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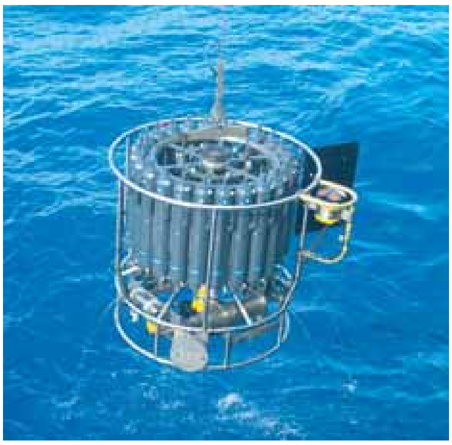
A Global Land Cover Reconstruction AD 800 to 1992 - Technical Description -

Julia Pongratz, Christian Reick, Thomas Raddatz, Martin Claussen



Berichte zur Erdsystemforschung 51/2008

Reports on Earth System Science

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ISSN 1614-1199

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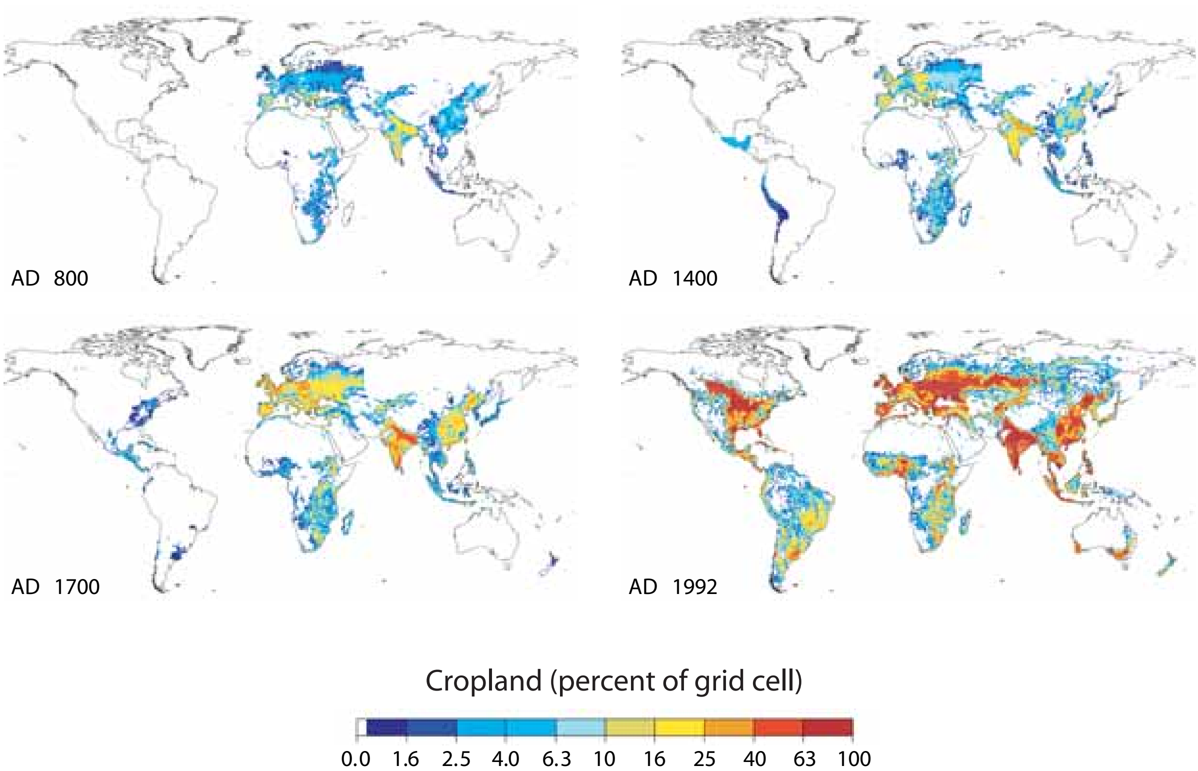

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Contents

Abstract

Humans have substantially modified the Earth's land cover, especially by transforming natural ecosystems to anthropogenically managed areas. In pre-industrial times, the expansion of agriculture was probably the dominant process by which humankind altered the Earth system. This study presents a simple approach to reconstruct spatially explicit changes in global land use and land cover over the last millennium. The reconstruction is based on the land use maps of Ramankutty and Foley [1999], Foley et al. [2003], and Klein Goldewijk [2001] for the last three centuries. For earlier times, a country-based method is developed that uses population data as a proxy for agricultural activity. With this approach, the extent of permanent cropland and pasture is consistently estimated since AD 800. The resulting land use reconstruction is combined with a map of potential vegetation [Ramankutty and Foley, 1999] to estimate historical changes in land cover. Uncertainties associated with this approach, in particular owing to technological progress in agriculture and uncertainties in population estimates, are quantified. About 5 million km^2 of natural vegetation are found to be transformed to agriculture between AD 800 and 1700, slightly more to cropland (mainly at the expense of forested area) than to pasture (mainly at the expense of natural grasslands). Historical events such as Black Death in Europe lead to considerable dynamics in land cover change, especially on regional scales. The reconstructions can be used with global climate and ecosystem models to assess the impact of human activities on the Earth system in pre-industrial times. The data set is available from the World Data Center for Climate (DOI: 10.1594/WDCC/RECON_LAND_COVER_800-1992).

1 Introduction

One of the most striking impacts of humankind on its environment is the transformation of natural ecosystems to anthropogenically managed areas. At present, 30–50% of the Earth's land cover have been substantially modified by human activities, primarily by the expansion of agriculture [Vitousek et al., 1997]. In recent years, remote sensing offers a valuable tool for monitoring such changes in land use and land cover, and historical data of agricultural activity allow rather solid estimates for the last 300 years [e.g. Ramankutty and Foley, 1999, Klein Goldewijk, 2001]. By contrast, little is known about extent, timing and spatial pattern of land use and land use change prior to AD 1700, although it is well known that humans have actively managed and transformed the world's landscapes for millennia already [Grigg, 1974]. In particular, no consistent data set exists which indicates global changes on a spatially explicit basis. In the time period between AD 800 and the early 18th century the world's population tripled [McEvedy and Jones, 1978]. As more people required more food and commodities from agriculture and natural resources, this period must have been associated with agricultural expansion at an unprecedented pace [Grigg, 1974, Richards, 1990]. But how large was this expansion, and did it occur in all regions with equal strength? Which ecosystems were most affected by human land use in pre-industrial times? And how does the pace of historical land cover change compare to more recent times?

As long as these questions remain unanswered, the understanding of the impact humans exerted on the environment in pre-industrial times will remain poor. The effects might range from changing ecosystem composition and hydrology to possible alterations of atmospheric composition and global climate [e.g. Ruddiman, 2007]. Furthermore, a better understanding of such past changes in the Earth system helps to interpret recent observations about its present functioning. On the socioeconomic side, a quantification of human land use in historical times might also deliver new insights into the understanding of the interplay between the availability of natural resources and the development of human societies. For these reasons, it is of major scientific concern to develop a spatially explicit reconstruction of land use comprising pre-industrial times.

As reliable data on historical land use activity is sparse, we develop a simple method for its reconstruction based on population estimates. Land use is inherently linked to population [Vasey, 1992], which allows us to use the population estimates of McEvedy and Jones [1978] as proxy for agricultural area for every country in the world. With this method, the land use maps of Ramankutty and Foley [1999] and Foley et al. [2003] at 0.5 degree resolution for the last 300 years are extended back into the past to give consistent estimates of cropland and pasture since AD 800 on a geographically explicit basis. This land use reconstruction is combined with a map of potential vegetation to estimate historical changes in land cover. The reconstructed data covers the last millennium reaching from AD 800 to 1992; special focus of this study is on the time period prior to AD 1700, as it has not been subject of consistent analysis before. To our knowledge, this study is the first attempt towards a consistent quantification of human impact on the Earth's surface in pre-industrial times at high spatial and temporal resolution.

2 Main data sets used in this study

Dealing with geographically explicit historical land use data, two major efforts have to be mentioned: the History Database of the Global Environment (HYDE) from the Netherlands Environmental Assessment Agency (MNP) and the data sets from the Center for Sustainability and the Global Environment (SAGE) at the University of Wisconsin. Both groups compiled various contemporary and historical statistical inventories on agricultural land. They then applied different spatial analysis methods — SAGE based on "hindcast modeling", HYDE using reconstructed historical population density maps — in order to create time series of human land use for the last 300 years (AD 1700 to early 1990s). This data is the starting point for our analysis of the last millennium and will be described briefly in the following, as will be the data of historical population used for the reconstruction prior to AD 1700. The data for potential vegetation cover will be described in Sec. 5.

2.1 Land use maps from the SAGE project

Crop fractional maps

Ramankutty and Foley [1999] used a simple algorithm which links present remote sensing data and historical cropland inventories. They first derived a crop cover map for the year of 1992 by calibrating a remote sensing map (AVHRR DISCover global 5 min land cover data, [Loveland and Belward, 1997]) against statistical data [Ramankutty and Foley, 1998]. For each pixel, this map indicates the fraction of the grid cell that is covered with crop. They then compiled a database of historical croplands on the level of today's political units (subnational data for some of the largest countries). It is based on data from the Food and Agricultural Organization (FAO) for 1961-1992 and a variety of sources for earlier times, most notably continental estimates from Houghton and Hackler [1995] and Richards [1990] where no detailed information from other sources was available (detailed sources start at 1850 or later, depending on region). Keeping the spatial pattern of their 1992 map, they adjusted national totals for each year in the past so that the cropland total of each country matches the historical inventory data. The annual maps were aggregated to a resolution of 0.5 degrees for publication. Recently, a revision of the West Africa region for the early 1990s was published after high-resolution remote sensing data and more reliable inventory data became available [Ramankutty, 2004].

The crop fractional maps represent "permanent croplands" following the FAO definition of "arable and permanent crops". This category includes land under temporary crops (which are sown/planted and harvested at least once a year), land under permanent crops (which occupy the land for some years without having to be replanted annually, such as cocoa, coffee and rubber, including all tree crops except those grown for wood or timber), temporary meadows for mowing or pasture, land under market and kitchen gardens, and land lying temporarily fallow (less than five years). The abandoned land resulting from shifting cultivation is not included.

Pasture fractional map

The SAGE project provides a map of "grazing land" for the year of 1992 [Foley et al., 2003]. Like the crop maps, the data is fractional at 0.5 degree spatial resolution. The map focuses on the representation of the FAO category "permanent pasture". This includes all land used permanently (five years or more) for herbaceous forage crops, either cultivated or growing wild (wild prairie or grazing land). As a result of the FAO definitions, temporary pastures are not included in this map but are part of the crop fractional maps described above.

2.2 The HYDE database

Land cover maps

The HYDE database was originally designed for testing and validating the IMAGE 2 model. Klein Goldewijk [2001] compiled a database of historical croplands similar to the SAGE efforts, and also one for historical pastures, both covering the years AD 1700–1990. A map indicating the current extent of agricultural land is derived by combining satellite and statistical data. Using this current extent as maximum boundary for historical agriculture, the national totals of crop and pasture were allocated within each political unit using population as proxy for location. Based on the maps of population density described below, the 0.5 degree grid cells with the highest population densities were assigned to cropland first, then those with the second highest, etc., until the total amount of cropland was allocated in that unit. Pasture is later allocated with the same method on those pixels that are not assigned to crop yet. Different maps of potential vegetation were used as background to the land use data. Unlike SAGE, a Boolean approach was chosen, so each grid cell was, for simplicity, totally allocated to either crop, pasture, or a natural vegetation type.

Population density maps

The 1994 National Center for Geographic Information and Analysis (NCGIA) population density map at 0.5 degree resolution [Tobler et al., 1995] was extrapolated back in time via historical census data. The historical data was mostly available at national level and scaled to match the United Nations data in 1950 [for details, see Klein Goldewijk, 2001]. The HYDE method does not take into account that population patterns within census units may have changed during the last centuries. For the present study, however, only country totals derived from the HYDE population and land cover maps are used, taking full advantage of

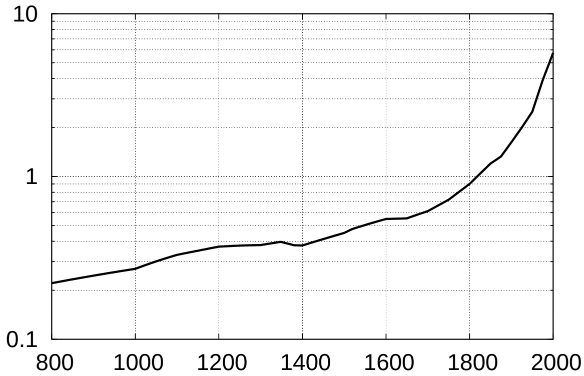

Figure 1: World population (in billion) from McEvedy and Jones [1978]

the consistent data compilation while being unaffected by possible errors introduced by the full geographical resolution.

2.3 Population data AD 800 to 1700

Population estimates are a key component in our approach for a historical land use reconstruction (Sec. 4.1). The main source of population data for AD 800–1700 is the Atlas of World Population History by McEvedy and Jones [1978], with regional modifications based on Clark [1967]. McEvedy and Jones provide national totals for most countries in their current political borders from 400 BC to AD 1975 and support their estimates with short essays stressing among others the role of agriculture. They keep close to earlier publications. Largest differences exist in Central and South America and in Africa, where the authors allow for higher dynamics, which most likely is the more plausible scenario [Caldwell and Schindlmayr, 2002].

We use the country-based estimates for population as given in McEvedy and Jones. Their world population from AD 800 to present is shown in Fig. 1. Where only data for larger regions is provided, we break the historical numbers down to national level using the HYDE population density map of AD 1700, assuming that the national proportions within a region remain constant. For overseas regions with historical development different from their political home country (e.g. Hawaii, Madeira, the Canaries) we use separate time series. The U.S. is further split into Alaska (6% of the national population prior to colonization [McEvedy and Jones, 1978]) and the conterminous states. For the Former Soviet Union, we provide subnational data as described in App. A. For the Americas, we use estimates of Clark [1967] and compile subnational data to account for the change in population pattern following European conquest (see App. B). All data is interpolated linearly to annual values.

3 Adapting existing land use data AD 1700-1992

3.1 Choice of data

Both SAGE and HYDE data sets have been extensively used and compared in Earth system studies (see, e.g., Myhre and Myhre [2003], Klein Goldewijk and Ramankutty [2004], Matthews et al. [2004], Hurtt et al. [2006], Ramankutty et al. [2006]). A major advantage of the SAGE maps with respect to application in spatially resolved studies is their continuous description of the landscape. While SAGE allows each pixel to have a crop fraction between 0 and 1, the HYDE data set is a discrete land cover classification. A fractional, 5 min resolution data set from HYDE is in progress, but not yet validated at the time of this study (Klein Goldewijk, personal communication). At a resolution of 0.5 degrees, however, the Boolean method introduces spatial discontinuities and distorts actual patterns. The error is greatest in countries and years where agricultural area is small and actual coverage of a grid cell with agriculture is low; errors must thus be expected to generally increase the further the Boolean approach is taken into the past. Due to this disadvantage, the SAGE reconstructions were chosen instead as basis for the post-industrial time period (AD 1700–1992) of our "millennium reconstruction" of land use and land cover, and as starting point for the earlier time period (AD 800–1700). The HYDE data set is only used to specify the temporal variation in the extent of pasture, as described in Sec. 3.3. The millennium reconstruction adopts the land use types of SAGE, crop and pasture, as defined in Sec. 2.1.

3.2 Adapting cropland data

The land use reconstruction for cropland by Ramankutty and Foley [1999] provides annual maps of crop fraction at 0.5 degree resolution — the earliest time step is shown in Fig. 3. The authors mention two regions where their methods lead to implausible results: West Africa and the Former Soviet Union. A third region, Australasia, was identified in this study. While we use the original data with only minor changes for all other regions, we improve the data set in these three regions.

West Africa

After the global crop data set was published, Ramankutty [2004] compared the West Africa region to higher resolution satellite data and came to the conclusion that the AVHRR DISCover data set originally used in their approach was clearly not very accurate in this region. The reasons mentioned are sensor-, algorithm- and region-specific. Besides, new inventory data was meanwhile available that more accurately determined agricultural area on subnational level than the so far employed FAO data. Ramankutty thus created a new regional data set of cropland distribution by synthesizing statistical data, a population density map and a high-resolution remote-sensing-based cropland intensity map for the Sahel. The result is a single map at 5 min resolution, which is representative of the early 1990s. Differences to the previous version lie in the general pattern of cropland distribution and in a significant increase of total crop area for Nigeria (where the inventory data is not scaled to match the national totals of FAOSTAT). We aggregate this map to 0.5 degrees and use it to replace West Africa in the original 1992 map. Compared to the original map, cropland is increased from 0.30 to 0.86 million km^2 in this region. The large revision of crop area questions the applicability of FAOSTAT data also for earlier times. The replacement in previous time steps is thus done independent of FAO data. Ramankutty [2004] showed that population density was a good predictor of cropland pattern in West Africa. Considering the low-intensity subsistence type practiced over much of the area, population may also be assumed a good predictor of total cropland area. Thus, the 1992 map is extrapolated to the past applying the trend in population to crop area. Demographic information is derived from the HYDE population density maps, which are interpolated linearly in time and extrapolated to 1992 assuming exponential growth of population.

Former Soviet Union (FSU)

The representation of significant crop area far east into Siberia in the 18th and 19th century in the SAGE maps is an artifact and recognized as such by their authors. The lack of subnational data led to maintenance of the 1992 crop pattern back into the past. However, while having an area larger than Europe, Siberia comprised not even one percent of Europe's population in 1800 [McEvedy and Jones, 1978]. It was the emancipation of peasantry in the 19th century that brought ten to hundred thousands of farmers per year across the Urals. To take this historical development and associated change in distribution of agricultural area into account, the crop area indicated by Ramankutty and Foley [1999] for the FSU is redistributed using subnational population data derived from McEvedy and Jones [1978] (as the SAGE data, HYDE is not based on subnational data for the FSU and thus not applicable here). Four regions are distinguished with respect to their historical development: (a) FSU in Europe (b) Russian Turkestan (South Kazakhstan, Tajikistan, Uzbekistan, Turkmenistan, Kyrgyzstan) (c) Siberia including North Kazakhstan and excluding the Amur region (d) Amur region (App. A). Until the Emancipation Reform of 1861 in Russia, total crop area is split up between the four regions according to population fraction and the crop pattern within each region scaled correspondingly. As trade becomes increasingly important with time, population data steadily lose their predictive value. The maps following 1861 are thus obtained by interpolation between the population-based and the remote-sensing-based 1992 crop map, steadily decreasing the importance of population with time while the predictive power of the present-day crop pattern increases. No smoothing is applied across the borders between two regions, so that presumably unrealistic, sharp gradients may occur, especially along the Urals. Still finer resolved land use or population data would be necessary to describe the agricultural expansion in the FSU in full detail.

Australasia

Similarly to the FSU, the lack of subnational data for Australia and New Zealand prior to European immigration in the SAGE maps causes an inappropriate extension of more recent crop patterns into the past. Crop in Australia is constantly concentrated in the southeast and southwest, although Aboriginal population was spread throughout the continent [Jones, 1969]. To take into account this change in human habitat, total crop area of the original maps is evenly distributed over the whole continent prior to European settlement (AD 1788). The resulting low crop fractions of less than one percent reflect the Aborigines' being primarily hunter-gatherers and their low-intensity "fire-stick farming" [Jones, 1969]. For 1788 to 1850, i.e. the phase of beginning European settlement and decreasing native population, a temporal-linear interpolation is performed between even distribution and the original maps, conserving total area. No changes are applied after 1850, when Europeans are the dominating force of land cover change.

The same procedure is also applied for New Zealand, with the only difference that total crop area is evenly distributed over the North Island only, since the South Island did not feature very suitable climate for the Polynesian form of agriculture practiced by the Maoris [McEvedy and Jones, 1978]. When compared with Australia, in terms of population density, a measure can be gained for the advantage of agriculture.

3.3 Creating a time series for pasture

Unlike for crop, SAGE did not provide information about the time evolution of the area used as pasture, but only a single map for the year 1992. Still this data set was preferred over the HYDE time series because of consistency: the differentiation between crop and pasture is extremely difficult and strongly dependent on the individual definitions. A significant part of the differences between HYDE and SAGE crop data is due to different methods, data, and terminology, rather than to errors in either or both of them [Klein Goldewijk and Ramankutty, 2004]. Using both land use types from one source reduces errors caused by omitting or double counting of agricultural areas.

The single SAGE pasture map is extended back in time by keeping the spatial pattern of land use and changing regional totals of pasture area with time. Total pasture area is calculated from the 1992 SAGE pasture map and rates of change from Klein Goldewijk

[2001]. Calculations are performed for the 10 regions defined by Houghton et al. [1983], since his regional estimates are also the basis of the temporal variations in the HYDE data. The land use pattern is maintained by keeping the relative share of each pixel's agricultural area (crop plus pasture) in total agricultural area of a region fixed in time. The advantage of this method over simple scaling of pasture fractions is that it allows to account for the expansion of crop on pasture area.

The modifications applied to the crop time series concerning Australasia are also applied to the pasture time series. The modifications concerning the FSU are unnecessary as the pasture areas here are connected to the extensive areas of traditional nomadic pastoralism of Kazakhstan and Mongolia [Kerven et al., 2006]. Whenever, for a pixel, a pasture fraction larger than the vegetated area not yet covered by crop was calculated, pasture was redistributed on the remaining pixels within today's national borders proportionally to the relative share of each pixel in total pasture area of the country. The crop maps produced in Sec. 3.2 are thus given priority, with the pasture area distributed around the given crop area. Finally, pasture is divided into C3 and C4 pasture. The split-up into C3 and C4 fractions is done following the temperature-dependent regression determined by Knorr and Heimann [2001] and 100-year monthly averages of temperature from the Climatic Research Unit's (CRU) TS 2.0 product [Mitchell et al., 2004]. Figure 4 shows the resulting map of pasture for AD 1700 (sum of C3 and C4 type). The adaptation of published crop and pasture data to a consistent time series of land use AD 1700 to 1992 is summarized in step 1 of Fig. 5, which sketches the complete procedure developed to reconstruct land use and land cover for the last millennium.

4 Reconstructing land use AD 800–1700

4.1 Method for reconstructing historical land use

Statistical databases built by international organizations and, more recently, remote sensing provide us with data and methods to consistently measure land use and land cover change of the last decades. Great efforts have been undertaken to extend this data back into the past; most notable with respect to its global coverage is the work by Houghton [1999], who compiled a multitude of regional studies related to historical land cover, and the data compilation by Richards [1990]. However, sources which address continental or global scale become scarce when going back in time and rarely go beyond AD 1650. Thus, we search for a proxy of human land use for which historical data is more readily available on global scale.

We therefore utilize in this study the fact that land use is inherently linked to population. For example, the growth of population in the early Holocene is assumed to be a result of the advent of agriculture. Technology played a minor role in resource extraction prior to the 19th century [Vasey, 1992]. Transportation was a limiting factor in pre-industrial times for trading large quantities of agricultural input and output over long distances [Vasey, 1992]. Even if most societies had outgrown individual subsistence farming, autonomy for basic needs still had to be largely realized on a regional level [Allen, 2000]. It is therefore appropriate to assume that land use occurred where people had settled, and the amount of land under human use is likely well correlated to the number of people who had to be nourished on the harvest. For this reason, we use population estimates as proxy for human land use activity. Information on historical population numbers are much more readily available than on land use, and we compiled a global database of population for AD 800–1700 on national level, based predominantly on McEvedy and Jones [1978] as described in Sec. 2.3. Population numbers are then translated for each country into estimates of crop and pasture area. In the absence of further information, it seems inappropriate to use anything more than the simplest assumptions. Thus, our basic assumption is that in each country the ratio of area used per capita for crop and pasture did not change prior to AD 1700. This ratio — the inverse of the nutritional density — is calculated for AD 1700 from the earliest land use map of the 300-years series described in Sec. 3 and our population database, and is shown in Fig. 2. Today's political borders, with a few subnational divisions where necessary (Sec. 4.2), were chosen in order to be consistent with the scale of Ramankutty and Foley [1999] and to allow for easy comparison with today's statistical data. Using population as proxy for land use activity is not a new approach; it has been suggested e.g. by Ramankutty et al. [2006] and has been applied to more recent times by Houghton [1999]. Possible errors resulting from this method will be discussed in Sec. 6.

In order to convert national totals of crop and pasture area to geographically explicit

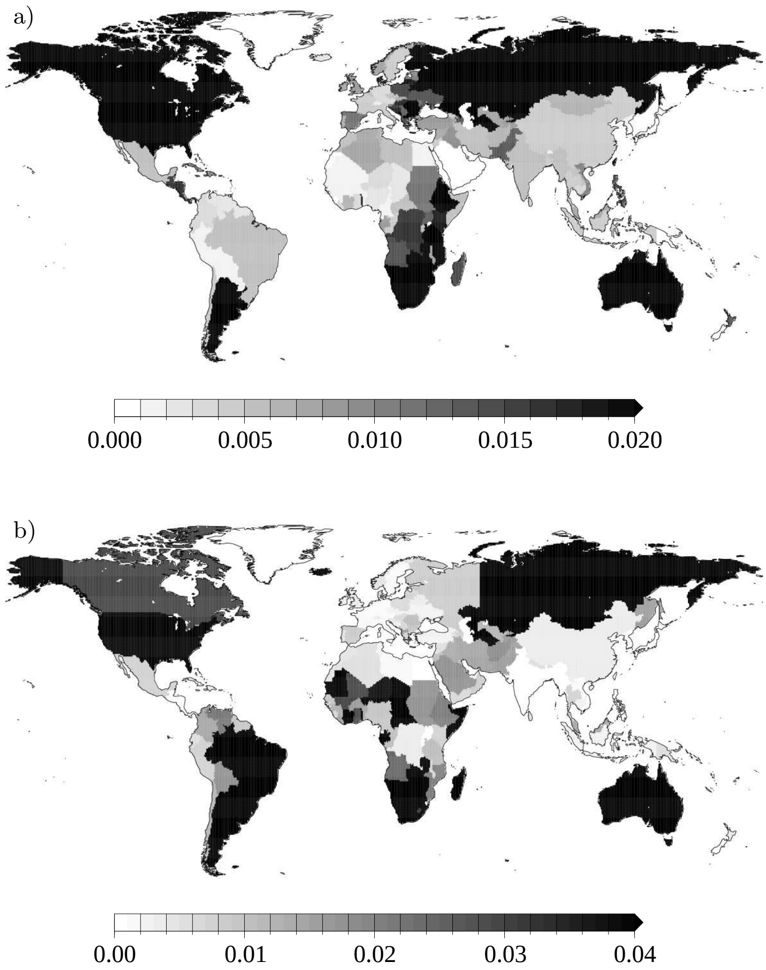

Figure 2: Country-based per-capita land use area AD 1700 for crop (a) and pasture (b). Units are km^2 per capita.

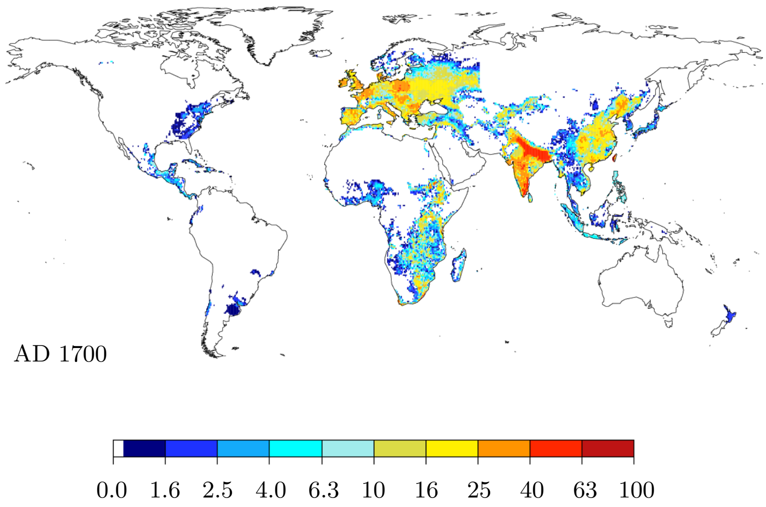

Figure 3: Global historical cropland area AD 1700. Units are percent of grid cell. Values smaller than 1% are colored white. Note the logarithmic scale.

information, we make a second basic assumption: The pattern of land use that we observe in each country in AD 1700, shown in Figs. 3 and 4, is similar to earlier spatial patterns. The persistence of the land use pattern in each country through time is a basic assumption in claiming only that the relative intensity of agricultural use of areas within one country does not change. In other words, this generally means that suitable areas are cultivated more intensively than less suitable ones within a country independently of total cultivated area. The supra-national pattern, however, is reconstructed independently each year from the population-based national estimates of land use area. Within the accuracy of the AD 1700 global pattern, the relative importance between countries is thereby correctly represented in earlier times, as human migrations across political borders are implicitly taken into account by using country-based population data. The shift of settlement and cultivation pattern within the countries of the New World after the European conquest is explicitly corrected for (see Sec. 4.2).

Combining the above stated key assumptions with the land use and population numbers of AD 1700 on national level, the existing time series is scaled back in time (step 2 of Fig. 5): The total area of land use of a country — crop and the two pasture types are each treated separately — is calculated for each year from the agricultural area per capita and census population. The pattern of AD 1700 determines the relative fractions of land use of the pixels within a country. In countries where agricultural area in earlier years exceeds the AD 1700 value it may occur that the land use fraction of single pixels becomes larger than 1. For these timesteps the surplus crop area is redistributed among the other pixels relative

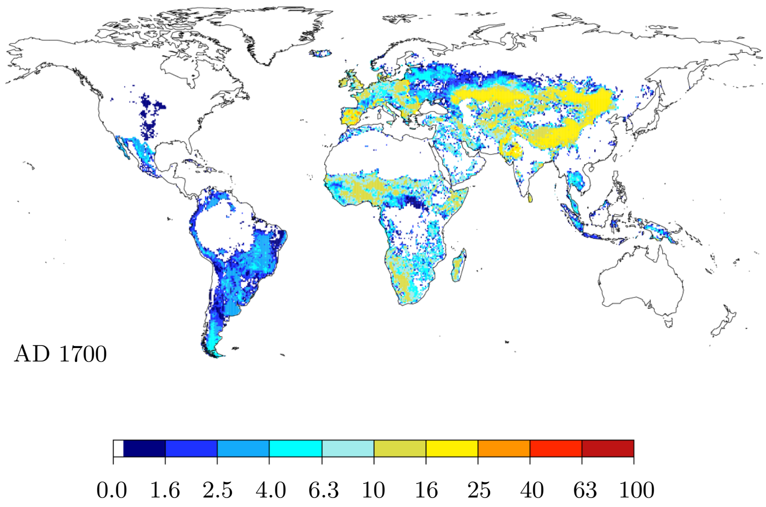

Figure 4: Global historical pasture area AD 1700. Units are percent of grid cell. Values smaller than 1% are colored white. Note the logarithmic scale.

to their fractions such that the total land use area of the country is conserved. Since we keep agricultural area per capita constant throughout time, we call the resulting millennium reconstruction the "persistent" estimate in the following.

4.2 Regional modifications

For some regions it is well known that either land use pattern or agricultural practices changed severely over time. With such knowledge we had already modified the original crop time series by Ramankutty and Foley; the new patterns of land use we introduced also reflect back in time when extending the time series to AD 800. For the Former Soviet Union, we continue to provide population data on subnational level in the same way as in Sec. 3.2. Some more modifications had to be made in regions where not only pattern but also agricultural methods changed prior to AD 1700.

Australasia

Population density of New Zealand has been extremely low far into the 19th century. Prior to the 15th century we further reduce agricultural area per capita by half to take into account that the early settlers of the islands were primarily Moa-hunters [McEvedy and Jones, 1978]. Having the hunters outruled by agricultural tribes in the 15th century, we return to our original method.

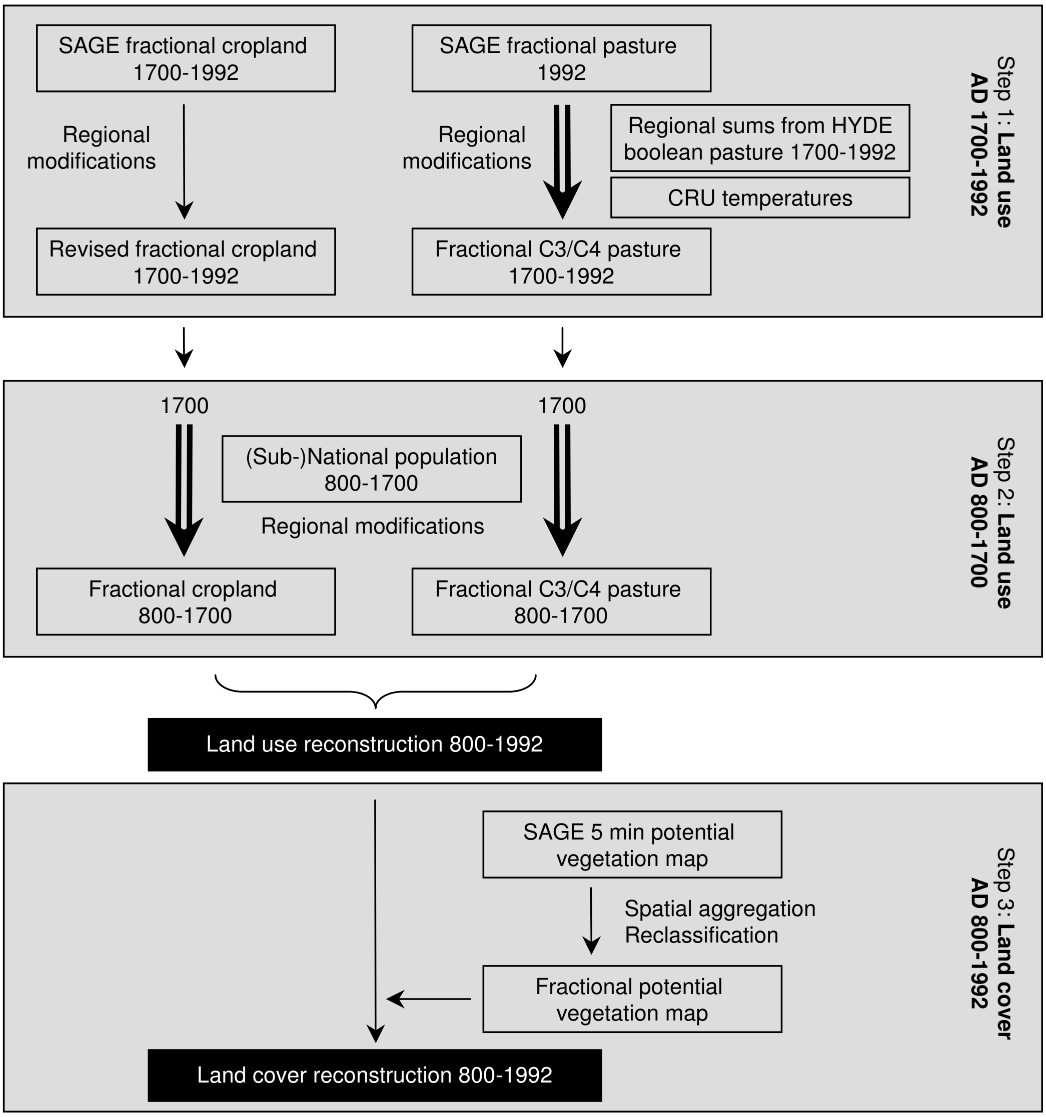

Figure 5: Scheme for reconstructing land use and land cover AD 800 to 1992. Double arrows indicate linear backscaling.

Pre-conquest Americas

European conquest of the Americas was extremely effective in fundamentally replacing traditional cultures with the ones of the invaders. The pattern of land use we observe in AD 1700 thus already reflects much of the European influence. We implement these historical changes in land use pattern by using subnational population data indicating the pre-conquest population distribution (App. B). We further abandon the figures for agricultural area per capita derived from the AD 1700 map prior to colonization since the European agricultural behavior is inherently different from the native one.

For the Andean culture sequence we assume a value of 0.002 km^2 crop per capita [Kolata, 1986][1] and a value of 0.0057 km^2 pasture per capita[2]. The intensity of agricultural activity of the lowland Amerindians has become subject of much academic argument (see, e.g., Heckenberger et al. [2003]). We keep close to McEvedy and Jones [1978], who summarize sources describing peoples as mainly food-gathering only or with less developed agriculture, and — due to the lack of other quantitative estimates — assign a factor of 0.25 to the per-capita crop values stated above. Pastoral activity is assumed negligible. The same procedure is used for Central America. These figures are combined with the subnational population data to calculate subnational land use area, which is evenly distributed within each unit. The resulting land use pattern is kept until 1519, when the Spanish arrived at the Aztecs and Old World diseases started to spread to South America. A linear interpolation of the pattern is subsequently performed to the crop and pasture maps of AD 1700.

North American agriculture was not an important sector of the Amerindian world. Population density was extremely low, and the North American Indians lived predominantly of simple hunting, fishing and semi-agricultural activities, and long fallow systems rather than permanent agriculture prevail [Vasey, 1992]. The nutritional density is assumed to be comparable to the lowland tribes of South America. As there is evidence for pasture management in some regions [Brown, 2000, Davis, 1977], a low value (25% of the South American high-culture efficiency) for pasture activity is chosen. An evenly distributed land use pattern is kept until 1607, when the English founded Jamestown, European population spread, and Indians were reduced in number. Again, a linear transition is performed to AD 1700.

[1] Kolata's figures are lower than the ones assumed here; the modification seemed necessary to account for the fact that his study region was highly productive with 100% utilization of fields. Our value equals the figure of Collins [1983] for today's Aymara people of Peru, a people of indigenous background upkeeping their traditional subsistence agriculture and herding.

[2] This number is calculated from the estimates of Foreman [1950] for people and domestic animals of the Aymara period and the numbers cited by Lane [2006] for animals per unit pasture.

5 From land use to land cover

So far, the reconstruction of a land use time series was described, indicating area and pattern of global agricultural activity in the course of the last millennium. For many applications involving human impact on natural ecosystems and the climate, it is essential to know the land surface properties before agriculture emerged or after it ceased. For this purpose, the land use reconstruction is transformed into a time series of land cover by overlaying it with a map of potential vegetation (step 3 of Fig. 5).

5.1 Map of potential vegetation

We use the 5 min resolution potential vegetation classification described by Ramankutty and Foley [1999], which is consistently derived from the same sources as their land use maps. This data set represents potential rather than natural pre-agricultural vegetation, i.e. the vegetation that would exist in the climax state under today's conditions after humans were removed from the scene. This differs from pre-settlement vegetation to the extent that vegetation types may have changed due to altered environmental conditions. We first reclassify the 15 existing classes into the 11 natural vegetation types listed in Tab. 2. These are the natural plant functional types (PFTs) used in the Biosphere-Energy-Transfer-Hydrology Scheme (BETHY) [Knorr, 2000] and the Jena Scheme for Biosphere-Atmosphere Coupling in Hamburg (JSBACH) [Raddatz et al., 2007]. The reclassification is performed on the basis of the descriptions of the cover types as summarized in App. E, which in many cases is straightforward. For mixed classes, which cannot be handled by PFT-based vegetation models, bioclimatic limits are in general taken from Sitch et al. [2003] and are applied to the monthly CRU temperature averages [Mitchell et al., 2004] to assign the mixed classes fractionally to the participating vegetation types. The temperature criterion of Knorr and Heimann [2001] is again used to give fractions of C3 and C4 vegetation for grasses. This reclassified data set is then aggregated from 5 min to 0.5 degree resolution keeping the relative proportions of vegetation types in the half-degree grid cell. Our classification scheme does not contain classes for desert or barren ground. Instead, we use a remote-sensing-based map of maximum vegetation cover to reduce the relative fractions of natural vegetation to fractions of the total grid cell [Hagemann, 2002].

5.2 Merging land use and potential vegetation

The next step is to introduce agriculture into the reclassified, aggregated potential vegetation map. Different methods are used for crop and pasture to determine how much each vegetation type in each 0.5 degree grid cell is affected by human land use. For crop AD 1700–1992, we compare 5 min resolution crop cover maps (N. Ramankutty, personal communication) for each year with the reclassified 5 min potential vegetation. This indicates what fraction of each vegetation type in a half degree pixel is lost to crop. Where several potential vegetation types were assigned to one 5 min cell during the reclassification process, the types are reduced proportionally. A linear interpolation in time is performed between the high-resolution crop maps, which were generated for every 10th year only. Prior to AD 1700, the proportions of area lost to crop between the natural types are kept constant as far as possible. Only in cases where the crop area assigned to a certain vegetation type exceeds its area, the surplus crop area is proportionally distributed on the other types. For pasture, where no sub-grid information is available, we assume a certain land cover priority. Pasture is first allocated on grass as far as possible, then, proportionally, on the area of the woody vegetation types. This procedure reflects human behavior of minimizing effort: Clearing of forest is generally not performed if sufficient natural grassland is available for grazing [Houghton, 1999, Ramankutty et al., 2006].

Abandoned agricultural area is attributed to the natural vegetation indicated by the potential vegetation data set. The different structure of this secondary vegetation compared to primary one, specifically the gradual regrowth of vegetation, needs to be adequately represented when the proposed land cover reconstruction is used to derive land surface properties. Many biosphere models allow for these gradual transitions. In such cases errors are limited to abandoned agricultural area that does not return to potential vegetation, e.g. where forest re-establishment is inhibited through degraded soil conditions.

6 Assessing uncertainty and validity

The purpose of the millennium land use reconstruction is to give consistent estimates of cropland and pasture areas on country (or regional) level. The evolution of area estimates captures historical events likely to imprint themselves on agricultural activity. When historical sources and modern estimates failed to provide the necessary information, we used only the most basic assumptions. The aim is to keep methods, results, and uncertainties at any time straightforward and comprehensible. In the following, we discuss uncertainties and sources of possible errors in creating and applying our land use reconstruction: First, we identify the types of land use and land cover transformations not included in our analysis. Secondly, we compare our base data, the land use maps AD 1700 to 1992, to other published estimates. Thirdly, we estimate uncertainties propagating from the population data used as proxy in the millennium reconstruction. Finally, we review our method of reconstruction; most importantly, we assess the possible range of land use area through agrotechnical development.

6.1 Inclusiveness of the millennium reconstruction

This study focuses on land use that permanently changes the type of vegetation. The land use types considered are temporary and permanent croplands and pastures, including garden land and temporarily fallow areas (see Sec. 2.1). This also covers the cultivated land of shifting cultivation, but not the fallow area if abandoned for more than five years. Distinguishing between shifting and permanent cultivation leads to large uncertainties, as the very high resolution data needed to resolve such small-scale processes is usually not available on a large spatial scale. Even today the quantification of shifting cultivation poses a major problem. A sensitivity analysis [Hurtt et al., 2006] showed that the omission of shifting cultivation may lead to a significant underestimation of secondary land area created by land use. However, shifting cultivation only increases the area undergoing gross transition, while net transition on national level as represented by the millennium reconstruction is unaffected. Our results thus remain valid as long as no subnational and sub-grid information is derived.

A land use system not taken into account in this study is wood harvesting. Our land use reconstruction can be combined with wood harvest data once such statistics become available for historical times, but it should be kept in mind that the clearing of forest for timber or fuelwood is not an entirely independent land use alongside agriculture (as e.g. Houghton [1999] assumes). A part of the area cleared for wood harvest is subsequently used for agriculture, and another part is quickly regrown in a system of managed forest and does thus not represent a permanent change of the type of vegetation.

The processes captured by our land cover reconstruction are the transformation of natural vegetation to agriculture and the abandonment of agricultural land, followed by recovery of the original vegetation. Abandoned land in this analysis always returns to its potential vegetation; we do not take into account land degradation that might inhibit the regrowth of the original vegetation. Similarly, we do not consider changes of natural vegetation through natural disturbances, such as wildfire, or natural vegetation dynamics, which should be accounted for by dynamic vegetation models. All these processes, however, as well as a representation of wood harvest or shifting cultivation, would only alter the area of natural vegetation types, or the localization of crop and pasture. The area estimates of land use on the national level remain unaffected.

6.2 Validation of the base data AD 1700 to 1992

Ramankutty and Foley [1998] compared their remote-sensing-based cropland map of 1992 to three other estimates, two ground-based data sets, and one satellite-based data set in order to validate their global pattern of cropland intensities. From this comparison they show that the data set provides a "reasonably accurate and quantitative depiction of croplands across the globe". The largest differences exist in regions of recent land cover change and can probably be explained by the fact that the maps represent different time periods. In Africa, the Ramankutty and Foley data set may underestimate the low-intensity subsistence agriculture, which is difficult to classify using satellite-based data sets especially when mixed with natural vegetation. In most regions, however, their approach of mapping out natural vegetation/cropland mosaics gives good results in capturing low-intensity cultivation. The SAGE maps have also been compared to the HYDE data for cropland in both present and historical times (for details, see Klein Goldewijk and Ramankutty [2004] and Ramankutty et al. [2006]). They are found to be generally consistent with HYDE in representing cropland over the last 300 years. A strong caveat of this comparison is the fact that the two data sets are not entirely independent and partially rely on the same input data. The SAGE time series has further proven to represent common knowledge about the evolution of cropland in different parts of the world [Ramankutty and Foley, 1999].

Few independent data sets exist that could be used to validate the pattern of pasture. It is often impossible to distinguish between pristine grasslands and such used for grazing in observation data, and classification strongly depends on subtleties in definition. When compared to the HYDE data, the present-day pasture extent of Foley et al. [2003] agrees well in Europe, South America and Africa, though in the latter the HYDE data concentrates pasture stronger in the Maghreb coast and the Sahel. Some differences exist in the Middle East. Most notably, the semi-desert and desert of the Arabian peninsula show much higher intensities of grazing in the HYDE data, while the SAGE map is more closely coupled to the maximum possible vegetation cover and allows high intensities only where a certain amount of vegetation exists. We believe that this is the more appropriate pattern for historical times, where population pressure was low and less suitable areas did not have to be included into agricultural activity. A further difference existed in Southeast China, where SAGE allocated significantly less pasture than HYDE, but this region has been revised in the forthcoming new HYDE version 3.0 (Klein Goldewijk, personal communication). With this version, the North American pattern also largely agrees with SAGE. The interior of the Australia continent is less-intensely used for pasture in the SAGE data, but the uncertainties related to both the statistical data and different allocation schemes are specifically large in this part of the world (Klein Goldewijk, personal communication). This discrepancy in pattern, however, is unimportant for historical times as aboriginal agricultural activity was very low. The most extensive grazing lands in Mongolia and Tibet are identified in both SAGE and HYDE 3.0, but with a higher intensity in the SAGE data. In our reconstruction, this high intensity reflects back to historical times.

We can conclude that the overall pattern of cropland and pasture of Ramankutty and Foley [1998, 1999] and Foley et al. [2003] are in good agreement with other studies. This is an important point, as historical patterns are derived from present day data in both the SAGE approach and our method and errors would propagate to earlier times. Concerning total land use area, some uncertainty exists not only for historic, but also present times. In absolute numbers, the 1992 Ramankutty and Foley map used in this study (including the modifications described in Sec. 3.2) shows a cropland area of 18.8 $\cdot 10^6$ km^2, while estimates by Richards [1990] for the year 1980 are 15.0 $\cdot 10^6$ km^2, by Houghton [1999] for the year 1990 are 13.6 $\cdot 10^6$ km^2, and by Klein Goldewijk [2001] for the year 1990 are 14.7 $\cdot 10^6$ km^2 (note that all estimates partially rely on the same input data). The pasture map used in this study shows an area of 29.6 $\cdot 10^6$ km^2 as opposed to the estimate of Klein Goldewijk [2001] for the year 1990 of 34.5 $\cdot 10^6$ km^2. Obviously, notable uncertainties exist despite the growing availability of ground- and satellite-based observations and international statistical databases. We cannot assume that data uncertainties are any smaller between AD 1700 and 1992 than at present. As this time series is also the base data for our reconstruction, this uncertainty is passed on to all earlier time steps.

6.3 Uncertainty of the population data

Despite the long tradition of demographic research, no outright consensus exists concerning quantitative estimates of historical population, especially for times earlier than the 18th century. Global numbers differ by up to a factor of two for the first millennium AD; regional estimates can be even more disputed. The data set predominantly used in this study [McEvedy and Jones, 1978] is largely acknowledged in recent literature and stands out through its consistency and high spatial and temporal resolution. The uncertainties introduced by the choice of this specific population database are estimated in the following.

The population database of this study is compared to six other historical estimates, Clark [1967], Durand [1977], Biraben [1979] and Maddison [2001]. Durand provides us with high and low bounds for reasonable estimates, which are used in this study as two separate data series beside the mean value. For the Americas, we further include the original data from McEvedy and Jones [1978] without the modifications of App. B. Data for the years AD 1000, 1500 and 1700 are used in aggregated form for four regions: Europe including the Former Soviet Union, the Americas, Asia and Australasia, and Africa, following Maddison [2001]. They are shown in Tab. 1. There is good agreement between the studies with respect to Europe and Asia, where estimates differ by less than a factor of 2 even for early years. Not surprisingly, however, large differences exist for Africa and the Americas, where much of the continents was still unexplored by the end of the period shown. Still in debate, for example, is the number of native Americans prior to European arrival, where estimates range between 14 and 63 Million, as well as the strength of population growth before.

The population dynamics of the temporally high-resolved data used in this study are superimposed on the alternative estimates. For each year and each region the two data sets are then chosen that give the highest and lowest changes in population relative to their AD 1700 value. This method thus results in an uncertainty range around the population estimates used for the millennium reconstruction. This range is assigned to each pixel within one of the four regions proportionally to its land use area, implying that all countries within one region have equal uncertainties considering demographic estimates. The procedure results in an uncertainty range around our "persistent" land use estimates. It is important to note that the extreme ranges do not represent consistent time series of likely alternative scenarios. Rather, they indicate the entire range of possible land use estimates for a given year. If at all, the outer bounds can only be reached for a certain time period throughout the millennium, as they do not reflect one consistent time series anymore. They furthermore imply that the population numbers used deviate systematically from the real value for all countries within a region. The maximum uncertainty range we assign to the persistent estimate due to uncertainties in population estimates, based on the described approach, for the year AD 800 is 1.1 to 1.6 $\cdot 10^6$ km^2 around the persistent estimate of 1.4 $\cdot 10^6$ km^2 for crop, and 1.1 to 1.7 $\cdot 10^6$ km^2 around the estimate of 1.4 $\cdot 10^6$ km^2 for pasture. In relative terms, the largest underestimation that could occur in AD 800 due to errors in the population data used in this study is in the Americas. Here, the high estimate of Durand [1977] does acknowledge that there has been significant decrease in population with European conquest, but believes in steadily high population before that. The largest overestimation of our study is to be expected in Africa. Here, Biraben [1979] suggests much stronger population dynamics prior to AD 1700 than all other data sets.

	Europe and FSU			Asia and Australasia			Africa			The Americas		
	1000	1500	1700	1000	1500	1700	1000	1500	1700	1000	1500	1700
This study	39.1	85.1	125.0	186.4	277.2	411.8	32.3	46.6	61.3	13.2	41.1	14.4
Clark 1967	44.2	73.8	111.8	173.0	227.0	416.0	50.0	85.0	100.0	13.0	41.0	13.0
Durand 1977 (mean)	45.5	79.0	126.8	189.5	304.0	443.0	37.5	54.0	79.0	37.5	47.5	16.5
Durand 1977 (low)	36.0	70.0	107.8	134.0	226.0	385.0	25.0	36.0	58.0	22.0	32.0	11.0
Durand 1977 (high)	55.0	88.0	145.8	245.0	382.0	501.0	50.0	72.0	100.0	53.0	63.0	22.0
McEvedy and Jones 1978	–	–	–	–	–	–	–	–	–	9.0	14.0	13.0
Biraben 1979	43.0	84.0	125.0	152.0	245.0	436.0	38.0	87.0	107.0	18.0	42.0	12.0
Maddison 2001	39.0	87.7	126.8	183.4	284.4	402.4	33.0	46.0	61.0	12.9	19.8	13.3

Table 1: Alternative population estimates (in million) on continental scale. Except for the Americas, the estimates of this study and McEvedy and Jones [1978] are identical.

6.4 Effects of agrotechnical improvements

A major assumption of our approach in reconstructing historical land use is that the ratio of agricultural land per capita did not change prior to AD 1700. Aim of the following paragraphs is to test its plausibility. Land used per person is the inverse of nutritional density and corresponds to land (not labor) productivity — per-area yields — in the absence of major dietary changes and trade. We subsume both nutritional density and land productivity under agricultural efficiency in this context. Dietary changes and trade are considered to be minor drivers of land use changes. Trade, specifically, was largely limited to high-value products such as silk, wool, and spices, unless water transport became possible [Grigg, 1974]. Costs of transport were too high to move general foodstuff. It was only in the 1870s that the railway replaced the ox- or horse-drawn carts as most common form of land transport, and steamships and railways opened up world markets; iced and insulated railway cars came into use in the 1880s [Grigg, 1974, Vasey, 1992]. Only recently in human history has it thus become possible to move agricultural products on a large scale.

There is little doubt, however, that the amount of land required to meet the needs of a person varied considerably over a time period of several centuries. In theory, within a civilization, farming becomes more productive as agrotechnical innovations are continuously triggered through population pressure and shortages [Sieferle, 1997, Boserup, 1965]. This process was not taken into account in this study for the following reasons:

- Published data on measures of agricultural efficiency, e.g. yield ratios, land productivity, or land used per person, is marked by inconsistencies of sources and is restricted to certain regions and time periods.

- The steady increase in efficiency predicted by theory cannot be observed in the data. Slicher van Bath [1963], e.g., shows that the general increases in European agricultural productivity were frequently offset for times by bad weather, change to inefficient farming methods, or economic depressions, and some countries, especially in Eastern Europe and Russia, show almost no net increase at all.

- Increase in agricultural productivity on existing fields may be offset as population pressure forces the development of land use on less suitable grounds.

Nevertheless, an estimate of the uncertainties of the persistent estimate of the millennium reconstruction is desireable. For this, we recalculate crop area within a maximum range of possible changes in agricultural efficiency. In this efficiency, we try to not only include agrotechnical progress, but also regression due to land degradation and socioeconomic disturbances, changes in crop types, and changes in the fraction of population incorporated in an agricultural system in those regions where we know that these factors play a non-negligible role. We use data on nutritional density and land productivity where available and try to give an upper and lower boundary of possible changes in efficiency due to the mentioned factors (App. D). Where quantitative data is missing, we classify regions as one of three cases based on the information of Grigg [1974] and Vasey [1992]: regions with general increase, regions with no change, and regions with general decrease in efficiency. For the first, an upper boundary is chosen with per-capita land use area two thirds higher in AD 800 compared to AD 1700; this is half the increase of Northwestern Europe, the region with likely strongest improvements in agrotechnology (except for China, where even higher rates of efficiency change result from the linear data extrapolation we perform). The lower boundary is given by a land use area per person one third lower. We reverse these numbers to gain an upper and lower boundary for regions with general decrease of agricultural efficiency (i.e. only one third higher but down to two thirds less per-capita land use in AD 800 compared to AD 1700). Regions with no change are given a possible range of land use area per person of ± 50%. Changes in the productivity of pastures have not been assessed for historical times in literature. Here, we generally use the same ranges for pastures as for cropland. Generally, changes in pasture efficiency will be less pronounced as for crop, but the general trend may be similar as many agrotechnical improvements such as manuring can also be applied to forage crops and the number of draught animals per capita is linked to cropland efficiency.

The compiled numbers of change (App. D) are small compared to those of the so-called agricultural revolutions: The domestication of cereals during the first thousand years following the Neolithic Revolution must have increased yields by a factor of about 2 to 3 [Gepts, 2004]. Post-war yields increased in a comparable order of magnitude resulting from genetically improved cultivars and better cultural methods (e.g. global yields of wheat increased from 1 t/ha in 1951 to 2.5 t/ha in 1995, Curtis et al. [2002]). The time period under consideration in this study, however, is marked by the absence of agricultural revolutions, and the overall pace of technological change in farming has been "remarkably slow" [Grigg, 1974, p. 50]. Most of the pre-industrial increases in crop and animal production occurred as a result of increases in agricultural area [Ruttan, 2002].

The maximum uncertainty range we assign to the persistent estimate due to changes in agricultural efficiency, for the year AD 800, is 0.8 to 2.2 $\cdot 10^6$ km^2 around the persistent estimate of 1.4 $\cdot 10^6$ km^2 for crop, and 0.8 to 2.1 $\cdot 10^6$ km^2 around the estimate of 1.4 $\cdot 10^6$ km^2 for pasture. Changes in the agricultural systems of the world thus introduce a significantly higher uncertainty in our approach than the decision for a specific population data set (Sec. 6.3). Except for the Americas, this statement also holds true at regional level. For the following analysis of historical land cover change, we combine both uncertainty factors, efficiency and population, in a way that results in the maximum possible range at every timestep in every part of the world. Joining highest agrotechnical progress with lowest population growth and vice versa give possible, but unlikely estimates of land use. This range of uncertainty assigned to the persistent estimate therefore does not indicate a range of equal preference, which would be much smaller. Instead, it is intended to define limits of possible errors in the estimates caused by our approach. We did not assign an uncertainty range to the base data AD 1700 to 1992, but it should be taken into account that errors in the maps of AD 1700 propagate back in time (Sec. 6.2).

7 Changes in land cover AD 800–1992

We present our reconstructions in two ways: The full spatial information is depicted in the maps for historical crop and pasture in Figs. 7 and 8. These maps are shown at time intervals of 200 years with the difference between them shown alongside. The distinct agricultural development of specific countries as well as the general global pattern can be followed there. More information about the temporal evolution of cropland and pasture and the resulting land cover change are presented in Figs. 9 and 10. Here, the total area of land use and natural vegetation is shown for the 10 regions defined in App. C. The persistent estimates are surrounded by the range which were determined from the uncertainties in our method associated with population data as well as agrotechnical development (Sec. 6). We regard estimates outside this range as unrealistic. Additionally shown with the natural vegetation types is the persistent estimate for land cover change due to the expansion of cropland only, disregarding pasture. It is thus possible to separate the impact of changes in cropland on natural vegetation from the impact of changes in pasture. Global values of the persistent estimates for land use and natural vegetation are shown in Fig. 6.

The general pattern of land use activity is closely linked to the history of human civilizations. The map for AD 800 clearly highlights the regions with the longest history of agriculture (Fig. 7): High intensities of crop cultivation are found in the Mediterranean, the Fertile Crescent, and India. Large areas of cropland are also deduced for China. In all these regions, the domestication of cereals or the spread of cereals into the region had taken place

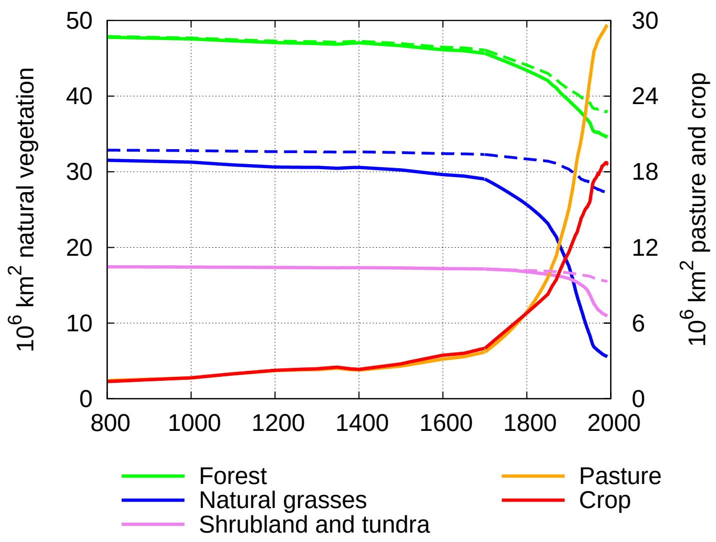

Figure 6: Global area of natural vegetation (left axes) and the land use types crop and pasture (right axes) from AD 800 to 1992 (in 10^6 km^2). Dashed lines are land cover change due to cropland only.

thousands of years ago. On the other hand, many parts of the world have seen little human impact 1200 years ago. Agriculture had developed early also in the Americas, but intensity remained low outside the centers of high cultures until Europeans arrived. Most of central Asia was not settled until the 19th century, and the agricultural tribes in Australasia were few and low in numbers. Much of Africa must still have been pristine in AD 800, but the continent competes with India for the strongest and steadiest growth of cropland over all centuries in pre-industrial times. At the same time, other regions experience repeated set-backs in their agricultural history, driven by political and economic instability as in China and Europe, by epidemics as in Europe and the Americas, or changes in cultural habit and environmental conditions as in Southwest Asia and the Mediterranean.

The distribution of pasture is quite different from that of cropland in both historical and present times (Fig. 8). Some of the most important areas are found in AD 800 in Europe and Southwest Asia, where animals had been used early already as draught animals. Vast areas of grazing land are found in the steppe and semi-deserts of Asia and the savannas of Africa. In these regions, animals were rarely incorporated in crop production, and nomadic pastoralism prevailed in pre-industrial times, often persisting until today. As for crop production, general cultural development and historical events imprint their dynamics on the extend of pasture. The many factors that contribute to both pattern and changes of the extent of crop and pasture are highly variable through time and space.

Table 2 and Fig. 6 summarize the human-induced changes of land cover on a global scale. By AD 800, 2.8 $\cdot 10^6$ km^2 of natural vegetation have already been transformed to agricultural land, which is about 3% of the area potentially covered by vegetation. This transformation was almost equally caused by cropland and pasture, but both types of land use affected quite different ecosystems. On the one hand, 0.8 $\cdot 10^6$ km^2 of pristine forest were cleared for the cultivation of crop, large parts of it in the temperate and the tropical broadleaf deciduous forests. On the other hand, 1.3 $\cdot 10^6$ km^2 of pastures are located on areas that were naturally covered by grassland anyway and are thus not associated with major changes in the type of vegetation. By AD 1700, agricultural area has extended to 7.7 $\cdot 10^6$ km^2: 3.0 $\cdot 10^6$ km^2 of forest have been cleared, 85% of this for cropland, the other 15% for pasture; 4.2 $\cdot 10^6$ km^2 of natural grassland have been transformed to human use, but only 22% are used for the cultivation of crop. By contrast, the 0.5 $\cdot 10^6$ km^2 of shrubland lost to land use are almost exclusively cleared for crop. C3 and C4 grassland, temperate and tropical broadleaf deciduous forest remain the most strongly affected ecosystems. Within the next 300 years, total agricultural area rises to 48.4 $\cdot 10^6$ km^2, especially pasture expanded. The ecosystems that lose the largest areas to human use are now natural grasslands, summergreen shrubs, temperate and tropical broadleaf deciduous forest and tropical evergreen forest. Between AD 800 and AD 1700, there were thus 4.9 $\cdot 10^6$ km^2 of natural vegetation brought under human use, compared to

$40.7 \cdot 10^6$ km^2 in the following three centuries. Despite this discrepancy, we should not consider the land cover change during the early centuries of our reconstruction as irrelevant. First, the expansion of land use during these 900 years was likely much greater than during the millennia that had passed since the Neolithic Revolution. Secondly, there are significant differences between different parts of the world. Some regions developed amazing rates of agricultural expansion that cannot be discerned on global scale, and regional dynamics, including decline of agriculture, are remarkable. In the following subsections, we present the reconstruction of human land use on the regional level in the context of agricultural history. We will mainly focus on the time period prior to AD 1700; for details on the last 300 years we refer the reader to Ramankutty and Foley [1999].

7.1 Europe and Former Soviet Union

Farming and herding were spreading westward from the ancient centers of agriculture in Southwest Asia to Europe and reached the shores of the North and Baltic Seas as well as the Iberian peninsula by 4000 BC [Grigg, 1974]. Some local domestications added on the imported agricultural spectrum of animals and crops. With about $3.2 \cdot 10^5$ km^2 of cropland and pasture in AD 800, Europe has become one of the agriculturally important regions of the world by early medieval times (Fig. 9). European agricultural colonization progressed fast until the 14th century. Agrotechnical advances opened up land that was previously considered unsuitable for agricultural use: Marshes were drained, effective irrigation systems were introduced to the dry regions of Iberia and Italy, the spread of the heavy wheeled moldboard plough allowed to work finer textured soils, the coulter facilitated the cultivation on previously forested area. The improvement of the ox yoke, the increased use of horses and the invention of the horse collar made work faster and allowed for more area being cultivated by one farmer [Crombie, 1977]. Social changes like the spread of feudalism and organization of rural population in villages spread risk and improved efficiency — population grew. The steady increase in agricultural area and the corresponding clearing of forest came to a sudden halt with Black Death, the plague epidemics AD 1347–53, when a quarter to a third of the population died. In the following decades an estimated $2.3 \cdot 10^5$ km^2 of farmland were abandoned and allowed for some regrowth of forest (Fig. 10 a). Fast rates of land cover transformation were returned to in the 15th century, but agricultural expansion stagnated again in the early 1700 century in Europe as a whole as a consequence of several more regional processes, including the Thirty Years War and economic crises in the Mediterranean countries. A rapid expansion of cropland on forested areas dominated until the middle of the 19th century.

The large uncertainties of agricultural estimates in Europe are a consequence of the uncertain changes in land productivity rather than disagreement in population numbers. Tech-

	Potential vegetation	800	1100	1400	1700	1992
Tropical evergreen forest	16.57	16.43 (16.46)	16.37 (16.41)	16.29 (16.35)	16.11 (16.20)	13.31 (14.42)
Tropical deciduous forest	5.87	5.60 (5.61)	5.50 (5.52)	5.41 (5.43)	5.11 (5.16)	2.99 (3.82)
Temperate evergreen broadleaf forest	1.50	1.43 (1.43)	1.38 (1.38)	1.39 (1.39)	1.30 (1.31)	0.70 (0.86)
Temperate/boreal deciduous broadleaf forest	8.98	8.72 (8.77)	8.55 (8.62)	8.48 (8.57)	7.97 (8.16)	5.25 (5.85)
Temperate/boreal evergreen conifers	13.23	13.09 (13.11)	12.99 (13.02)	12.95 (13.00)	12.65 (12.75)	10.01 (10.62)
Temperate/boreal deciduous conifers	2.53	2.52 (2.52)	2.52 (2.52)	2.52 (2.52)	2.51 (2.52)	2.35 (2.36)
Total forest	48.68	47.78 (47.89)	47.31 (47.47)	47.05 (47.26)	45.65 (46.09)	34.60 (37.93)
Raingreen shrubs	13.24	13.02 (13.02)	12.97 (12.97)	12.92 (12.92)	12.75 (12.76)	7.84 (11.26)
Summergreen shrubs	0.35	0.35 (0.35)	0.35 (0.35)	0.35 (0.35)	0.34 (0.34)	0.19 (0.31)
C3 natural grasses	14.19	13.47 (14.06)	13.10 (14.00)	13.00 (13.95)	12.32 (13.80)	2.82 (11.44)
C4 natural grasses	19.01	18.05 (18.79)	17.81 (18.73)	17.57 (18.68)	16.72 (18.48)	2.77 (15.88)
Tundra	4.08	4.07 (4.07)	4.06 (4.07)	4.06 (4.06)	4.05 (4.06)	2.94 (3.98)
Total natural vegetation	99.55	96.75 (98.19)	95.60 (97.58)	94.95 (97.22)	91.84 (95.54)	51.16 (80.80)
Crop	—	1.36 (1.36)	1.97 (1.97)	2.33 (2.33)	4.01 (4.01)	18.76 (18.76)
C3 pasture	—	0.65 (0.00)	0.99 (0.00)	1.08 (0.00)	1.77 (0.00)	12.08 (0.00)
C4 pasture	—	0.79 (0.00)	0.99 (0.00)	1.19 (0.00)	1.94 (0.00)	17.56 (0.00)
Total land use	—	2.80 (1.36)	3.95 (1.97)	4.60 (2.33)	7.71 (4.01)	48.39 (18.76)

Table 2: Estimated global extent of land cover types (in 10^6 km^2). Values in brackets are estimates disregarding pasture.

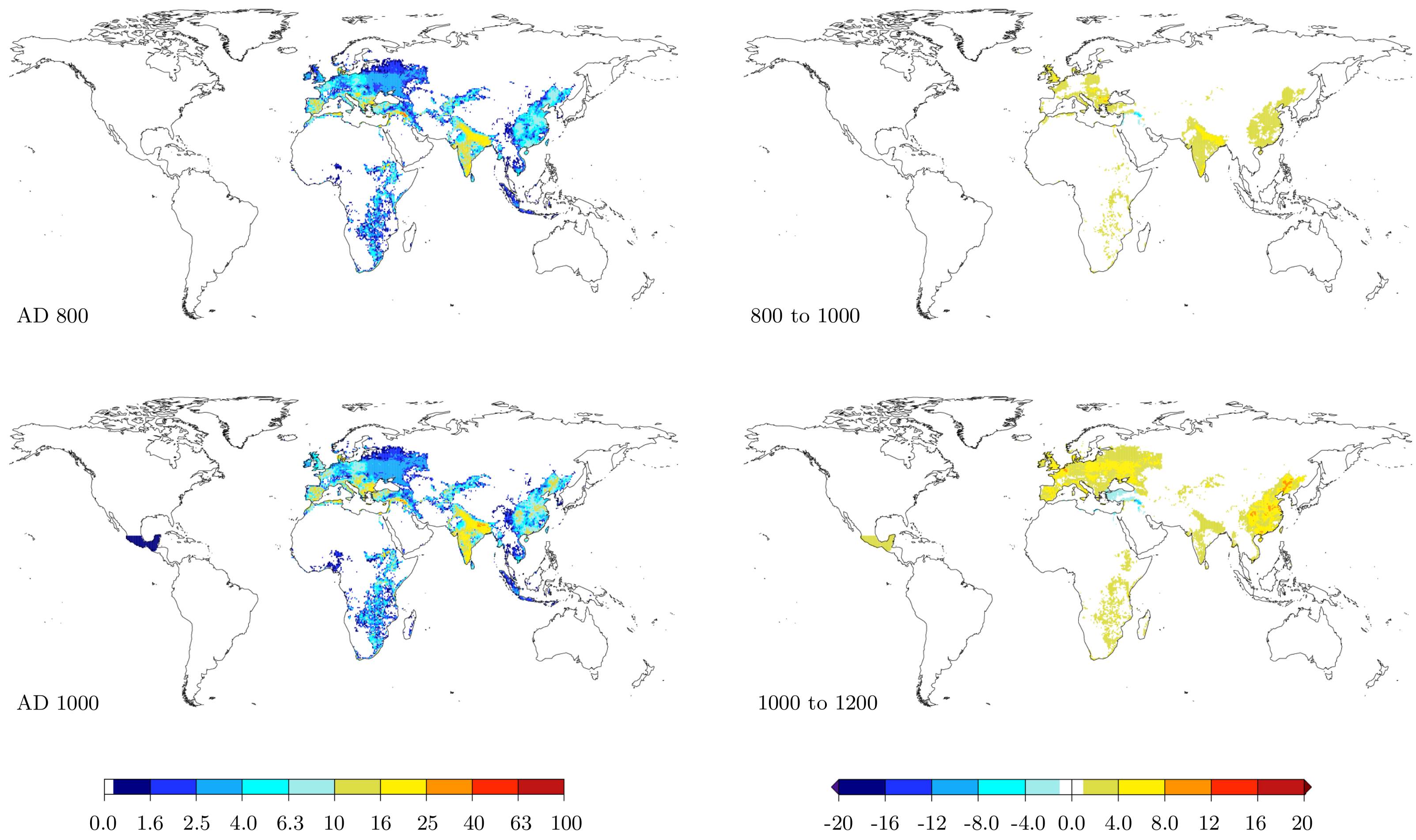

Figure 7: Global historical cropland area (left) and changes during given time interval (right). Units are percent of grid cell. Values smaller than ± 1% are colored white. Note the logarithmic scale for area estimates.

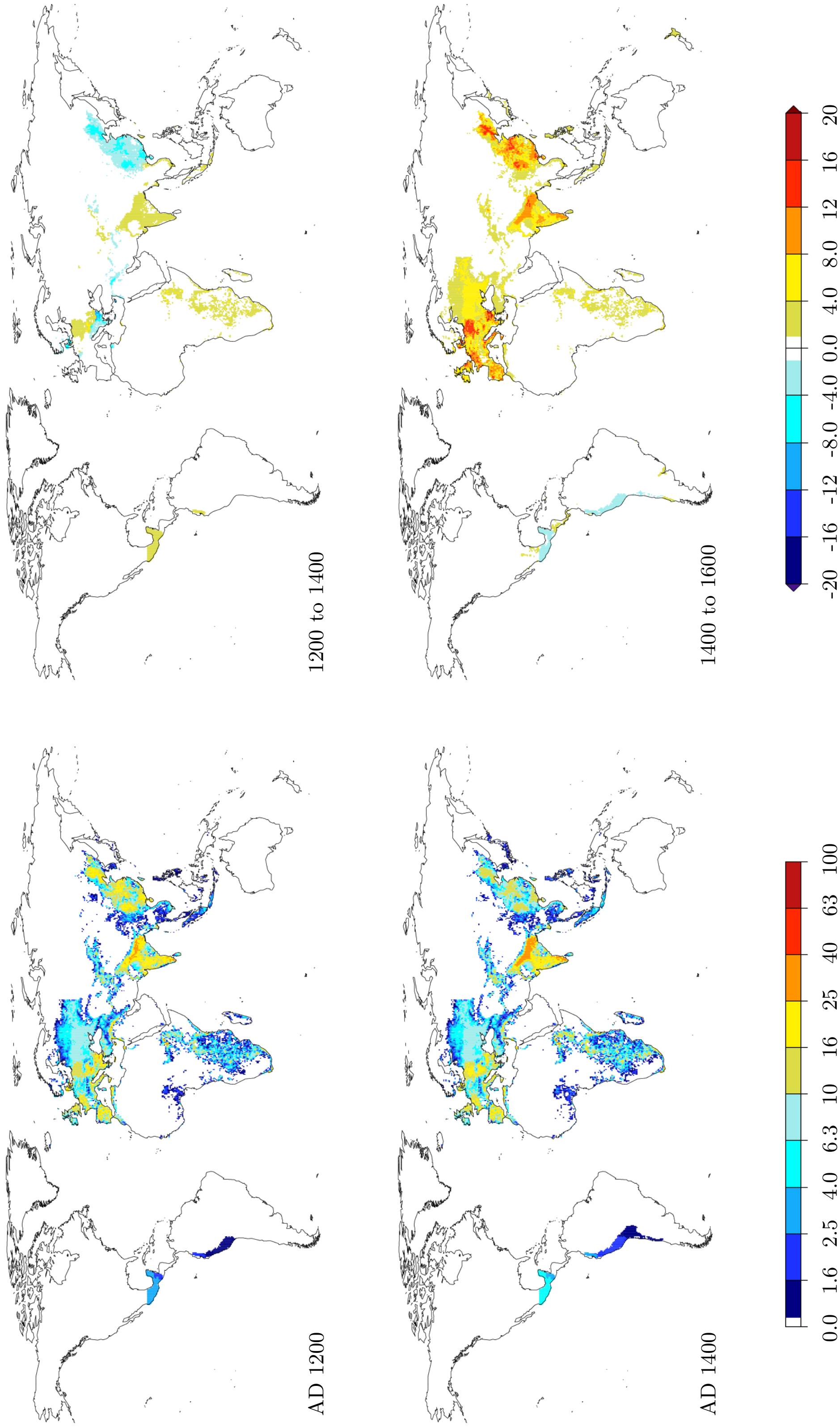

Figure 7 (continued)

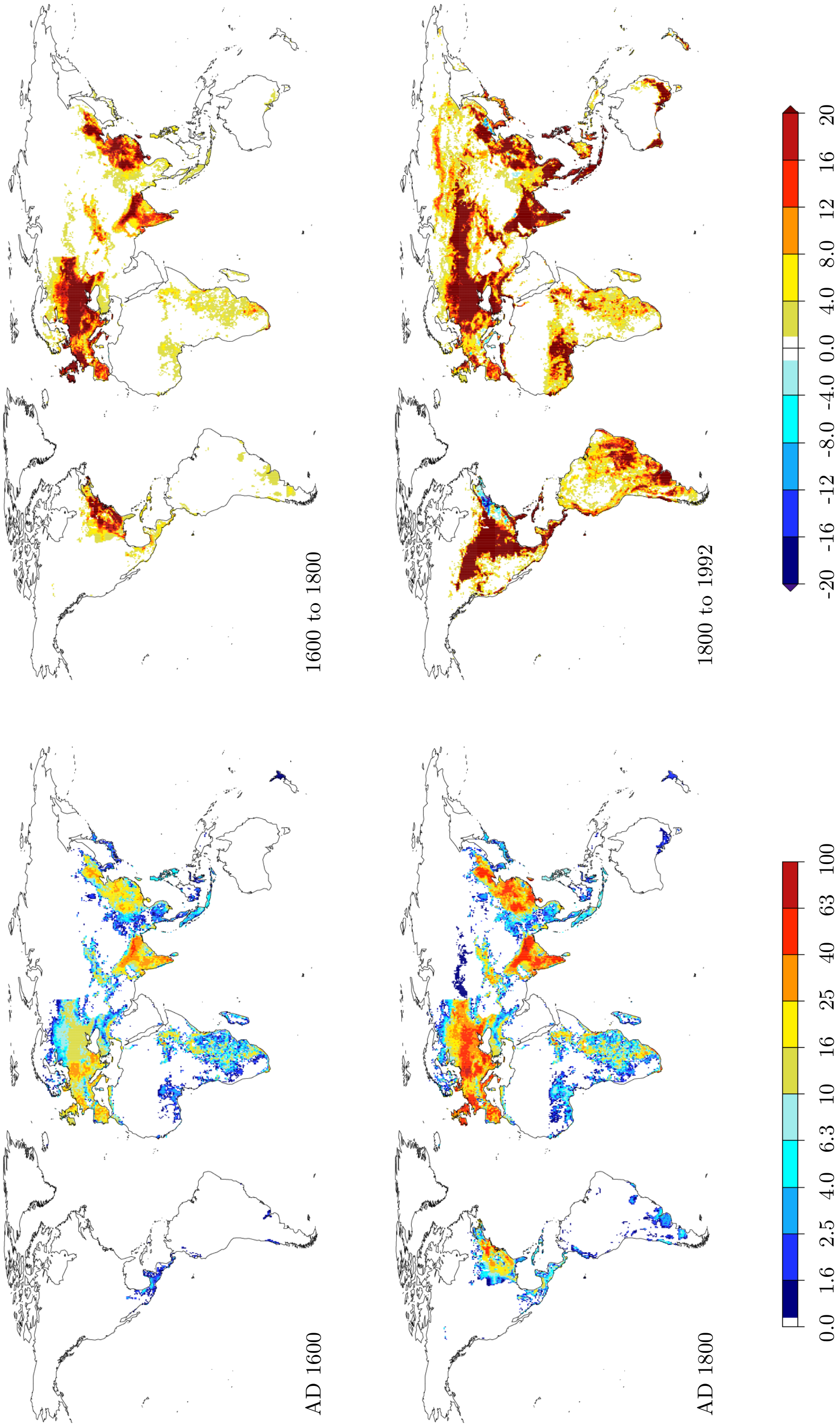

Figure 7 (continued)

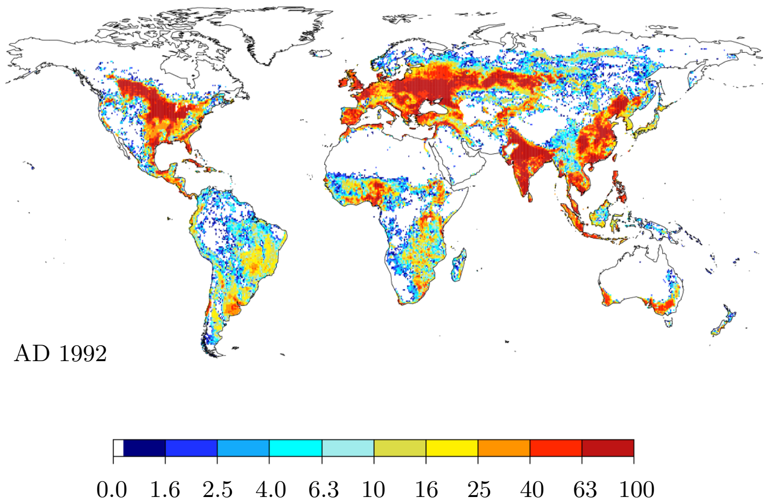

Figure 7 (continued)

nological progress was fast, especially in the Northwestern countries, but at the same time centuries had to pass before a useful innovation found widespread application, and more marginal land had to be brought under cultivation. Still, we estimate total land use area in the early centuries of the reconstruction more probably at the low than at the high end of the displayed uncertainty range.

While rates of change slowed down in most of Europe in recent decades and even allowed for regrowth of natural vegetation, notable land cover changes occurred in the FSU. In this region agriculture had mainly been restricted to the European part prior to the 19th century, when for the first time significant numbers of settlers started to colonize Siberia. Only Russian Turkestan looks back on an ancient history of agriculture with a strong predominance of pastoralism [Vasey, 1992]. During 1940-1960 rapid land cover conversions took place in the FSU associated with the opening up of the "New Lands" [Ramankutty and Foley, 1999]. While agricultural expansion took place mainly at the expense of forested regions in Europe, expansions in the FSU affected both forests and steppe and reduced natural grasslands to a fifth of their potential area.

7.2 North Africa/Middle East

In Southwest Asia lies one of the birthplaces of agriculture. Wild cereals, among them the progenitors of wheat and barley, were harvested already in the 10th millennium BC and seed agriculture developed, associated early with the use of ploughs and draught animals [Grigg, 1974]. Crops as well as the domesticated animals — sheep, goats, cattle and pigs — spread from this place to Europe, India and North Africa. Intensive agriculture in AD 800 is

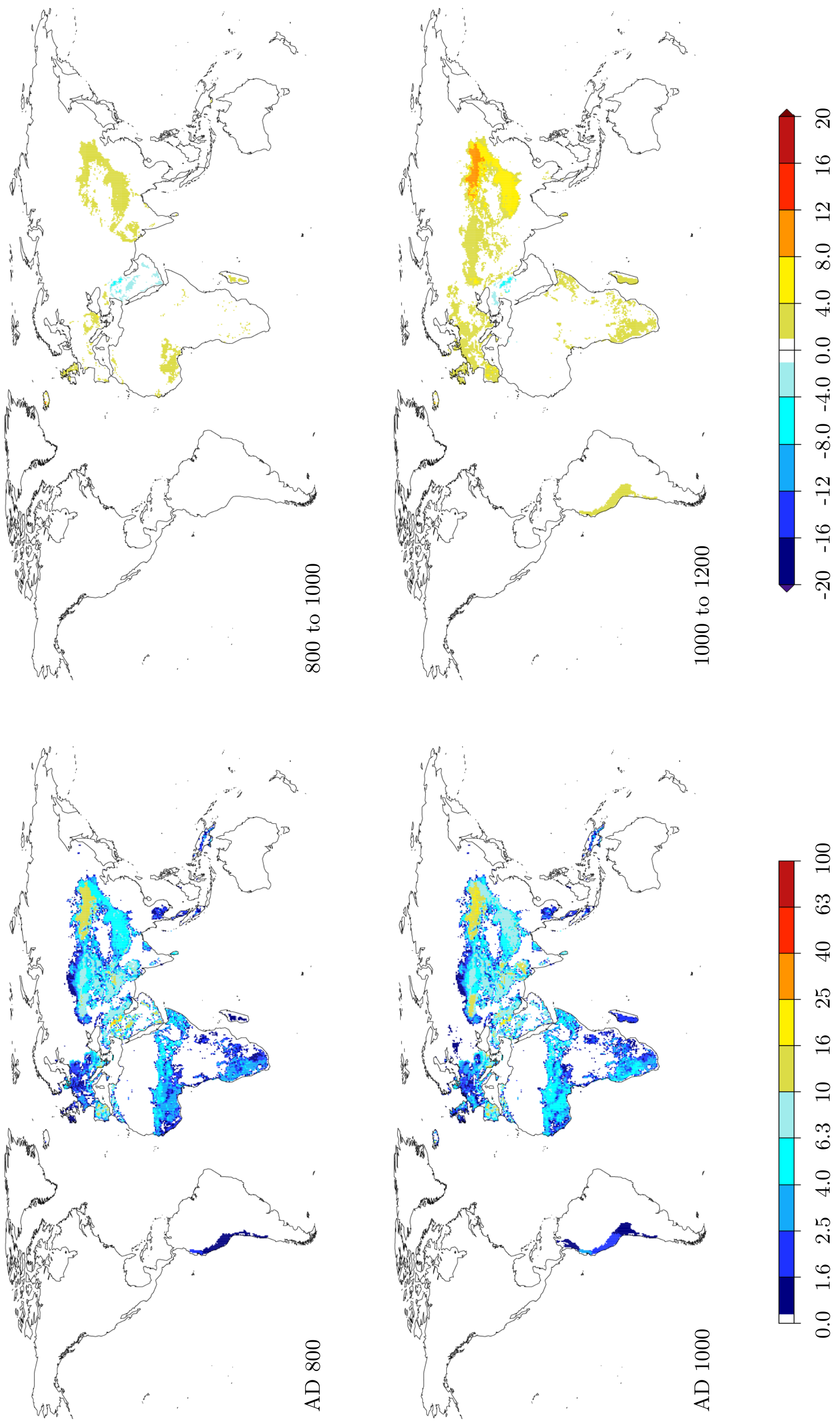

Figure 8: Global historical pasture area (left) and changes during given time interval (right). Units are percent of grid cell. Values smaller than ± 1% are colored white. Note the logarithmic scale for area estimates.

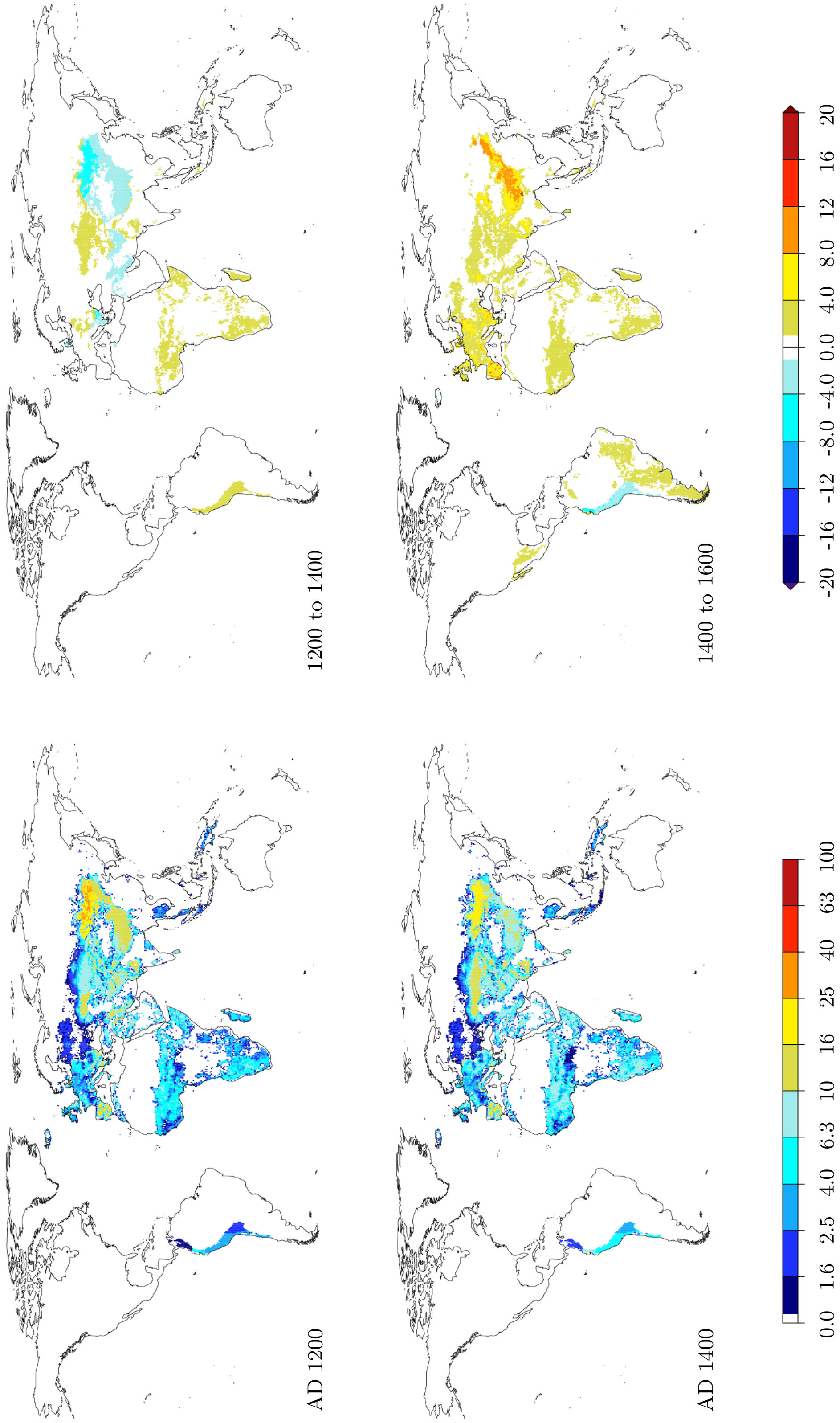

Figure 8 (continued)

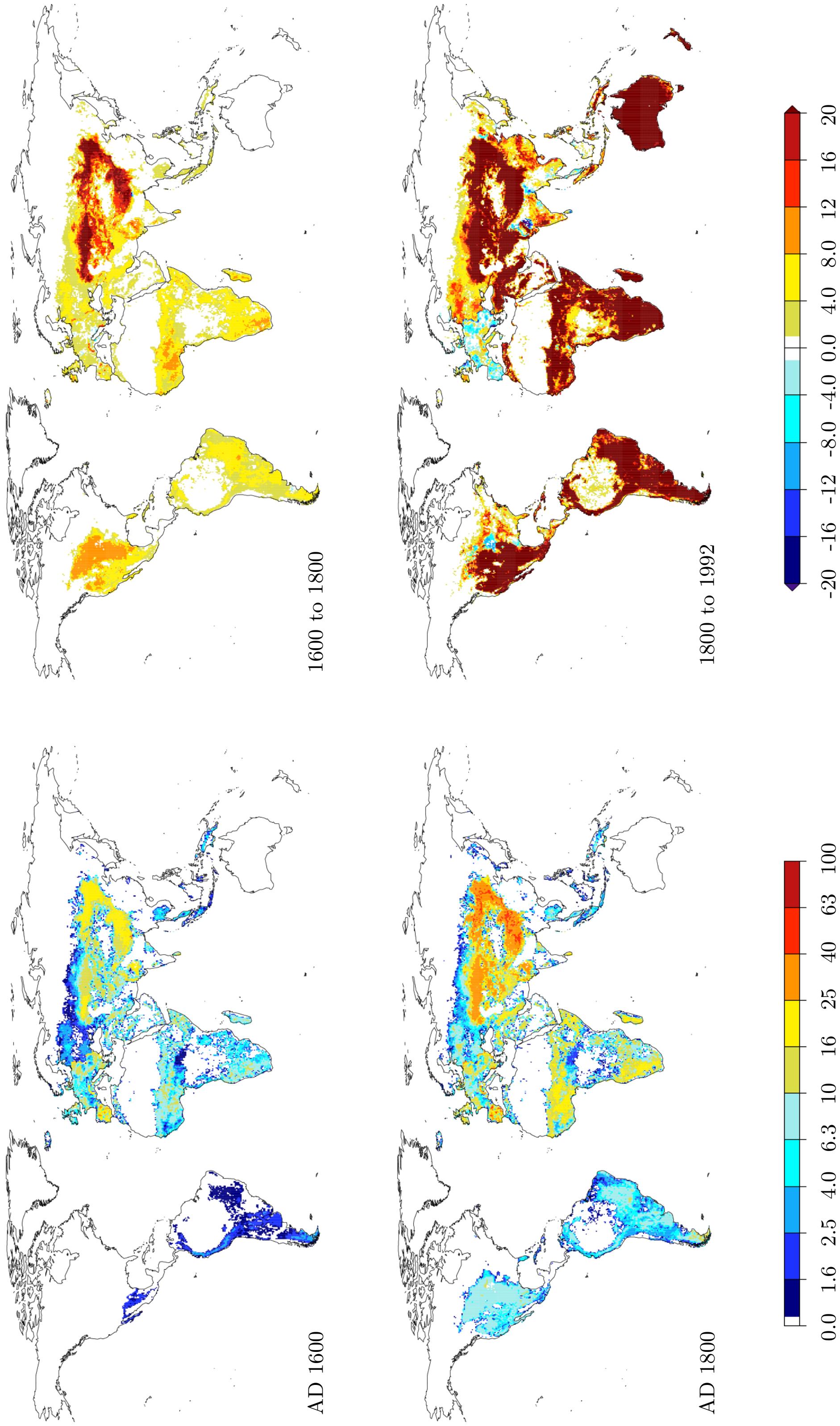

Figure 8 (continued)

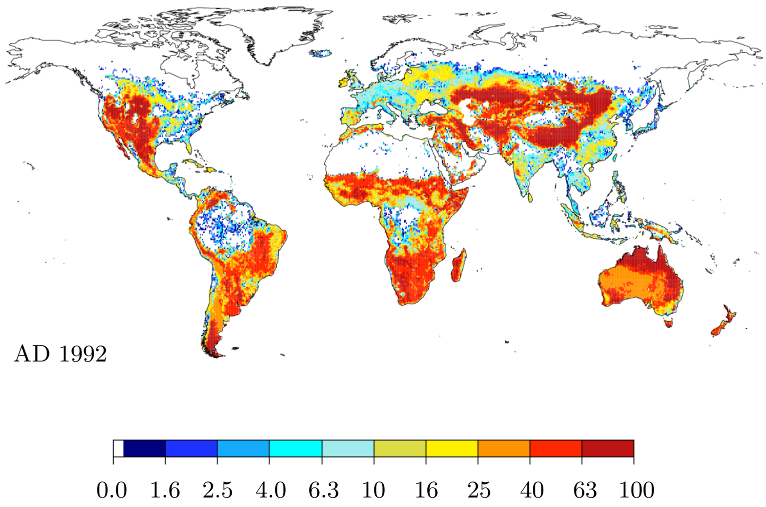

Figure 8 (continued)

restricted, however, to the Mediterranean coast and Anatolia, where climate is more favorable, and to the irrigated fields of Egypt and the Fertile Crescent (Figs. 7 and 8). The latter is the most intensely cultivated area world-wide at the beginning of our reconstruction, with crop fractions of up to 50%. This prominent role, however, is lost during the next few centuries, and a multitude of reasons led to stagnating agriculture also in the other regions of the Middle East and North Africa (Fig. 9 c). In Persia, Turkish invasions between AD 1000 and 1500 strongly inhibited sedentary farming and the prosperity gained during the Islam's golden age gradually ebbed away [McEvedy and Jones, 1978]. Turkish invasions also affected Anatolia, one of the more fertile regions. In North Africa, the Hilali Bedouin in the 11th century, the plague in the 14th and the general Mediterranean economic recession in the 17th century had negative effects on peasant activity [Grigg, 1974, McEvedy and Jones, 1978]. In Egypt, all land was already exploited as far as technology allowed. Crop and pasture thus remained at a relatively low extent for many centuries until population gradually grew from the 18th century onwards. With pastoralism being the dominant form of agriculture, much natural grassland was now used for grazing (Fig. 10 c). Crop production became more important in the 20th century, associated with a steep increase of population, and with it woody vegetation was reduced.

The long history of cultivation in this region most probably degraded land productivity in many regions, with salinization becoming a common problem in irrigated areas. Permanent agriculture was frequently given up in favor of nomadism in times of economic recession and warfare [Grigg, 1974]. Our persistent estimate thus lies at the higher end of crop estimates, and uncertainties are large for natural and managed grassland areas. Errors in the population estimates play a minor role only — though absolute numbers are still subject to dispute,

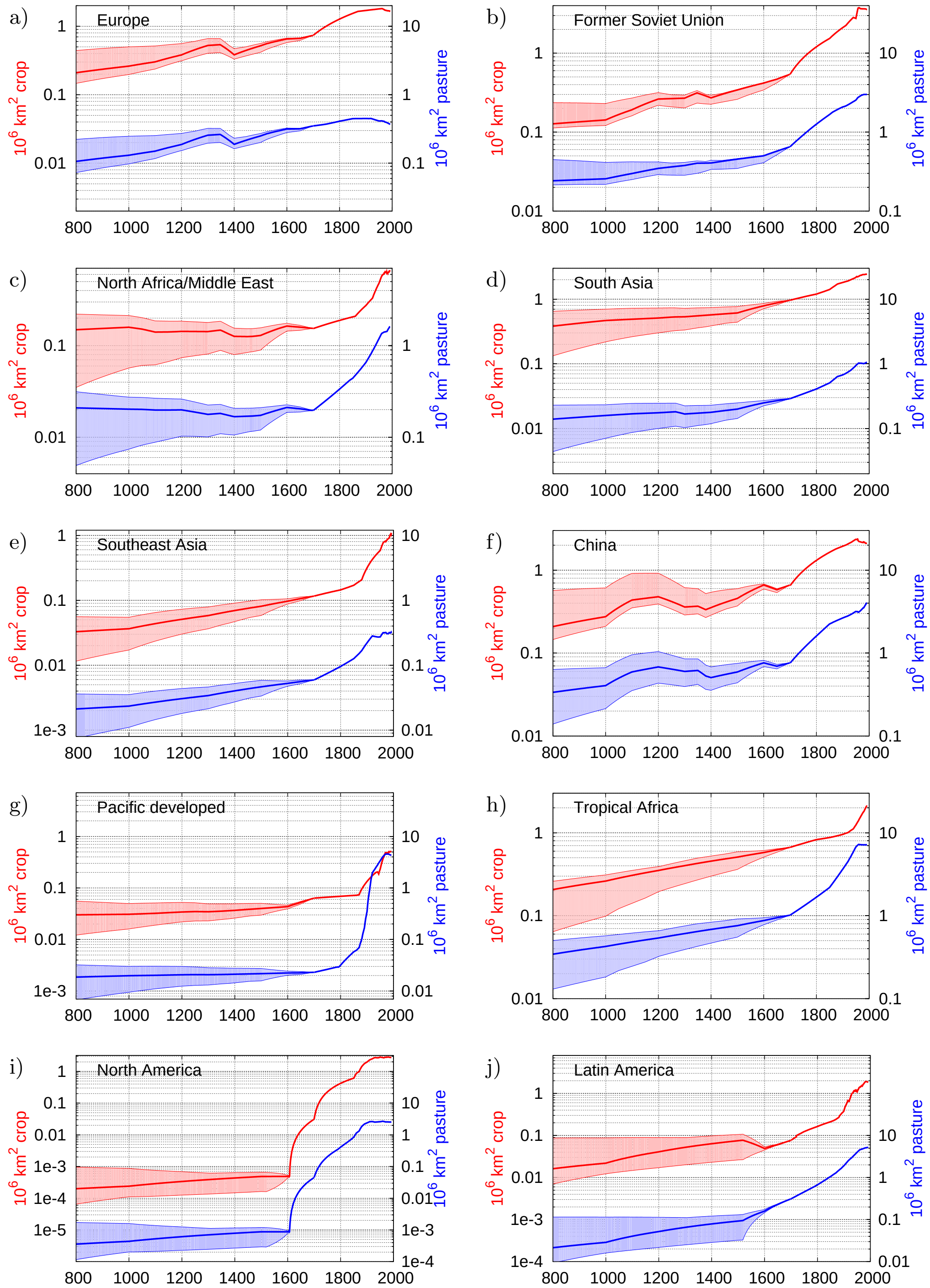

Figure 9: Total area of crop (red, left axes) and pasture (blue, right axes) for the 10 regions defined in App. C from AD 800 to 1992 (in 10^6 km^2). Shaded area indicates uncertainty range (see text for explanation).

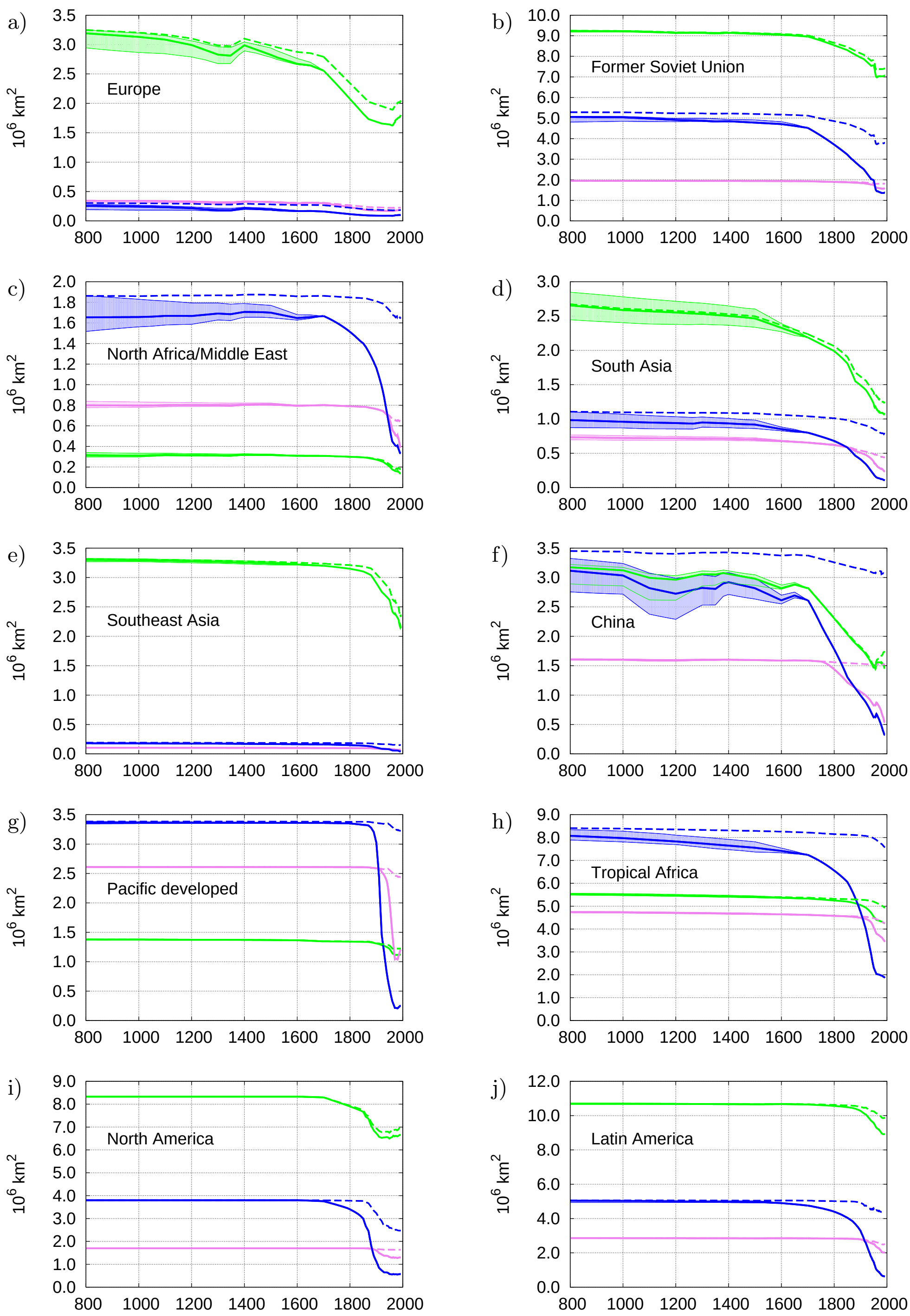

Figure 10: Total area of natural vegetation — forest (green), grasslands (blue), and shrublands including tundra (magenta) — for the 10 regions defined in App. C from AD 800 to 1992 (in 10^6 km^2). Shaded area indicates uncertainty range (see text for explanation). Dashed lines are land cover change due to cropland only.

growth rates are rather similar in all literature estimates.

7.3 South Asia and Southeast Asia

The Indian subcontinent experienced early, though temporary, peasant settlement in the Indus valley already 5000 BC. In the 8th century BC the introduction of iron tools and wet rice cultivation brought large areas in the Ganges valley under cultivation. Population boomed, but low nutritional densities suggest that population pressure has not been a problem until more recent times [Grigg, 1974, Vasey, 1992]. So, although South Asia was the major player in global crop production in AD 800 with about $4 \cdot 10^5$ km^2 cultivated land (Fig. 9 d), the potential for further agricultural expansion was still large. Crop areas consequently grew steadily, though at moderate pace first. Population most certainly has been set back several times throughout the centuries, but historical evidence is sparse. A significant part of the indicated uncertainties must thus be attributed to demographic data. From the 16th to the 19th century agricultural expansion accelerated, significant amounts of forest were cleared for cropland, and grass and shrubland used for grazing (Fig. 10 d). Under European control and after independence, the pattern became more complex with agricultural expansion set off by abandonments in various parts of India.

Compared to the Indian subcontinent, agricultural activity was low in Southeast Asia in AD 800 and remained so for the next thousand years. On the Malay Archipelago peasant population has always been concentrated on the southern islands, a pattern reflected in Figs. 7 and 8. On Luzon, terrace farming and irrigation certainly existed at that time, but areas are too small to show up in AD 800. Much of the increase in cropland area that happened in Southeast Asia (Fig. 9 e) must be attributed to the spread of wet rice, which had been introduced from China or India about 2000 years ago. Rice also has a key role in the high expansion rates of crop in the mainland countries in the 19th and 20th century, when Myanmar and Thailand grew to become major exporters of rice. In recent decades, the Southeast-Asian region has one of the highest deforestation rates globally. Pasture areas are small compared to cropland in Southeast Asia with a total of $3.1 \cdot 10^5$ km^2 in 1992, but some of the highest stocking rates of the world are found in these countries [Asner et al., 2004].

7.4 China

An independent development of seed agriculture took place in Northern China in the 5th and 6th millennia BC including the domestication of pigs, while tropical vegeculture was practiced further south. Based on these traditions, it is not surprising that Chinese crop area was large by AD 800, estimated at $2.1 \cdot 10^5$ km^2. Large-scale migration from the Yellow River south in the preceding centuries had probably led to a crop pattern similar to today, covering much of the Eastern part of the country. Not reflected in pattern, however, is the following further concentration of agriculture in the southeastern areas. With it, agricultural methods changed notably, with increasing focus on rice and the introduction of double-cropping. The possible range of crop area prior to the 14th century is thus large, and the persistent estimate is at its lower end (Fig. 9 f). Population data contributes only marginally to the uncertainties thanks to meticulous dynastic censi. Two dramatic events interrupted the otherwise strong growth of population and agriculture: the country lost about a third of its population in the course of the Mongol invasions starting in AD 1211, and again population decreased by about a sixth in the upheavals after the fall of the Ming Dynasty in 1644. Thereafter, growth was resumed at unprecedented pace, and half of China's natural forest cover was transformed to cropland.

The $3.4 \cdot 10^5$ km^2 of pasture in AD 800 is almost exclusively located in Mongolia and Tibet, where herding, be it horse-ridden or not, was the traditional form of agriculture well into the 20th century. The large uncertainties of the estimates should be seen as tribute to nomenclature — nomadism makes it difficult even today to define permanent pastures. The expansion we see is largely at the expense of natural grassland or tundra vegetation (Fig. 10 f).

7.5 Pacific developed

A clear break occurs in the late 19th century in the developed countries of the Pacific with very little land use area and dynamics over the preceding millennium and a steep increase of agriculture — mainly pasture — afterwards (Fig. 9 g). In Japan, fish has been a major part of the traditional diet, and meat and dairy products were uncommon, so that farming played a minor role compared to India or China. The major crop was rice, which had been introduced from China around AD 300 and was cultivated in Japan with high nutritional density. The agricultural area needed per capita in AD 1700 is thus extraordinarily small. We see notable increases in cropland only between 1870 and 1960 and of pastures after 1920, but even at present only about 20% of Japan are under agricultural use. Most of the increase in crop area in the Pacific developed region after 1945 results from expansion in Australia. Prior to the 19th century only the low-intensity agriculture of the Aborigines existed. After 1870 crop expanded in Southeast Australia, later in Western Australia, affecting grass as well as woody ecosystems. An additional $4.1 \cdot 10^6$ km^2 of pasture exist in 1992 in Australia, making it the country with the most land area in grazing systems. Europeans brought pastoralism to the arid and semiarid regions of Australia in the form of ranching, and pastures have steadily expanded since the late 19th century [Vasey, 1992]; only the last decades saw a slight reduction of pasture area. For a large part natural grasslands were used as pastures, but also shrubland with woody vegetation, which was not always permanently cleared for herding.

The reduction in shrubland seen in Fig. 10 g for the last century may thus be overestimated when defining pastures as open grassland. New Zealand shows a similar trend in crop and pasture as Australia though at much smaller absolute numbers. On the North Island some cropland emerged after the 15th century, when the semi-agricultural Maori population, which had immigrated from Polynesia, steadily grew. By contrast, the South Island remained unaffected until European immigration.

7.6 Tropical Africa

By 1700 the region south of the Sahel was still largely unexplored outside the coastal regions and population numbers and agricultural habits are still a matter of dispute. Vegeculture must have existed from the 5th millennium BC onwards in West Africa and cereal cultivation developed in the Horn region. The Northern savannas were agriculturally used by the 3rd or 2nd millennium BC. Important plants and animals found their way from Southwest Asia to Africa. The plough, however, was not adopted until the 19th century [Grigg, 1974]. Livestock was domesticated in East Africa already in the early Holocene and moved westward and southward in the following millennia. The Bantu expansion is one of the key factors in spreading cereal cultivation, pastoralism and iron technology throughout much of sub-Saharan Africa [Grigg, 1974, Hanotte et al., 2002], and with it the pattern of agriculture may have been subject to some change especially in the early centuries of our reconstruction. The uncertainty range suggests low values for cropland and pasture extent to account for the possibility that Bantu culture gradually replaced cultures based on hunting and gathering. Much of the uncertainty in this part of the world, however, is due to contradictory population estimates ranging, e.g., between 25 and 50 million for AD 1000.

In general we observe a steady increase of agriculture in all countries of tropical Africa, which comprises the most different cultures, some of which are almost exclusively depending on herding while others mix husbandry with significant cultivation [Vasey, 1992]. Animal husbandry is and has always been a significant sector of agriculture in this part of the world, and features as the dominant type of land use in West Africa, the Horn and Southwest Africa in the early centuries of our reconstruction (Fig. 8). Grazing focuses on the vast savanna regions and it seems reasonable to assume that their woody fractions are notably affected only during the last two centuries, with the onset of exponential population growth and increasing pressure on ecosystems. Figure 9 h shows that the expansion of pasture came to a halt in the 1960s, while croplands further increased. The pattern of cropland changed to form new centers in South Africa, the Lake Victoria region and Nigeria, though much of today's crop cover in tropical Africa still remains under low intensity subsistence farming [Ramankutty and Foley, 1999].

7.7 The Americas

While there was a lively dispersal and interchange of domesticated plants and animals across the three continents of the Old World, the Americas developed their very own forms of agriculture: cultivation was based on notably different crops than in Eurasia and Africa, among them maize and potatoes, no herding animals existed, and metals were rarely used in agriculture until the European conquest in the 15th century. There are two regions, Meso-America and coastal Peru, where plant domestication took place. From the first evidence dating back to the sixth and fifth millennium BC farming gained gradually more importance and by about AD 500 crops had spread as far north as the Great Lakes [Grigg, 1974]. In Central and South America, notable cropland intensities developed only within the high cultures, while outside these regions low-intensity swidden cultivation was practiced (Fig. 7). The centuries preceding European colonization saw a rapid increase of population, by a factor of 4 between AD 800 and 1500, which expanded crop areas to some $0.8 \cdot 10^5$ km^2 in our estimates. Pasture at the same time is estimated to be $0.9 \cdot 10^5$ km^2 and located mainly on the grasslands in the Andes, where some peoples are known to have kept llamas and other cameloids [Vasey, 1992]. The uncertainty range around these estimates, however, is large despite the small total area, based on the historians' dispute about pre-Columbian population (Sec. 6.3). Significant agricultural areas must have been abandoned as the Indians struggled with European weapons and diseases, and cultivated areas were shifted from the West towards the East coast (Figs. 7 and 8). In the tropical and subtropical lowlands, Europeans first intensified the existing swidden system, later cleared land for export-oriented plantation crops [Williams, 1990]. With the arrival of the Europeans started a large-scale transformation of natural vegetation for crop cultivation as well as for ranching. Much of the natural grasslands of the steppe and savanna is used today for grazing (Fig. 10 j).

If Central and South America played a minor role in global agricultural production a millennium ago, North America's part was marginal. Some clearing of natural vegetation took place in a kind of swidden system that often also included shift of settlements, but wild food remained important [Vasey, 1992]. The spatial pattern and the distinct cultures of the different peoples in North America are not resolved by our global reconstruction, which should thus not be applied in small-scale studies in this part of the world prior to colonization. Land cover change under European rule is much better documented, and with the settlers the European form of agriculture was introduced to the East Coast and subsequently spread west. While the crop maps of Ramankutty and Foley [1999] are based on state-level data from 1850 onwards and are thus able to catch this relocation, our algorithm for historical pasture is based on national totals. Some of the grassland in the Great Plains and further west, which Fig. 8 classifies as pasture in AD 1800, was thus probably still pristine, and pastures located further east instead. Robust features, after centuries of very low agricultural activity, are the steep increase of cropland and pasture extent on continental scale during the 18th and 19th century with stagnating numbers in the 20th century.

8 Conclusion

This study has presented a simple approach to reconstruct global historical land use for time periods where agricultural data is scarce. Country-based population numbers have been used as proxy for agricultural activity. A method, based on few, basic assumptions, has been developed that allows to consistently translate these population data into estimates of extent of cropland and pasture. Its transparency enables the user to easily identify possible errors in specific regions, and we have tried to specify the uncertainties associated with our approach. The reconstruction shows that overall land cover change was small between AD 800 and AD 1700 compared to industrial times. Considering, however, the strong population growth during this period and the steadily growing dominance of agriculture over hunting and gathering cultures, land cover change during the pre-industrial time period of the last millennium must have been large compared to previous millennia. Notable fluctuations and distinct histories of agriculture are revealed on regional scale. To our knowledge, this study is the first attempt to reconstruct a consistent time evolution of global land use at spatially explicit resolution that covers the entire last millennium.

There are no global data available that could be used to validate our reconstruction. Local studies can be found for specific time periods, but the subnational scale is not the proper basis for comparison. Except for a few regions, no subnational data were included in our approach, so that meaningful tests can be performed only at the country level or higher. Once independent estimates of historical land use from proxies such as pollen profiles, archeological evidence, and historical records become available for larger regions, we hope to compare our reconstruction against these estimates. The results of the millennium reconstruction are, however, in general agreement with common knowledge about the history of agriculture, and we are confident that our approach captures the global pattern of land use change and gives a sound approximation of the regional dynamics.

In addition to reconstructing historical land use, estimates of human-induced changes in natural vegetation cover have also been derived. They provide a better picture of what types of vegetation were transformed to cropland and to pasture. Our estimates show that up to AD 1700 temperate and tropical broadleaf deciduous forests were most severely affected by crop cultivation, while large areas of natural grassland were used as pasture.

The history of land use and land cover change is interesting in its own right. Additionally, its knowledge is an essential prerequisite to assess early human impact on the environment. Changes in land cover can strongly influence climate through biogeophysical and biogeochemical effects [see, e.g., Pitman and Zhao, 2000, Claussen et al., 2001, Houghton and Hackler, 2001, Zhao et al., 2001, Bounoua et al., 2002, Brovkin et al., 2004]. Several model experiments suggest that pre-industrial land cover change exerted a notable impact on the Earth system [Brovkin et al., 1999, DeFries et al., 1999, Bertrand et al., 2002, Brovkin et al., 2006], but they also acknowledge that strength, timing and location of the land forcing need to be better known. In combination with ecosystem and climate models, geographically explicit data sets like the reconstruction presented in this study can contribute to a better understanding of the human role in past changes of the Earth system.

A digital version of the millennium reconstruction of global land use and land cover is available from the World Data Center for Climate (DOI: 10.1594/WDCC/RECON_LAND_COVER_800-1992). Please contact the authors for further information.

Appendices

A Population of the Former Soviet Union AD 1700–1992

year	FSU in Europe	Russian Turkestan	Siberia	Amur region
1700	21.75	4.50	0.08	0.23
1750	26.13	5.25	0.39	0.26
1800	38.00	6.00	0.70	0.30
1850	63.25	8.00	2.16	0.34
1900	107.50	11.00	5.63	0.38
1950	136.00	18.00	26.59	0.41
1975	185.00	36.00	32.16	1.84
2000	222.00	60.00	36.72	3.28

Table 3: Population (in million) for FSU regions as defined in the text. Values from McEvedy and Jones [1978]. To take into account that much of Siberia's population was concentrated in the Amur region prior to the European immigration wave, McEvedy and Jones's data for Siberia is split up: Until 1700, 75% of the population is assigned to the Amur region, until 1950 population in this region is linearly extrapolated using the data for 1600 and 1700, the remaining population is assigned to Siberia. This ensures that the immigrants from Europe are assigned to West and central Siberia. Since the Amur region strongly developed after World War II, a linear interpolation is done from 1950 to a population estimate for 2000 derived from United Nations Statistics Division [2006].

B Population data for pre-conquest America

For no other region in our study do published population numbers differ as much as for pre-conquest Central and South America, spanning one order of magnitude. Population data, also of indigenous people, was gathered soon after the conquest. The point at issue is how steep the previous decimation of the Amerindians was. McEvedy and Jones choose pre-conquest values at the very low end of estimates, summing up to 13 million in 1500, but reason only by analogy to other parts of the world at comparable levels of culture. Most other authors argue that population must have been much larger, given how many must have been killed by the invaders and the Old World diseases they brought, and the impacts of other, more subtle demographic effects [Newson, 1993]. We follow the majority of authors in assuming larger numbers and adopt the figures of Clark, whose 40 million lie at the persistent high end of estimates.

Since population is concentrated in the Mexican and Andean high cultures, national numbers are broken down to better represent this spatial heterogeneity. First, Clark's estimate is divided between countries using relative proportions from McEvedy and Jones while assuming that the difference in absolute numbers between the authors arises mainly from mismatch in the high cultures. Then, population is further divided between high cultures and other tribes where appropriate. It must be kept in mind that this process is not done in order to give detailed population estimates for use outside this study, but is an attempt to reduce implausible features in land use that would be introduced if the knowledge of differences between cultures was simply ignored. The details of population allocation are as follows: The settled region of the high cultures — Incas and their predecessors of the Andean culture sequence, Mayas, Toltecs, Aztecs — are regionally defined as an overlay of the heights of expansion and kept constant throughout AD 800 until European conquest. In Chile, all population is located in the Inca Empire, leaving the southern part of the country unpopulated. For Argentina and Uruguay (combined here), the main part of the population is assigned to the Inca Empire, only the Guarani tribe in the northeast is assumed to have a population density similar to the Indians in Paraguay. In Bolivia, Peru, Ecuador and Colombia a population density of the lowlands is assumed that imitates the ones of Venezuela and the Guyanas, the remaining, major part of the population is attributed to the Inca Empire. The same population density outside the high cultures is assumed in Central America, again attributing most people to the region of the high cultures.

C List of countries of the 10 analysis regions

Europe

Albania	Luxembourg
Andorra	Macedonia
Austria	Malta
Belgium	Monaco
Bosnia	Montenegro
Bulgaria	Netherlands
Croatia	Norway
Czech Republic	Poland
Denmark	Portugal
Finland	Romania
France	San Marino
Germany	Serbia
Greece	Slovakia
Hungary	Slovenia
Iceland	Spain
Ireland	Sweden
Italy	Switzerland
Liechtenstein	United Kingdom

North Africa and Middle East

Algeria	Libya
Bahrain	Morocco
Cyprus	Oman
Egypt	Qatar
Iran	Saudi Arabia
Iraq	Syria
Israel	Tunisia
Jordan	Turkey
Kuwait	United Arab Emirates
Lebanon	Yemen

Tropical Africa

Angola	Malawi
Benin	Mali
Botswana	Mauritania
Burkina Faso	Mauritius
Burundi	Mozambique
Chad	Namibia
Congo	Niger
Cameroon	Nigeria
Cape Verde	Reunion
Central African Rep.	Rwanda
Comoros	Sao Tome and Principe
Djibouti	Senegal
Equatorial Guinea	Sierra Leone
Eritrea	Somalia
Ethiopia	South Africa
Gabon	Sudan
The Gambia	Swaziland
Ghana	Tanzania
Guinea	Togo
Guinea-Bissau	Uganda
Ivory Coast	Western Sahara
Kenya	Zaire
Lesotho	Zambia
Liberia	Zimbabwe
Madagascar	

Former Soviet Union

Armenia	Lithuania
Azerbaijan	Moldova
Belarus	Russia
Estonia	Tajikistan
Georgia	Turkmenistan
Kazakhstan	Ukraine
Kyrgyzstan	Uzbekistan
Latvia	

China

China	Mongolia

Pacific developed region

Australia	South Korea
Japan	Papua New Guinea
New Zealand	Taiwan
North Korea	Other Oceania

South Asia

Afghanistan	Myanmar
Bangladesh	Nepal
Bhutan	Pakistan
India	Sri Lanka

South East Asia

Brunei	Malaysia
Cambodia	Philippines
Indonesia	Thailand
Laos	Vietnam

North America

Canada	United States
Greenland	

Latin America

Argentina	Haiti
The Bahamas	Honduras
Belize	Jamaica
Bolivia	Martinique
Brazil	Mexico
Chile	Nicaragua
Colombia	Panama
Costa Rica	Paraguay
Cuba	Peru
Dominican Republic	Puerto Rico
Ecuador	St. Vincent and the Grenadines
El Salvador	Suriname
Falkland Islands	Trinidad and Tobago
French Guiana	Uruguay
Guadeloupe	Venezuela
Guatemala	Virgin Islands
Guyana	

D Agricultural efficiency AD 800–1700

We use the following data for the estimates of agricultural efficiency relative to AD 1700, summarized in Tab. 4:

Europe

Several points of evidence hint to an increase in agricultural efficiency in Europe: Early already the three-course system was introduced and became more common as the medieval period wears on, especially during the two centuries of population increase prior to the onset of plague, but the trend is far from even. The three-course system is known in the seventh and eighth centuries in western Europe, whereas two courses are still in use in the eighteenth century in England, France and Germany [Vasey, 1992]. Low temperatures in the north and low rainfall in the south also restricted the three-course system regionally. Later, fallows are reduced through green manuring, and livestock feeding improves, increasing the supply of animal manure [Vasey, 1992]. Based on yield ratios published by Slicher van Bath [1963], we distinguish two groups of countries with different developments of agricultural productivity: The economically highly developed and densely populated Northwestern Europe, which, led by Britain, shows the highest increases in productivity, specifically after AD 1700, and Central, Northern, and Eastern Europe including Russia, which show little or no changes in productivity (large increases occur only after AD 1700). We use trends derived from these yield ratios as an upper boundary for the increase in agricultural efficiency. Numbers are likely to be too high for average farmland as yields are recorded on model farms, where agrotechnical progress is more readily and more successfully implemented, and as population pressure forces man to open up less fertile land. For the lower boundary, we retain our persistent estimate for the first group, and start with an efficiency 10% lower in AD 800 than in AD 1700 for the second group, with the total range linearly decreasing with time.

Mediterranean and Southwest Asia

Arabian conquest and rule of Southwest Asia and the Mediterranean had very opposing effects on agriculture. In North Africa and the Levant, the invasions led to a decline of sedentary agriculture in favor of pastoralism, a similar effect as resulted from the Turkish and Mongol invasions to Anatolia and the Near East some centuries later [Grigg, 1974, McEvedy and Jones, 1978]. Also, some agricultural systems of this region had reached highest levels of refinement during millennia of cultivation and left little potential to improve. To Spain, on the other hand, Arabs brought sophisticated knowledge of irrigation techniques adopted from Mesopotamia and Egypt, as well as Asian crops and horticulture [Grigg, 1974].

year	Europe			Asia			
	1	2	3	4	5	6	7
800	2.39 – 1.00	1.43 – 0.90	1.67 – 0.67	1.33 – 0.33	3.65 – 1.00	1.10 – 0.64	1.50 – 0.50
900	2.32 – 1.00	1.36 – 0.89	1.59 – 0.70	1.30 – 0.41	3.33 – 1.00	1.08 – 0.67	1.44 – 0.56
1000	2.23 – 1.00	1.28 – 0.86	1.52 – 0.74	1.26 – 0.48	3.00 – 1.00	1.05 – 0.70	1.39 – 0.61
1100	2.15 – 1.00	1.20 – 0.85	1.44 – 0.78	1.22 – 0.56	2.68 – 1.00	1.03 – 0.72	1.33 – 0.67
1200	1.94 – 1.00	1.14 – 0.84	1.37 – 0.81	1.19 – 0.63	2.36 – 1.00	1.00 – 0.75	1.28 – 0.72
1300	1.50 – 1.00	1.08 – 0.84	1.30 – 0.85	1.15 – 0.70	2.04 – 1.00	1.00 – 0.80	1.22 – 0.78
1400	1.37 – 1.00	1.02 – 0.85	1.22 – 0.89	1.11 – 0.78	1.72 – 1.00	1.00 – 0.84	1.17 – 0.83
1500	1.08 – 1.00	1.00 – 0.86	1.15 – 0.93	1.07 – 0.85	1.35 – 1.00	1.00 – 0.89	1.11 – 0.89
1600	1.00 – 1.00	1.00 – 0.85	1.07 – 0.96	1.04 – 0.93	1.00 – 0.98	1.00 – 0.94	1.06 – 0.94

year	Africa			Americas		Australasia
	8	9	10	11	12	13
800	1.33 – 0.33	1.00 – 0.33	1.67 – 0.67	1.50 – 0.50	1.67 – 0.67	1.50 – 0.50
900	1.30 – 0.41	1.00 – 0.41	1.59 – 0.70	1.44 – 0.56	1.59 – 0.70	1.44 – 0.56
1000	1.26 – 0.48	1.00 – 0.48	1.52 – 0.74	1.39 – 0.61	1.52 – 0.74	1.39 – 0.61
1100	1.22 – 0.56	1.00 – 0.56	1.44 – 0.78	1.33 – 0.67	1.44 – 0.78	1.33 – 0.67
1200	1.19 – 0.63	1.00 – 0.63	1.37 – 0.81	1.28 – 0.72	1.37 – 0.81	1.28 – 0.72
1300	1.15 – 0.70	1.00 – 0.70	1.30 – 0.85	1.22 – 0.78	1.30 – 0.85	1.22 – 0.78
1400	1.11 – 0.78	1.00 – 0.78	1.22 – 0.89	1.17 – 0.83	1.22 – 0.89	1.17 – 0.83
1500	1.07 – 0.85	1.00 – 0.85	1.15 – 0.93	1.11 – 0.89	1.15 – 0.93	1.11 – 0.89
1600	1.04 – 0.93	1.00 – 0.93	1.07 – 0.96	1.06 – 0.94	0.91 – 0.96	1.06 – 0.94

Table 4: Evolution of agricultural efficiency: numbers indicate high and low estimates of agricultural land per person scaled to 1 for AD 1700. Unless otherwise stated trends are linearly inter- and extrapolated from available data points. References are given in the text. Region IDs: 1 Northwest Europe, 2 North, Central, and East Europe, 3 Southwest Mediterranean Europe, 4 Eastern Mediterranean Europe and Southwest Asia, 5 China, Taiwan, Korea, 6 Japan, 7 Other Asia, 8 Mediterranean Africa, 9 Bantu-influenced Africa, 10 Other Africa, 11 North America, 12 Central and South America, 13 Australia and New Zealand

We therefore divide the region in two parts: We classify Spain and Italy as regions of general increase of efficiency. Here, farming intensified through Arabic influence as well as through population pressure, mainly by an expansion of irrigated area [Grigg, 1974]. On the other hand, these countries were also beginning to pay the penalty of their long history of settlement so that soil degradation was a common problem [Grigg, 1974]. This and other adverse effects let the Mediterranean countries lose their agricultural pre-eminence in Europe by the 16th century; a lower boundary with negative agrotechnical development reflects these considerations. All other Mediterranean countries and South West Asia, where permanent cultivation was negatively affected by history, are classified as regions of general decrease of agricultural efficiency.

Asia

Following migration, growing areas in China were shifted south and by the 14th century rice was established as a principal crop. Though wet rice cultivation is only possible in a few environments, it is important due to its favorable output per hectare — rice in Asia has a calorific value 1.7 times higher than wheat or maize [Van Royen in Grigg, 1974]. Irrigation and double cropping became more common after the 10th century. Later, in the 16th and 17th centuries, American crops altered Asian farming — maize, sweet potato, and peanut became principal crops on the coastal hill land of East Asia and opened up new land [Grigg, 1974]. We summarize these developments using changes in arable area from Perkins's in Grigg [1974] for AD 1400, 1600, and 1760-70 (we use relative numbers only as the areas cited by Grigg after AD 1700 are markedly lower than the estimates by Ramankutty and Foley [1999]). We allow for some uncertainty in Perkins's estimates starting with an additional 10% higher efficiency in AD 1400. We make a linear extension of Perkins's trend back until AD 800. This extrapolation is a rather high estimate given that prior to the 15th century frequent wars must have impaired agricultural development, and must be seen as upper limit. We combine the data with our persistent estimates and use the larger value as upper, the smaller value as lower boundary. Given the profound influence of Chinese agrotechnology on Taiwan and Korea, Chinese trends are also applied to these countries. Tibet and Mongolia, whose agriculture is mainly based on traditional nomadic pastoralism, are classified as regions of no change.

Wet rice and advanced agricultural techniques were gradually introduced from the mainland to Japan. We use estimates of arable area cited in Grigg [1974] for AD 1200, 1600 and 1700 reflecting these changes. We allow for some uncertainty of the estimates starting with an additional 10% higher efficiency in AD 1200 and again linearly extend the trend until AD 800. While this increases nutritional density by about 40% from AD 800 to 1700 with our census data, Grigg finds an unexplained decline in nutritional density using Perkins's population estimates. We use his estimate as a lower boundary.

Even where environmental conditions were similar, agricultural efficiency was much lower in most of Southeast Asia and in India than in China. Population pressure was low and the same extensive farming methods persisted for centuries [Vasey, 1992]. It seems appropriate to assume agricultural efficiency remained more or less the same. We therefore classify these countries as regions of no change.

Africa

Subsistence farming prevails in most of Africa outside the Mediterranean and Ethiopia in pre-colonial times, and low-intensity shifting cultivation dominates [Grigg, 1974]. Agricultural methods did not change significantly until the introduction of the plough in the 19th century. However, the fraction of people living from agriculture increased with time as the Bantu expansion brought crop — including Southeast Asian foodplants — and livestock to Central, East and South Africa, superseding the hunting and gathering cultures of the Pygmies and Bushmanoid peoples. Incorporating an increasingly larger fraction of the population in an agricultural system implies that the arable area per person increased, in contrast to the effect of decreasing area with agrotechnical improvements. Though exact dates are still subject to discussion, the Bantu expansion was probably still in progress until about the 13th century [Oliver, 1966, Grigg, 1974]. For the population south of the equator we assume that only a third of the fraction agriculturally active in AD 1700 were so already in AD 800 and adapt nutritional densities accordingly. Our persistent estimates would then become an upper limit suggesting that vegecultural people possibly preceding the Bantu [Oliver, 1966] held approximately as much arable land per person than the agricultural Bantu. The Sahel and the agriculturally advanced Ethiopian region are likely regions of general efficiency increase.

The Americas and Australasia

Central and South American farming systems had seen no radical changes until the time of European arrival, and population densities, except in the Valley of Mexico and parts of the Andes, were remarkably low [Grigg, 1974]. Some increase in intensification of agriculture may be inferred though from a growing number of drainage systems in Mexico and irrigation systems in the Inca Empire. We therefore classify Central and South America as regions of general efficiency increase. In pre-colonial North America, shifting cultivation and wild foods played an important role, and population pressure was low. There is thus no indication of significant changes in nutritional density of permanent agriculture until the Europeans arrived. Similar conditions can be assumed for the indigenous populations of Australasia [Vasey, 1992]. These regions are classified as no-change. We steadily adapt efficiency to values of Northwestern Europe in North America and Australasia and of Southern Europe in Latin America after European settlement began.

E Reclassification of natural vegetation

See Tab. 5 on the following pages.

Table 5: Rules for reclassifying the potential vegetation map of Ramankutty and Foley [1999] to the 15 vegetation types used in this study. T_{min} and T_{max} are mean temperature of coldest and warmest month, respectively.

Class of Ramankutty and Foley [1999]	Rules for reclassification		Class in this study
Tropical evergreen forest/woodland			Tropical evergreen forest
Tropical deciduous forest/woodland			Tropical deciduous forest
Temperate broadleaf evergreen forest/woodland			Temperate evergreen broadleaf forest
Temperate needleleaf evergreen forest/woodland			Temperate/boreal evergreen conifers
Temperate deciduous forest/woodland			Temperate/boreal deciduous broadleaf forest
Boreal evergreen forest/woodland			Temperate/boreal evergreen conifers
Boreal deciduous forest/woodland			Temperate/boreal deciduous conifers
Mixed forest	$T_{min} \geq 22°$		50% Tropical evergreen forest
			50% Tropical deciduous forest
	$18.8° \leq T_{min} < 22°$		33.3% Tropical evergreen forest
			33.3% Tropical deciduous forest
			33.3% Temperate/boreal evergreen conifers
	$15.5° \leq T_{min} < 18.8°$		25% Tropical evergreen forest
			25% Tropical deciduous forest
			25% Temperate evergreen broadleaf forest
			25% Temperate/boreal evergreen conifers
	$3° \leq T_{min} < 15.5°$		33.3% Temperate evergreen broadleaf forest
			33.3% Temperate/boreal deciduous broadleaf forest
			33.3% Temperate/boreal evergreen conifers
	$-2° \leq T_{min} < 3°$		50% Temperate/boreal deciduous broadleaf forest
			50% Temperate/boreal evergreen conifers
	$-20° \leq T_{min} < -2°$	$T_{max}-T_{min} \geq 43°$	40% Temperate/boreal deciduous broadleaf forest

Continued on next page

Table 5 – Continued

Class of Ramankutty and Foley [1999]	Rules for reclassification		Class in this study
			40% Temperate/boreal evergreen conifers 20% Temperate/boreal deciduous conifers
		T_{max}-T_{min} < 43°	50% Temperate/boreal deciduous broadleaf forest 50% Temperate/boreal evergreen conifers
	-32.5° ≤ T_{min} < -20°	T_{max}-T_{min} ≥ 43°	20% Temperate/boreal deciduous broadleaf forest 60% Temperate/boreal evergreen conifers 20% Temperate/boreal deciduous conifers
		T_{max}-T_{min} < 43°	25% Temperate/boreal deciduous broadleaf forest 75% Temperate/boreal evergreen conifers
	T_{min} < -32.5°	T_{max}-T_{min} ≥ 43°	20% Temperate/boreal deciduous broadleaf forest 80% Temperate/boreal deciduous conifers
		T_{max}-T_{min} < 43°	Temperate/boreal deciduous broadleaf forest
Savanna	|latitude| < 38°		40% Raingreen shrubs C3 grasses, C4 grasses [3]
	|latitude| ≥ 38°		20% Temperate/boreal deciduous broadleaf forest 20% Temperate/boreal evergreen conifers C3 grasses, C4 grasses [3]
Grassland/steppe			C3 grasses, C4 grasses [3]
Dense shrubland	T_{min} < -10°		80% Summergreen shrubs C3 grasses, C4 grasses [3]
	T_{min} ≥ -10°		80% Raingreen shrubs C3 grasses, C4 grasses [3]
Open shrubland	T_{min} < -10°		40% Summergreen shrubs C3 grasses, C4 grasses [3]
	T_{min} ≥ -10°		40% Raingreen shrubs

Continued on next page

Table 5 – Continued

Class of Ramankutty and Foley [1999]	Rules for reclassification	Class in this study
		C3 grasses, C4 grasses [3]
Tundra		70% Tundra 30% C3 grasses
Desert		C3 grasses, C4 grasses [3]
Polar desert/rock/ice		Tundra

Overriding climatic rules:

For pixels with forest and a temperature sum of months with mean temperature above 0° of less than 30°, the forest and grass covers are reduced to 25% each and tundra cover set to 50%.

At a few pixels, tropical forest occurs at latitudes higher than 40°. Here, the tropical types are reclassified to the evergreen or deciduous, respectively, broadleaf forest of the temperate/boreal region.

[3] Relative fractions of C3 and C4 grasses based on the temperature criterion of Knorr and Heimann [2001].

Acknowledgments

The authors would like to thank Pavel Tarasov and Andreas Dix for their valuable suggestions on our reconstruction method. We are grateful to Navin Ramankutty for providing us with the SAGE 5 min and West Africa crop maps and his useful comments on them. We would like to thank Kees Klein Goldewijk for sharing his expert knowledge on historical land use and providing us with the HYDE 3.0 version, and Alberte Bondeau for her valuable suggestions on pasture data.

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