wriver\ Wslope\ Wtemp\_crop \qquad (2)$$

where

Table 2 Global cropland and pasture area estimates for 10,000 BC to AD 2000, this study (baseline, in million km^2).

	Unit	10,000 BC	5000 BC	AD 1	AD 500	AD 1000	AD 1500	AD 1600	AD 1700	AD 1800	AD 1900	AD 1950	AD 2000
Cropland	Million km^2	0.000	0.048	1.31	1.24	1.53	2.32	2.55	3.00	4.19	8.50	12.14	15.32
Pasture	Million km^2	0.000	0.004	1.06	1.08	1.43	2.24	2.88	3.24	5.13	12.93	24.66	34.29
Population	Millions	2	18	188	210	295	461	554	603	989	1654	2545	6145
Cropland per capita	ha per capita	0.00	0.24	0.52	0.43	0.36	0.33	0.29	0.30	0.24	0.35	0.33	0.16
Pasture per capita	ha per capita	0.00	0.02	0.56	0.51	0.48	0.49	0.52	0.54	0.52	0.78	0.97	0.55

$$Warea_t = (Garea - Uarea_t)/Garea_{max}. \quad (3)$$

Garea is the total land area (no ice and snow), $Uarea_t$ is the urban built-up area for year t and $GAREA_{max}$ is the maximum area of a 5′ grid cell (see Fig. S1 for the cropland allocation scheme). Note that only *Warea* and *Wpopd* change over time.

Pasture

The method for allocating 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 are defined by the BIOME model (Prentice *et al.*, 1992) as they are more attractive for use of livestock/pastoral activities then other land-cover classes (*Wbiome*); and a different temperature map is used below −10 °C (*Wtemp_pasture*).

Allocation is as follows:

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

where

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

and $Carea_t$, is the area occupied by cropland in year t (see Fig. S2 for the pasture allocation scheme).

RESULTS

We have constructed historical maps of cropland and pasture for a 12,000-year period, on a 5′ × 5′ grid resolution. The development of agriculture was rather limited at the start of the Holocene. From the early hunter–gatherer 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 – the Stone, Iron and Bronze ages – population numbers were very low; the HYDE 3.1 estimate for 10,000 BC of 2 million is within the range found in the literature of 1–20 million with most estimates below 6 million (Klein Goldewijk *et al.*, 2009). 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 0.24 ha of cropland per capita and 0.02 ha of pasture per capita (Table 2). Due to a lack of technology, agriculture was sensitive to climate (change). See Figures 1 & 2 for a spatial representation of the spread of agriculture over time.

Agriculture became more developed in the Greek and Roman eras. It was already more widespread throughout the Mediterranean, northern India and in eastern China, where highly developed irrigation schemes already existed. Klein Goldewijk *et al.* (2009) estimated global population in AD 1 to be around 188 million (range 170–330), and very cautiously we estimate the global cropland area to be near 1.3 million km^2 during that

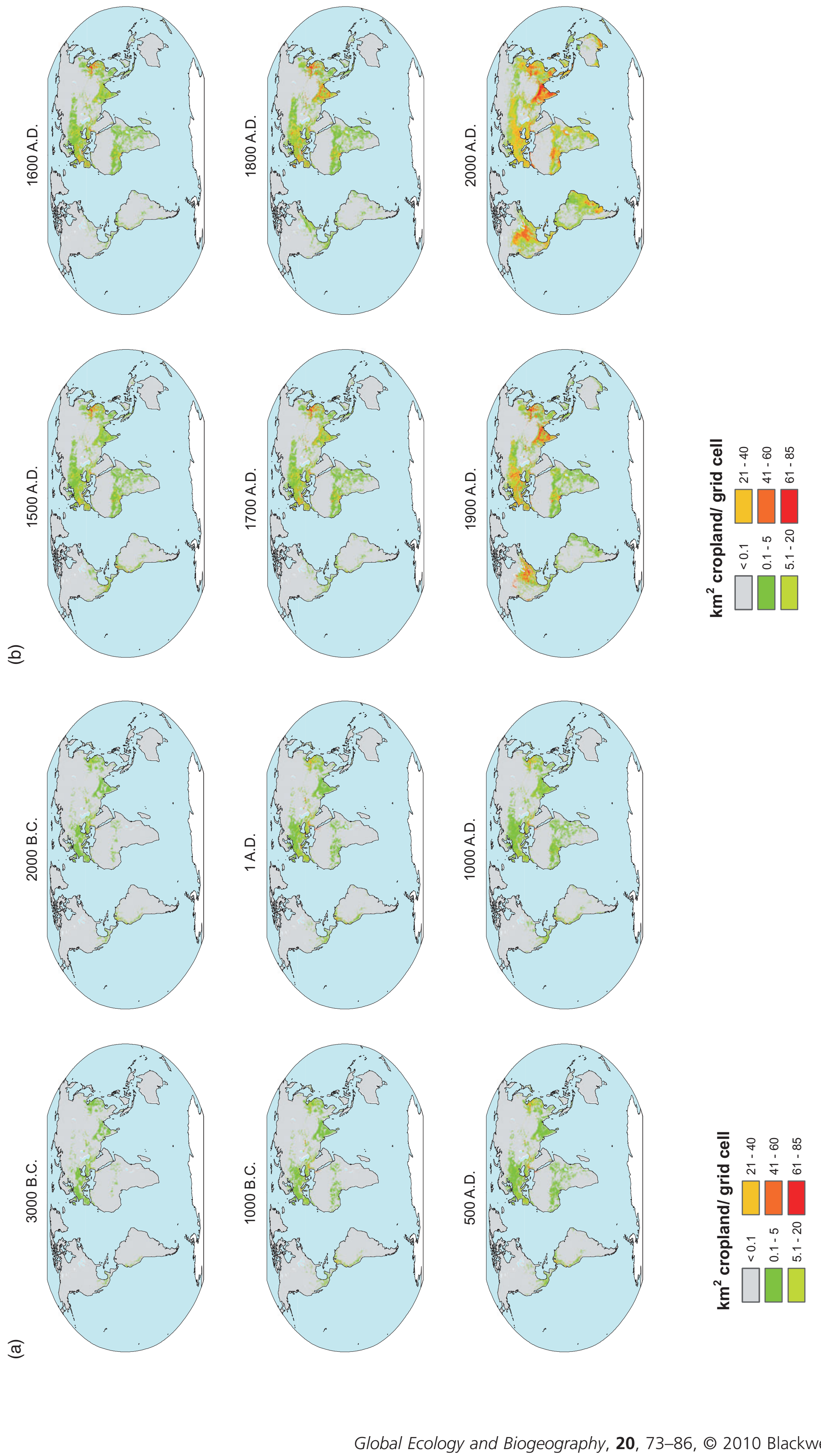

Figure 1 Historical cropland area (a) 3000 BC to AD 1000 and (b) AD 1500–2000.

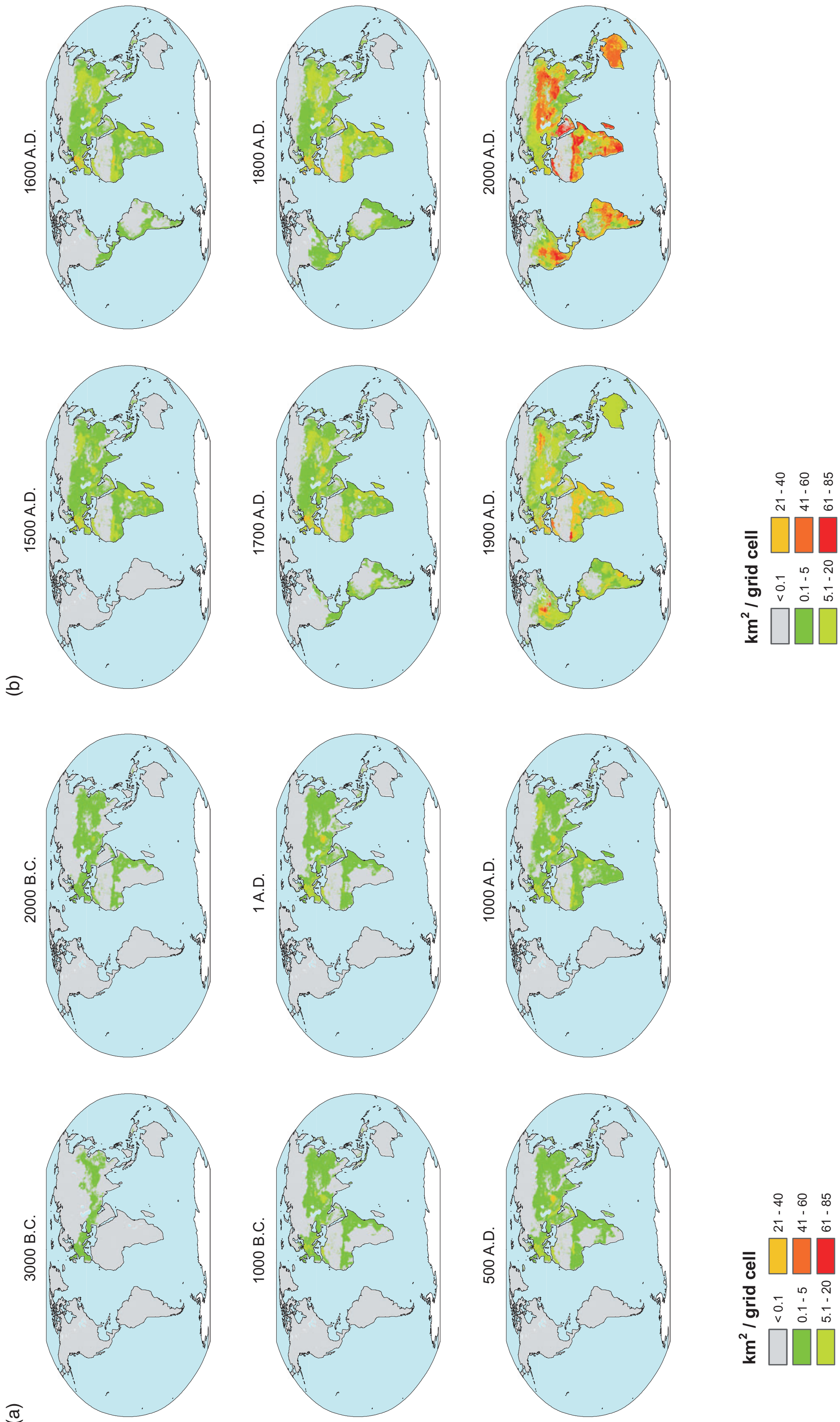

Figure 2 Historical pasture area (a) 3000 BC to AD 1000 and (b) AD 1500–2000.

time, while the pasture area is estimated around 1.1 million km^2 (see Tables 1 & 2) corresponding to 0.52 ha cropland and 0.56 ha pasture per capita, respectively.

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 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 the Black Death 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 relatively high population densities, but developments there did not spread widely because it became a more and more inward-looking empire, plagued by internal warfare and famines (Liu & Hwang, 1979).

In contrast to Europe, the Middle and Late Middle Ages (AD 500–1600) were the peak of the Central American civilizations (Mayas, Aztecs, Incas), 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). It is remarkable that before the arrival of Europeans in the late 15th century there was no pasture in the Americas; Europeans were responsible for introducing horses and cattle to the continent. Figures S3 and S4 depict the changes over time.

All these continental differences can be summarized in a global population of 210 million in AD 500 and 295 million in AD 1000. 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 (literature 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 and 0.51 ha pasture per capita), 1.5 million km^2 cropland and 1.4 million km^2 pasture in AD 1000 (0.36 ha cropland and 0.48 ha pasture per capita) and finally 2.3 million km^2 cropland in AD 1500 and 2.2 million km^2 pasture (0.33 ha cropland and 0.49 ha pasture per capita). Our cropland and pasture estimates for AD 1100 are 0.2 and 0.3 million km^2 lower, respectively, 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 Figs 1 & 2, and Tables 2 and 3, and for a graphical presentation Figs S3 & S4.

An important point in history was the decisive increase in world population that 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 then later in the tropics as well (see Fig. 3). In AD 1800 the global population reached 1000 million (1 billion), 1658 million in AD 1900 and 2520 million in AD 1950. The population really exploded after World War II to 3681 million in AD 1970 and 6096 million in AD 2000 (Klein Goldewijk, 2005; Klein Goldewijk *et al.*, 2009). Technology also leapt in parallel with the need to feed all these people by means of agricultural optimization such as the use of artificial fertilizer, mechanization, the Green Revolution, irrigation, etc.

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

Our computed global pasture area increased from 3.2 million km^2 in AD 1700 to 5.1 million km^2 in AD 1800, then accelerated to 12.9 million km^2 in AD 1900, finally reaching 34.1 million km^2 in AD 2000. Although Pongratz *et al.* (2008) adopted a different approach, they estimated 3.7 million km^2 for AD 1700, 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 & Jones (1978).

Globally, the area of cropland per capita increased until AD 1 to a maximum of 0.52 ha per capita, then it slowly decreased, with a temporary increase in the 19th century due to a large global agricultural expansion. After 1950 it decreased again, because of a huge population growth, to 0.16 ha per capita in AD 2000. Technology apparently could simply not compensate entirely for this explosive population growth, and as 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 per capita) then decreased to 0.55 ha per capita in AD 2000 (Table 2).

Uncertainties

Obviously, there are many and large uncertainties attached to hindcast attempts such as this study. We leaned heavily on historical population sources such as McEvedy & 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 would seem to be rather acceptable as a reasonable reconstruction of historical population trends (Klein Goldewijk *et al.*, 2009).

The same (and indeed with many more uncertainties) applies to the different land-use estimates. Starting with FAO numbers, although regarded as authoritative but still disputed for some countries even for the present day, the hindcasting technique

Table 3 Global historical cropland and pasture estimates; different scenarios (in million km²).

Cropland	10,000 BC	5000 BC	AD 1	AD 500	AD 1000	AD 1500	AD 1600	AD 1700	AD 1800	AD 1900	AD 1950	AD 2000
HYDE 3.1 (baseline)	0.000	0.048	1.31	1.24	1.53	2.32	2.55	3.00	4.19	8.50	12.14	15.32
HYDE 3.1 lower	0.000	0.018	0.66	0.71	0.99	1.68	1.88	2.26	3.46	7.65	11.21	14.50
HYDE 3.1 upper	0.000	0.077	1.97	1.77	2.07	2.98	3.23	3.76	4.93	9.35	13.06	16.10
HYDE 3.1 (constant 1960 per capita value)	0.000	0.022	0.93	1.00	1.38	2.16	2.38	2.63	3.85	8.30	12.08	15.32
Williams (0.43 ha per capita in 10,000 BC)	0.010	0.080	0.76	0.85	1.19	1.81	2.04	2.28	3.49	7.19	11.45	15.32
Nevle and Bird (1.0 ha per capita in 10,000 BC)	0.024	0.140	0.94	1.00	1.33	1.92	2.14	2.36	3.59	7.09	11.34	15.32
Ruddiman (4.0 ha per capita in 10,000 BC)	0.097	0.453	1.86	1.77	2.04	2.45	2.64	2.76	3.99	7.34	11.40	15.32

Pasture	10,000 BC	5000 BC	AD 1	AD 500	AD 1000	AD 1500	AD 1600	AD 1700	AD 1800	AD 1900	AD 1950	AD 2000
HYDE 3.1 (baseline)	0.000	0.004	1.06	1.08	1.43	2.24	2.88	3.24	5.13	12.93	24.66	34.29
HYDE 3.1 lower	0.000	0.000	0.53	0.62	0.92	1.61	2.12	2.43	4.23	11.63	22.77	31.95
HYDE 3.1 upper	0.000	0.006	1.59	1.54	1.93	2.86	3.64	4.05	6.00	14.19	26.52	35.31
HYDE 3.1 (constant 1960 per capita value)	0.159	0.422	2.50	3.08	3.93	5.50	5.59	5.86	7.59	14.78	24.67	34.29
Williams (0.67 ha per capita in 10,000 BC)	0.016	0.205	1.91	2.36	3.06	4.51	4.61	4.88	6.71	14.08	24.52	34.29
Nevle and Bird (1.0 ha per capita in 10,000 BC)	0.024	0.280	2.40	2.96	3.86	5.46	5.58	5.86	7.62	14.79	24.67	34.29
Ruddiman (4.0 ha per capita in 10,000 BC)	0.097	0.593	3.32	3.73	4.57	6.00	6.08	6.25	8.02	15.04	24.74	34.29

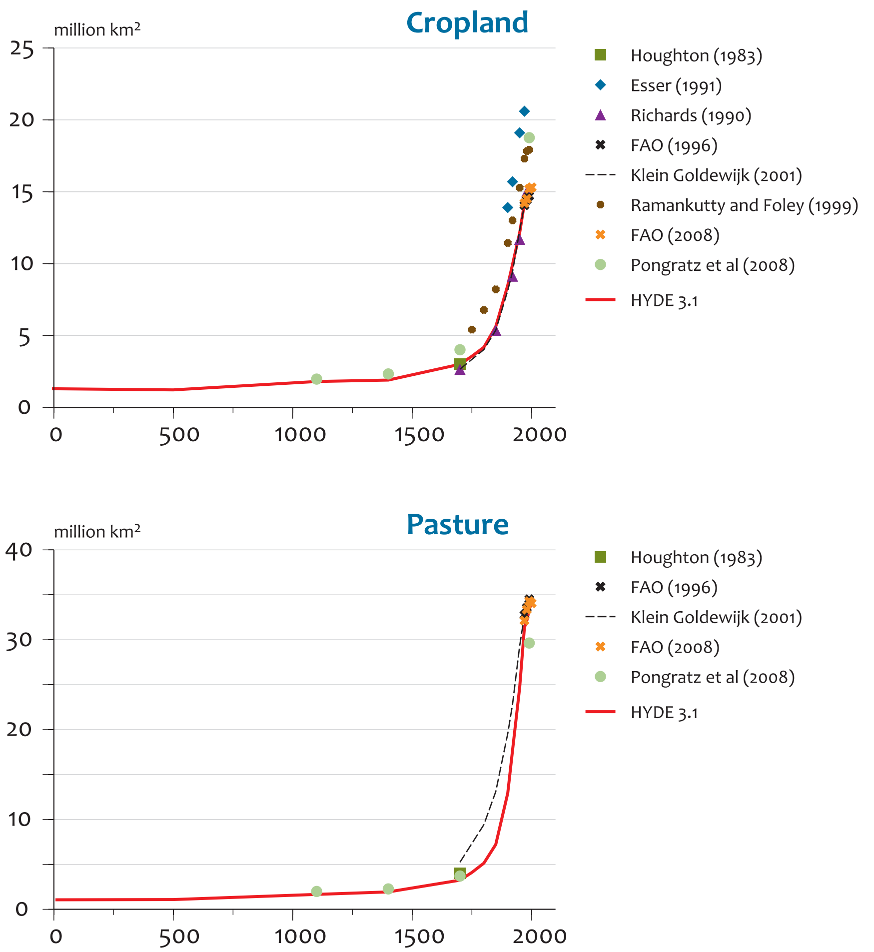

Figure 3 Overview of historical land-use estimates.

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 for each 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 what one person could feasibly handle with minimal technology – there is only so much a person can do in a day's hard work (Williams, 2000).

We have also estimated a lower and upper land-use scenario on the basis of an uncertainty range applied on top of 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 AD 2000, 10% in AD 1900, 25% in AD 1800, 50% in AD 1 and 75% in 10,000 BC. The years in between were linearly interpolated (see Tables S2 & S3 for the original input data for the baseline variant). A global summary of the resulting cropland and pasture areas is presented in Tables 2 & 3. A regional summary of cropland, pasture, population, per capita cropland area and per capita pasture area is presented in Table S4, Table S5 presents the resulting cropland areas for the different per capita scenarios and Table S6 for pasture. Table S7 presents lower, baseline and upper land-use variants of HYDE 3.1.

Furthermore, lacking transient Holocene climate and vegetation maps, we simplified the model process by using weighing maps for current climate and biome. Although the climate in 10,000 BC was certainly not the same as in the present day (Bertrand & Van Ypersele, 2002; Verschuren *et al.*, 2002; Tett *et al.*, 2005; Kröpelin *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 only factor. A similar reason can be given for the biome map. We acknowledge that the Sahara was a savanna-type region in the pre-5000 BC era (Verschuren *et al.*, 2000), and rapidly changed towards the current desert state since then, but as it was sparsely populated, and thus there was ample agriculture in that region, we decided to let our allocation procedure run unchanged during that era.

Please note that this study does not compute 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.

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, 2007) revealed many 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 modellers 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. Global (climate) change scientists already use results of the combined HYDE–IMAGE framework (Bouwman *et al.*, 2006) which provides consistent land-use time series on a 0.5° latitude/longitude grid for AD 1500–2100. Combined with other assumptions, it serves as input for global change modelling exercises for the Fifth Assessment Report of the IPCC (Hurtt *et al.*, 2006, 2009), demonstrating the usefulness of such a database.

Human impact across space and time is acknowledged by ecologists and macroecologists as an important factor that disturbs ecological processes and creates new biodiversity patterns. Nogués-Bravo *et al.* (2008) for example, suggest the huge impact of avoiding humans in ecological research. However, in general it is still not properly implemented in macroecological research, which in its turn influences the scientific debate and understanding of biodiversity patterns/processes. This database has the potential to help assess the driving factors behind biodiversity patterns.

It will be interesting to see whether the proposed theories as stated by Crutzen (2002) and Ruddiman (2003, 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 humankind changing the atmosphere) and the magnitude of the change are crucial for further understanding of the world's complex climate system. Arguably, the start of the Anthropocene 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 Supporting Information may be found in the online version of this article:

Figure S1 Cropland allocation scheme.
Figure S2 Pasture allocation scheme.
Figure S3 Global estimates of cropland, different scenarios.
Figure S4 Global estimates of pasture, different scenarios.
Table S1 Temporal and spatial overview different historical land-cover/land-use studies.
Table S2 Historical total and per capita estimates for cropland (baseline, lower and upper variant).
Table S3 Historical total and per capita estimates for pasture (baseline, lower and upper variant).
Table S4 Regional summary HYDE 3.1 land use estimates for 10,000 BC to AD 2000.
Table S5 Regional cropland areas 10,000 BC to AD 2000 (this study, different scenarios, in million km^2).
Table S6 Regional pasture areas 10,000 BC to AD 2000 (this study, different scenarios, in million km^2).
Table S7 Lower, baseline and upper land-use variants of HYDE 3.1 (this study, baseline, in million km^2).

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BIOSKETCH

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