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

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Chapter 4

Uncertainties in global-scale reconstructions of historic land use

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Abstract

Land use and land-use change play an important role in global integrated assessments. However, there are still many uncertainties in the role of current and historical land use in the global carbon cycle as well as in other dimensions of global environmental change. Although databases of historical land use are frequently used in integrated assessments and climate studies, they are subject to considerable uncertainties that often are ignored. This paper examines a number of the most important uncertainties related to the process of reconstructing historical land use. We discuss the origins of different types of uncertainty and the sensitivity of land-use reconstructions to these uncertainties.

The results indicate that uncertainties not only arise due to large temporal and spatial variation in historical population data, but also relate to assumptions on the relationship between population and land use. Improving empirical data to better specify and validate the assumptions about the relationship between population and land use while accounting for the spatial and temporal variation in this relationship could reduce uncertainties in the reconstructions. Such empirical evidence, needed to better parameterize reconstruction methods, could be derived from local case studies, such as those conducted in landscape ecology, environmental history, archeology and paleoecology.

4.1 Introduction

Historical land-use reconstructions play an important role in assessments of historical climate changes and the calibration of earth system models and dynamic global vegetation models (Gaillard *et al.*, 2010; de Noblet-Ducroudre *et al.*, 2011; Hurtt *et al.*, 2011; Pielke Sr *et al.*, 2011). Although an important input parameter in many assessments, only a small amount of the available historical land use data goes beyond local and regional case studies based on old maps, records, archeological findings and pollen data (Gustavsson & Lennartsson, 2007; Rhemtulla & Mladenoff, 2007; Rhemtulla *et al.*, 2009; Schulp & Verburg, 2009)(Fritschle, 2009; Gimmi *et al.*, 2011; Zhou *et al.*, 2011). For reconstructions on a global scale it is not possible to fully rely on data; these reconstructions, therefore, are mostly based on a combination of data and modelling. A number of such global-scale reconstructions are now available (Ramankutty & Foley, 1999; Olofsson & Hickler, 2008; Pongratz *et al.*, 2008; Klein Goldewijk *et al.*, 2010; Hurtt *et al.*, 2011; Klein Goldewijk *et al.*, 2011). An understanding and quantification of the uncertainties of these reconstructions is important as uncertainties are likely to propagate in the earth system, climate and vegetation assessments for which these reconstructions are an input. Moreover, insight into the uncertainties may help to explain differences in the results of different reconstructions (Gaillard *et al.*, 2010).

There are many different types of uncertainties around reconstructions of historical changes in land use. These uncertainties relate to the different stages of the reconstruction process and to the input data that is used. Examples of uncertainties relate to the trustworthiness of original data sources, the assumptions made about human behavior or data over periods from which data sources are lacking, the procedure for filling these data gaps, the choice of model parameters, or algorithms to reconstruct time series and/or allocate data in a spatially explicit manner. By addressing and documenting both known and unknown uncertainties, users may obtain a better understanding of the value of historical reconstructions. Furthermore, gaps in knowledge of historical ecology and land use can be identified and future efforts can be more efficiently targeted to reduce these uncertainties.

This paper explores the role of different sources of uncertainty in reconstructions of historical global-scale land use. It uses the History of the Global Environment (HYDE) database (Klein Goldewijk *et al.*, 2010; Klein Goldewijk *et al.*, 2011), one of the most frequently used reconstructions of land use, as the base for the uncertainty assessment. The multitude of sources of uncertainty and their often qualitative descriptions (resulting from a shortage of quantitative information) make it very difficult to conduct a fully fledged integrated uncertainty analysis using for example the Monte Carlo method, which requires quantitative information in the uncertainty of the different variables used. Therefore, this paper takes a more exploratory approach by analyzing the different types of uncertainty and describing for each of these the sources of uncertainty and their influence on reconstruction outcomes.

This paper first provides some background to the process of creating historical land use reconstructions and to alternative ways for conducting uncertainty analyses. This is followed by a description and assessment of uncertainties in input data on population and land use, uncertainties in model parameters and model structure and, finally, uncertainties in the methods used for the reconstruction itself. Finally, the paper presents an overall discussion of the different types of uncertainty and their potential impact on the use of these data in earth system and climate models. Based on the results we propose possible ways forward to reduce the uncertainties.

4.2 Background

4.2.1 Historical land use reconstructions

Global estimates of the historical areas of cropland and grassland are rare and rather uncertain (Le Quéré et al., 2009). A few approaches are available: Ramankutty & Foley (1998) calibrated the International Geosphere–Biosphere Programme (IGBP) 1-km resolution global land cover classification (GLCC) dataset against 1992 cropland inventory data to create a global map of cultivated land for 1992. They used a hindcast modeling technique to extrapolate these data, using a compilation of historical cropland inventory data to create a spatial dataset of croplands for the 1700–1992 period (Ramankutty & Foley, 1999). Another approach is a book-keeping model with conversion rates for different types of land cover (including cropland and pasture) to estimate carbon fluxes (Houghton *et al*., 1983; Houghton, 2003; 2010). Pongratz *et al*. (2008) reconstructed agricultural areas in the last millennium from 800 to 1992. Kaplan et al (2009, 2010) developed a model to simulate anthropogenic deforestation based on population density that accounts for technological progress. The method is based on a non-linear relationship between population density and land use, which translates into a decrease in per-capita land use over time, as population densities increase and land use intensification occurs.

In the HYDE 3.1 version (Klein Goldewijk *et al.*, 2010; Klein Goldewijk *et al.*, 2011), historical land use depends strongly on population numbers that are based on a combination of statistics and a spatially explicit computation on a 5 minute grid for the whole Holocene (10,000 BC to AD 2,000) with a variable temporal resolution of 1,000 year time steps for the BC period, 100 year time steps for the pre-1700 period and 10 year time steps for the 1700–2000 period. A simple method based on urban density curves was used to estimate the built-up area over past times, excluding these areas from agricultural land-use allocation. Figure 1 provides a simple overview of the hindcasting method applied to translate population data into land-use reconstructions. The approach uses a simple land use per-capita curve as a base for estimating the historical human influence on land use based on the literature (Ruddiman & Ellis, 2009). Historical land use (cropland, pasture and built-up land) patterns are allocated using a combination of maps of population density, distance to water, climate, soil suitability and slopes as location factors.

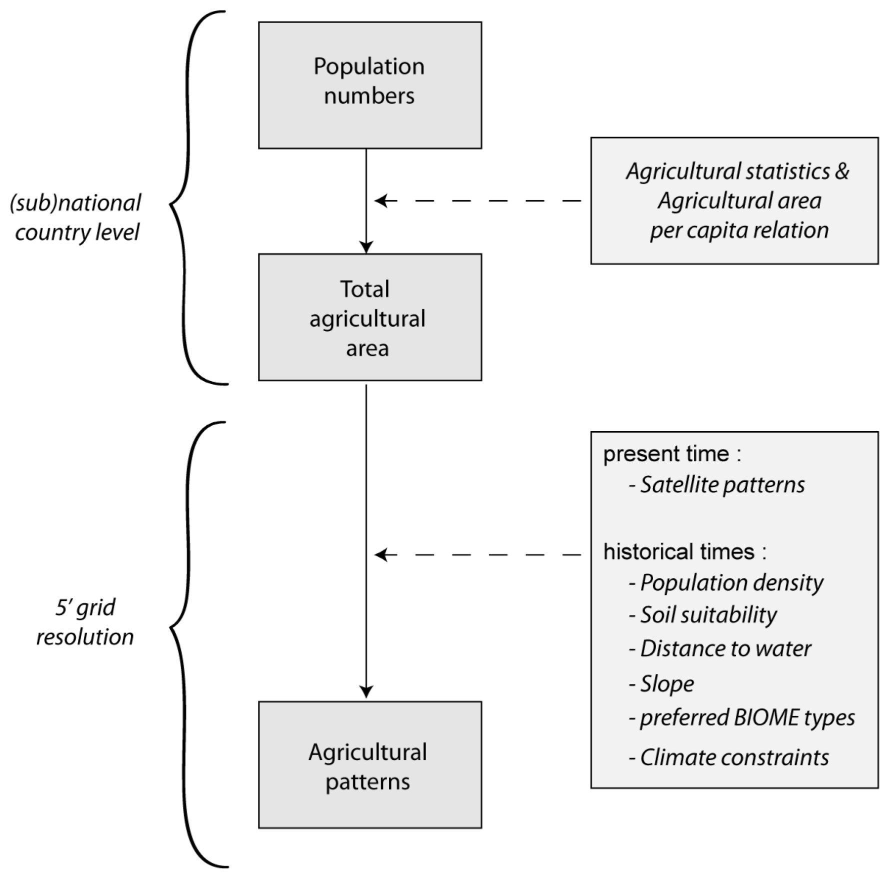


Figure 1. Land use allocation scheme used for hindcasting in the HYDE3.1 database.

4.2.2 Uncertainty analysis

The global-scale historic reconstructions of land use have in common that they are prepared using census data for the recent past, and the combination of historic data of population with a simple model for the deep past. The total uncertainty of such model-based reconstructions, the *model output uncertainty*, could be assessed by uncertainty propagation analysis taking all different sources of uncertainty into account. Such analysis normally uses sophisticated numerical techniques for analysis of error propagation (Larocque *et al.*, 2008; Peng *et al.*, 2011). However, the total output uncertainty can be subdivided into different types of uncertainty that may not all be easily quantified due to lack of independent data, or because they relate to assumptions that underlie the methodology used.

Numerous classification schemes for the different sources of uncertainty in environmental assessment have been introduced, and it is not always possible to reconcile the different taxonomies. Mattot et al. (2009), Refsgaard et al. (2007) and Walker (2003) provide an overview of the different uncertainties in environmental assessment and the methods used for addressing these uncertainties. Walker (2003) explains that the *nature* of uncertainty can be categorised into *Epistemic uncertainty*, i.e. uncertainty due to imperfect knowledge, and *Stochastic* or *ontological uncertainty*, i.e. uncertainty due to inherent variability of the underlying processes. Henrion and Fischhoff (1986) define uncertainty as 'a scientist's assessment of the probable magnitude of error', in which error is defined by the actual difference between a measurement and the value of the measured quantity, often not exactly known at the time of measurement. This lack of knowledge about the error in the original measurements is especially important for many of the input data used in historical land-use reconstructions (often census records), hampering quantitative assessments of model output uncertainty.

A well-known procedure for making quantitative uncertainty analysis is that of Monte Carlo simulations to estimate probability distributions of output on the basis of probability distributions from input variables (Eckhardt *et al.*, 2003; Verburg *et al.*, 2006). This is a stochastic approach which yields bandwidths of output variables in response to quantified uncertainty in the input variables of a model. Another way of dealing with uncertainty in input variables is to perform a scenario analysis that is designed to describe the uncertainty in socio-economic and political developments. In such analyses, consistent packages of input parameters are evaluated in order to estimate the range of possible outcomes; a well-known example is the suite of SRES scenarios of the IPCC (Nakicenovic et al., 2000).
Pontius et al. (2003; 2010) evaluated the uncertainty of land-change models by comparing model output with observational data for the periods over which data are available. Pontius et al. partitioned the uncertainties in model outputs based on errors in quantity and in spatial allocation. While their methods were specifically tailored to land-use analysis they are less suitable for long-term historical hindcasting, since independent and consistent data series on land use over longer time periods were not available.

Other studies focus on different aspects of uncertainty in environmental models. Van Asselt and Rotmans (2002) describe the origins of the thinking on uncertainty and the use of cultural theory to analyse how different perceptions of reality and policy preferences influence model routes in integrated assessment modeling, focusing on population development and climate issues (van Asselt and Rotmans 1996). Different perceptions of reality influence the representation and simplification of reality in the model structure. Therefore, perceptions of reality also play an important role in determining uncertainties in historical land-use hindcasts.

Out of the range of possible ways to address uncertainty we have chosen a straightforward approach that fits with the specific characteristics of historical land use reconstructions and the overall aims of this paper. The approach is based on the different types of uncertainties identified by Walker (2003), Sluijs (1997) and Refsgaard et al. (2007). The classification of sources of uncertainty by Walker et al (2003) has been adopted in this study to frame the different categories of uncertainty, including:
1) Uncertainties that result from c*ontext and framing* occur at the boundaries of the system to be modeled. Whereas in global studies the model context is not confined in a spatial sense, the temporal extent of backcasting is an important consideration and commonly uncertainties will increase with reconstructions further back in time. Important decisions of reconstructions that relate to context and framing also relate to which variables are exogenous and which are endogenous to the analysis. In the context of land use the endogeneity of population to land-use change is an important issue. Section 3 elaborates on issues related to context and framing.
2) *Input uncertainty* relates to data on external driving forces such as population and the spatial data on parameters that are used for the spatial allocation of historical land use. This is further elaborated in Section 4.
3) *Parameter uncertainty* relates to the uncertainties in model coefficients; for example, the coefficients used for translating population numbers into total land use estimates (Section 5).
4) *Model structure uncertainty* is the conceptual uncertainty due to incomplete understanding and simplified descriptions of the modeled processes as compared to reality. Although reduction of complexity is common in any model, a lack of feedbacks in the system description, the lack of spatial detail, and the linear representations of non-linear processes are all potential sources of error in model output. See Section 6.
5) *Model technical uncertainty* is the uncertainty arising from computer implementation of the model; for example, due to numerical approximations, resolution in space and time, and bugs in the software. The land-use reconstruction method discussed in this paper does not involve numerical approximations and has been frequently tested for possible bugs. We have not further elaborated this type of uncertainty in this study.

4.3. Uncertainties due to context and framing

Due to the scarcity of historical land-use data and the better availability of historical population data, population is often used as an important input in historical land-use reconstructions. A close relation between land use and population is obvious, but the cause–effect relationship is less straightforward and would argue for a more endogenous treatment of population in the model. Established cities tend to attract more inhabitants and often the initial clearing of forest and improved accessibility is followed by population settlement (Geist & Lambin, 2002). For recent periods, DeFries et al. (2010) even argue that it is not rural population growth but rather urban populations that induce deforestation. Also, it has been argued that historical declines in population numbers have been the result of large-scale degradation of land resources, leading to food shortages (Ehrlig *et al.*, 1993). In such circumstances, land use is a driver of population density rather than vice versa. This endogeneity of population dynamics has not been accounted for in historical land use reconstructions. In terms of temporal framing, different land-use reconstructions have used different time frames depending on the objectives of the study. Some studies have attempted to understand the drivers of land-use change processes over the past few decades (Gerard *et al.*, 2010), whereas others have tried to provide a consistent database of land use across the whole or part of the Holocene (Ellis *et al.*, 2010; Kaplan *et al.*, 2010; Klein Goldewijk *et al.*, 2011). These differences in temporal extent have an effect on the use of data and level of detail in land-cover classes. On shorter time scales, more detail, both in representation of land-use change processes and in land-cover classes, can be distinguished. This is not possible for longer time frames. The further back in time, the more scarce and questionable data sources become. In that sense, the uncertainty in historical land-use reconstructions is expected to increase strongly as we move further back in time. For many periods, the few available statistics, written sources and libraries simply are the only data available and we can only accept that most of the sources are approximations without being able to test their accuracy. Ideally, each source should have its own quality check and a trade-off should be considered by not using one or more sources and/or accepting higher uncertainty by using such sources. This choice is often made intuitively by the involved researcher and is not explicitly documented or quantified for the various, published global land-use reconstructions. Such intuitive choices are justified since it is often very difficult (or impossible) to compare sources of population and land-use data that are used as 'independent' sources. Alternative sources of information, which at first sight seem to be new or not related to one particular 'mother' source, often can still be traced back to the same original source and, therefore, turn out not to be independent at all. An example of this dependency between sources is the Atlas of World Population History by McEvedy and Jones (1978), which has been widely used and adapted by other studies, such as those by Maddison (2001) and Livi-Bacci (2007). It is, unfortunately, not possible to quantify the role of these uncertainties for the land use reconstructions. We lack knowledge in terms of our understanding of the interactions between land use and population while the lack of independent alternative data sources of historic population for earlier periods makes such assessment troublesome.

4.4 Uncertainties in input data on population and land use

Regarding the past century, many sources of historical population and land-use data can be found. However, land-use data often do not go back further than the 1960s, which is why for reconstructions that stretch further into the past, population data are used. Although we do not know the exact size of the world population, reliable estimates can be made using census data and state of the art demographic models. Well-known and trusted sources are the World Population Prospects database of the United Nations (UN, 2009) and the FAOSTAT database on land use from the Food and Agricultural Organization of the United Nations (FAO, 2008). Both databases have the advantage of covering the entire globe and are made internally consistent, which enables easy comparison between countries. However, both organizations have to rely on official, government approved country reports, and often data series are revised over time. Therefore, although most countries report on an annual basis, much effort is put into finding errors, filling in gaps (by interpolation, model simulations or expert estimations) and other measures to ensure consistency. This may cause data to appear to be more independent or accurate than the underlying data would warrant, as these data are sometimes less detailed as would be expected from the rather stable time series presented through these gateways.

Going back further in time, the historical reconstruction of time series faces many problems. The most obvious problem is the lack of data, which may be solved by interpolation between known data points to fill data gaps over certain time periods. In the absence of data with a reasonable interval, demographic growth rates (taken from the literature) are used for extending data series and creating first-order estimates. Figure 2 presents an example for Latin American countries, providing the first known sub-national population data from the Populstat database for Latin America (Lahmeyer, 2004). *Populstat* is a collection of sub-national population statistics from various sources, such as historical atlases, census data and other national data sets.

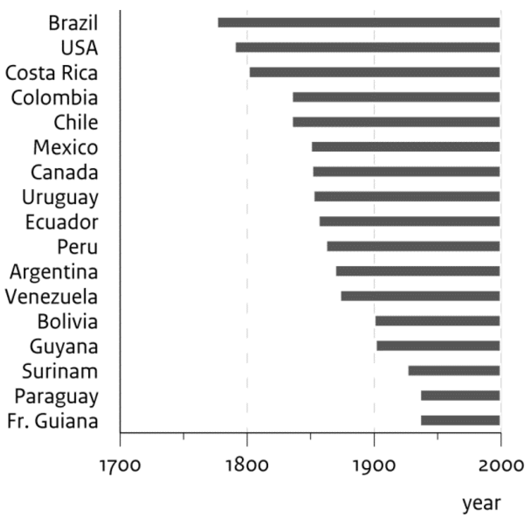


Figure 2. Example of first Populstat records with sub-national scale data points of historical population in the Americas, ranging from AD 1776 for Brazil to AD 1936 for French Guiana.

An illustrative example of the uncertainty embedded in reported population data is the discussion on the 'Missing Population' of the Americas before 1492, the year when Chistopher Columbus and the first Spaniards arrived. For the past 80 years, there has been ongoing debate on how many people where living in the 'New World' before the arrival of the European colonists, and on how many indigenous people died shortly after. The estimates vary widely, from between 12 and 100 million people in 1500, to a drastic decline to between 8 and 14 million in 1600 (see Table 1).

Table 1. Different estimates of native population of the Americas before the European settlers arrived (adapted from Denevan (1992) and Thornton (1924))

Source	Estimates (in 1000)
Rivet (1924)	40,000 - 50,000
Sapper (1928)	40,000 - 50,000
Spinden (1931)	50,000 - 75,000
Wilcox (1939)	13,101
Kroeber (1945)	8,400
Rosenblat (1945)	13,385
Steward (1949)	13,170
Steward (1952)	15,491
Rivet (1976)	15,500
Borah (1966)	100,000
Dobyns (1967)	90,043 - 112,554
Moerner (1969)	33,300
Driver (1976)	30,000
Denevan (1977)	57,300 (43,000 - 72,000)
Clark (1978)	40,000
McEvedy & Jones (1979)	13,200
Biraben (1992)	39,000
Denevan (2001)	57,200
Maddison	17,500
HYDE 3.1, baseline	39,220

These uncertainties are confirmed by findings that more directly relate to land use. The occurrences of dark earth or black soil in the Amazonian Basin reveals that agricultural activities must have been far more intensive and widespread than previously thought (Kern *et al.*, 2003). Based on such findings and combined with per-capita food production capabilities, it was suggest that at least 11 million people could have inhabited the Amazon Basin in the 1000–1500 period (pers.comm Bill Woods, University of Kansas, USA). In contrast, McEvedy and Jones (1978) estimated a much lower number of inhabitants (1 million) in 1500 for the whole of Brazil.

Figure 3 highlights the range of estimates on historical population numbers on a global scale, in comparison with the data used in the HYDE3.1 database. Please note that especially for the time around the start of the Common Era, the variation in estimations on population size is considerable – ranging from 170 to 300 million people – mainly as a result of the larger number of studies available on that particular time.

To explore the impacts of uncertainty in population numbers on land use estimates in the HYDE 3.1 database, a series of different population scenarios have been created.

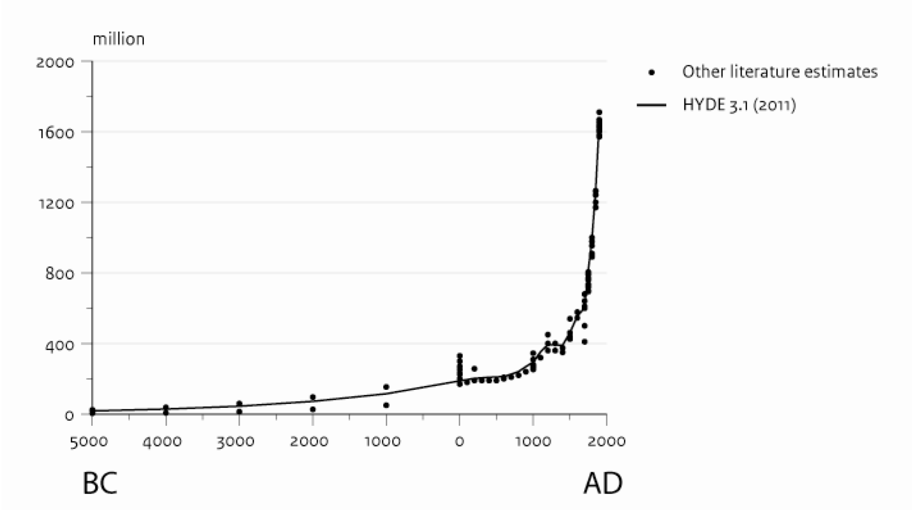
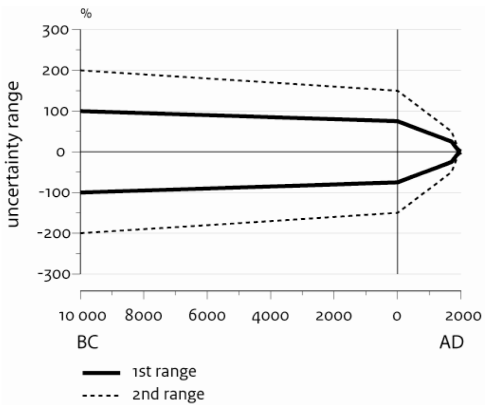


Figure 3. HYDE 3.1 compared with other estimates found in literature of total global population numbers for the period 5000 BC – AD 1900.

First, a comparison with literature estimates was made (see figure 3). The dots depict the range found in the literature and the solid line represents the HYDE 3.1 estimate. Then, based upon these estimates an uncertainty range was added upon selected years of the baseline in such a way that most literature estimates do fall within the resulting bandwidth of population numbers. A second uncertainty range was, arbitrarily, assumed to have double the variation of the first range. Between the selected years the uncertainty range was linearly interpolated. As expected, the uncertainty ranges get larger when going back time (figure 4). We chose to keep the upper and lower ranges at the same magnitude (plus and minus). Given the large deviations in population numbers in the upper range the second lower range exceeds in this way 100%. In those cases the resulting values would have been negative and were thus set to zero. Following the standard HYDE3.1 method, the global total amount of cropland is computed, including both uncertainty ranges. As an example, an illustrative example for Italy is given in figure 5, showing the effect of these uncertainty ranges in population on spatial cropland patterns.



Resulting global cropland area (million km^2)

	5000 BC	1AD	500 AD	1000 AD	1500 AD
HYDE 3.1 baseline	0.048	1.313	1.239	1.532	2.324
1st lower range	0.006	0.329	0.492	0.834	1.608
1st higher range	0.089	2.300	1.987	2.232	3.046
2nd lower range	0.000	0.000	0.000	0.135	0.890
2nd higher range	0.131	3.285	2.735	2.931	3.764

Figure 4. Uncertainty ranges assumed in HYDE 3.1 population numbers, and their effect on resulting cropland estimates over time.

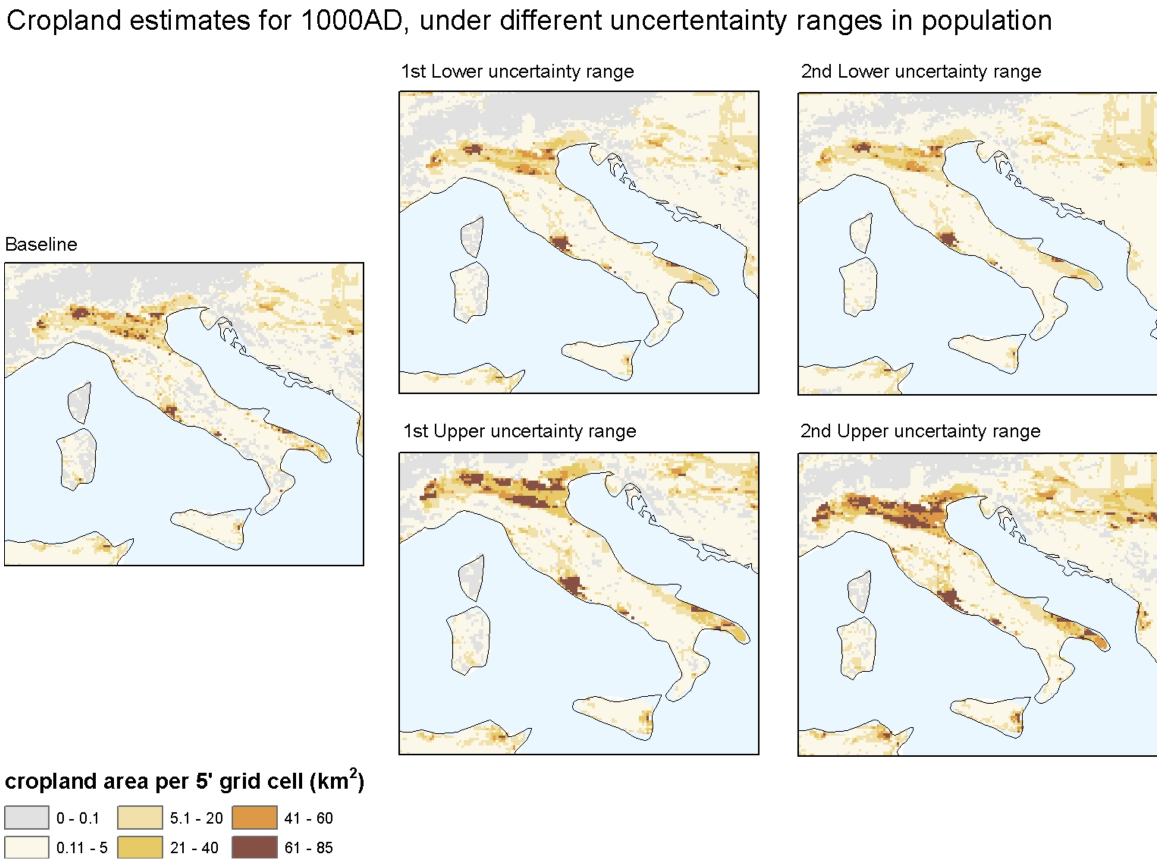


Figure 5. Spatial cropland estimates for AD 1000, under different uncertainty ranges in population numbers.

4.5 Uncertainties in model parameters and assumptions

Built-up area

The HYDE methodology for computing built-up areas is hard to compare or verify, since there are not many detailed studies on historical absolute city sizes. Many different definitions exist of what exactly belongs to the city area (e.g. the proper centre of a city, and whether to include agglomerations and/or suburbs or not). The method used for computing built-up areas as described in Klein Goldewijk et al. (2010) assumes that urban density follows a bell-shaped curve relating urban population and urban density. This functional form is based on a rather limited number of data points on size and urban populations of European and North American cities. The parameters that define the shape of the curve are computed on the basis of empirical data derived from remote sensing interpretations for the year 2000, assuming that the maximum of the curve is reached when the increase in total urban population starts to slow down in a country. Although the assumptions for deriving model parameters are strong simplifications of the urbanisation process and ignore its variation in time and space, the resulting present-day urban area corresponds well with the area reported in other studies. Potere and Schneider (2007) compared six studies and Schneider et al. (2009) compared ten different studies of estimates of the current global built-up area, based on various satellite imagery and other information. They found that the range in area in the different approaches varied from 276,000 km^2 to 727,000 km^2, with one outlier of 3,524,000 km^2, with HYDE 3.1 estimating it at 532,000 km^2. However, it should be noted that a good correspondence with present-day estimates does not necessarily imply that historical data have similar accuracy.

Agricultural land use

The most critical model parameters determining agricultural land use are those that determine the per-capita area used. In general, the amount of agricultural land per capita is considered to decrease towards the present time as a consequence of changes in farming systems (Ruddiman & Ellis, 2009; Kaplan *et al.*, 2010). Ruddiman and Ellis (2009) presented a table with a 'land-use sequence' according to which the amount of land needed for agriculture changes; from 2 to 6 hectare per capita (ha/cap) in changing agricultural societies with long fallow periods, towards 1 to 2 ha/cap in cases of short fallow periods. This was followed by more intensive agricultural stages with an annual cropping scheme (0.3-0.6 ha/cap) and multi-cropping scheme (0.05-0.3 ha/cap). Assuming such changes in farming system and land-use intensity is in line with the theory by Ester Boserup (1965), who assumed that increases in population density would lead to intensification as soon as land would become more scarce. Changes in diet also contribute to a change in the per capita use of land. Currently, people eat more meat, which requires much more pasture land. However, this higher requirement may be outweighed by the increasing intensity of cultivation.. The decrease in agricultural area with time is confirmed by other studies, but it is not clear whether this is valid for all regions of the world and for longer time periods (Grigg, 1979; Netting, 1993; Grubler, 1994; Keys & McConnell, 2005). Regional deviations in population growth rates and the adoption of technological changes may cause deviations in the generic global relationship and therefore errors in regional land-use estimates.

Neither the exact values nor the shape of the trajectory for agricultural land use per capita over time is known. To explore the sensitivity of the reconstructions to the assumed trajectory over time the HYDE 3.1 baseline scenario a number of variations of the near-constant land use per capita was created as pictured in Figure 6. The convex, linear and concave curves are based on the study by (Ruddiman & Ellis, 2009), the constant and S-curve have been added to evaluate the effect of alternative specifications. The S-curve is added to imply a sort of 'learning effect' of technical and/or societal innovations over time, but it is not clear if, and when such changes would have taken place. Thjs sensitivity analysis explored the land use reconstruction outcomes if the land use per capita would follow a certain curve.

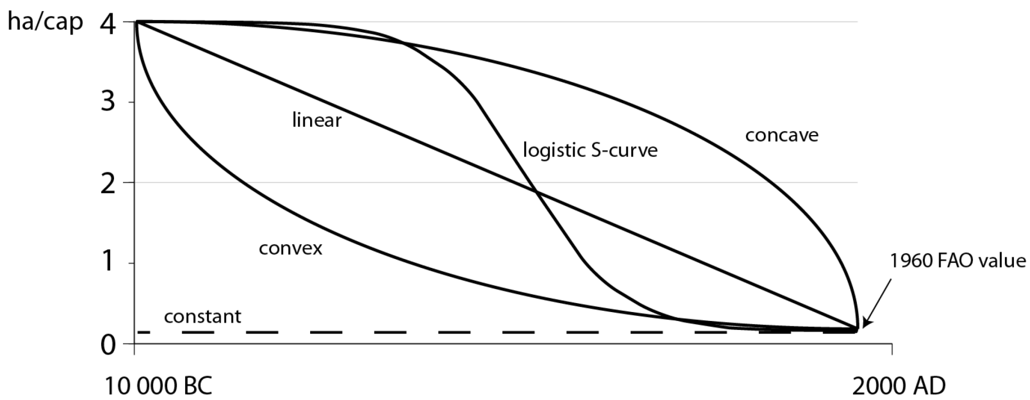


Figure 6. Different shaped curves for historical land use per capita trajectories.

Apart from uncertainty in the shape of the curve, the starting value is also uncertain. The assumed value of 4 ha/cap in 10,000 BC in Figure 5 is based on assumptions taken from a variety of literature sources. Ruddiman and Ellis (2009) estimated a range of 2 to 6 ha/cap, Olofsson and Hickler (2008) estimated a range of 4 to 6 ha/cap, and Gregg (1988) estimated it to be 4 ha/cap. Kaplan et al. (2009) presents per capita land-use numbers of 5.5 ha/cap for western Europe, 6.5 ha/cap for Central/Meso America and as much as 8 ha/cap for southern China in 10,000 BC, all derived from an assumed relationship between European population growth and deforestation rates. These computed shapes of the per-capita land-use curves by Kaplan et al. (2009) for China and western Europe resemble a concave curve (Kaplan *et al.*, 2009; Kaplan *et al.*, 2010). The results from Kaplan (2010) seem rather high compared with estimates for Sweden. Myrdal (2011) reports that a typical farm in Sweden, in the years between AD 1000 and AD 1300, used about 3 to 6 hectares for crops, and with a typical double cropping rotation this adds up to twice that amount in one farm. In the Late Middle Ages, this increased to between 5 and 7 hectares (2 hectares for marginal farms). Combined with an average household size of 5 to 8 people (Welinder, 2011), this yields between 0.60 and 0.75 ha/cap, while Gadd (2011) reports for Sweden 0.64 to 0.74 ha/cap for AD 1800. Chao (1986) reported much lower per-capita land use for China than Kaplan, namely less than 1 ha/cap in AD 1. One reason for this could be that the area used for cropland is usually around 1 ha/cap, while the area used for grazing and coppice and other forms of extensive land use are much higher. Therefore, the definition of reported land use is critical, often it refers to land under cultivation, which could include pastures, as well.

An explanation for the large differences between Kaplan et al. (2010) and other case studies mentioned before can be found in the evidence presented by Gregg (1988). She described a typical European Neolithical village, containing 6 households with a total of 34 individuals, which would typically need a total of 6.07 km^2. Translated to hectares this leads to 17.85 ha/cap, which can be broken down into 0.18 ha/cap for housing, 0.73 ha/cap of cropland, 1.05 ha/cap of pastures and hay meadows, but also including 15.89 ha/cap of forest land used for hunting and gathering. This large forest area would not be directly converted but simply used and to some extent degraded, compared to its natural state. A substantial part of the assumptions by Kaplan et al. (2010) on land use could relate to such forested areas.

To account for regional differences in farming systems in HYDE 3.1, the shapes of the S-curves are not identical for cropland and pasture. Thirty-one countries out of 238 do have much higher pasture per-capita values for 1960 than 4 ha/cap (e.g. Western Sahara 152 ha/cap, Mongolia 146 ha/cap). For those countries, the 1960 FAO value was kept constant over time. The choice of land use curves per capita also has consequences for the spatial patterns of historical land use. This is basically a result of the non-linearity in the shape of the curve. If all would be parallel linear curves, the pattern would only be different in intensity. In this case, however, also the pattern is clearly different. When allocating these different amounts for a certain administrative unit, this will result in different spatial patterns as illustrated in Figure 7.

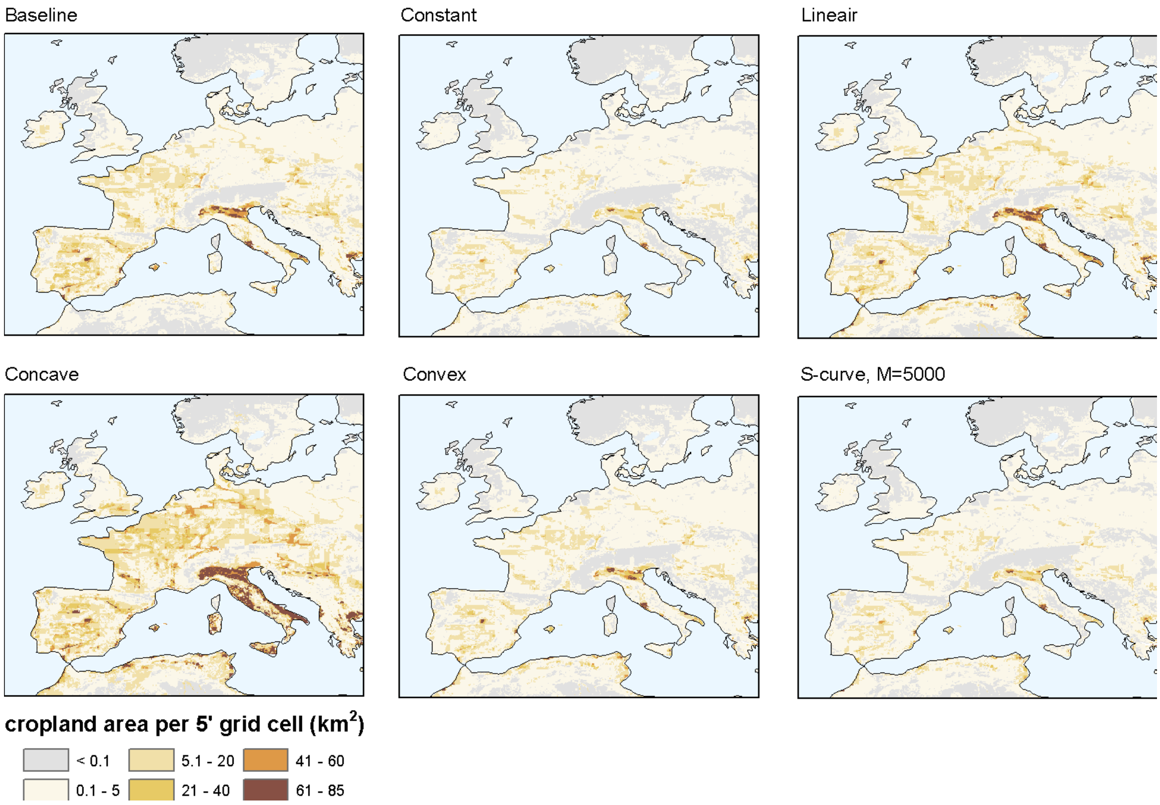


Figure 7. Cropland estimates for Europe for 0 AD, using different land-use-per-capita scenario's.

4.6. Uncertainties related to model structure

Importance of drivers of land-use change

The spatial allocation of historical cropland in HYDE is determined by a number of assumed equally important factors, namely population distribution, soil suitability, distance to coastal areas and lakes and rivers, slope, and climate. Although these factors are frequently used as locational factors in land-change modelling, the extent to which the individual factors determine the location of agricultural land use is still uncertain. In the current version of HYDE, all weighting maps use the same weight, which is an arbitrary assumption in the absence of more detailed knowledge. Keys and McConnell (2005) made a meta-analysis of a large number of case studies that reported agricultural changes. They found that population numbers and densities were indeed marked as important in 70 out of 108 case studies on agricultural change. However, market demand and access, property regime, governance and standard of living, in many cases, also played a role. Furthermore, also biophysical aspects such as soil properties and precipitation were mentioned in 30 case studies as being important. Verburg and Chen (2000) found a strong correlation between the presence of cultivated land in China and demographic conditions as well as soil suitability. Similar relationships were found for Central America (Kok & Veldkamp, 2001; Kok, 2004). It is likely that the weighting applied in the HYDE3.1 reconstruction is not valid and may vary, both spatially and temporally. However, as high population concentrations are often found in flat lands with fertile soils not far from rivers or coasts alternative weightings of the factors will result in similar spatial allocations in many areas. However, location factors depend on the regional context, farming systems and are likely to have changes due to cultural reasons and technology. Therefore, the precise spatial allocation in the land use reconstructions should be interpreted with care.

Functional form of relationships

As is shown in Figure 7, the type of function chosen for the land-use per-capita curve is important. Different curves lead to differences in the spatial pattern of allocation. Moreover, even while assuming an S-shaped curve, different parameters determining this curve can have a large impact. To illustrate this, three different settings have been arbitrarily chosen for the S-curve, where parameter M in the curve (see Figure 8) was set to either 5000, 2000 or 1000 (for a mathematical representation of the formulas see Appendix in the supplementary material). Again, the exact shape and form of the curve, defined by the values of the parameters are not known and the values are chosen for illustrative purposes. This also results in different amounts of total pasture at a given moment in time, and consequently in different spatial patterns (see Table 3).

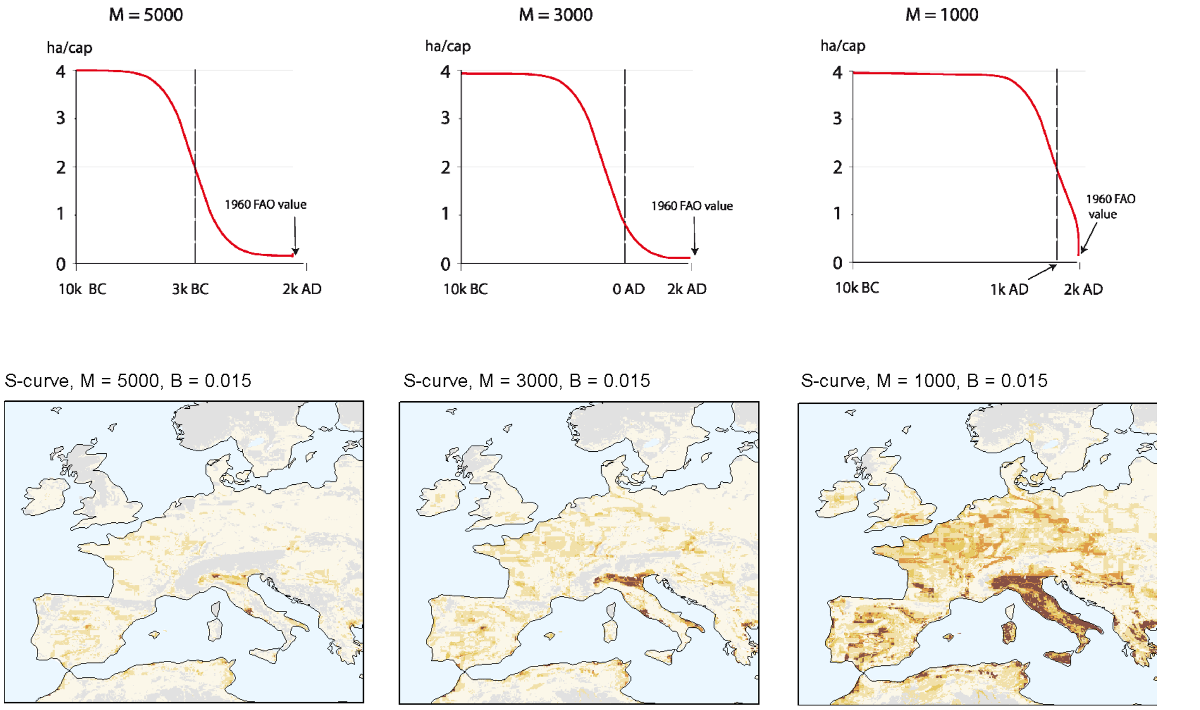


Figure 8. Example of three different M values in the S-curve for land use per capita, for Europe 0 AD.

The choice of the M variable in a S-shaped land use per capita development trajectory basically reflects the timing of the onset of intensification. Many of the case studies on intensification of agriculture in the meta-analysis of Keys and McConnell (Keys & McConnell, 2005) showed that different key indicators lead to different intensification paths. It is, therefore, rather likely that a globally uniform land-use population curve does not exist and that different M values would apply to different regions. Another example of the sensitivity of the reconstruction results for the shape of the land use-population curve is provided by changing the B value in the S-curve (see Appendix) while keeping the M value at 5000 (see Figure 9).

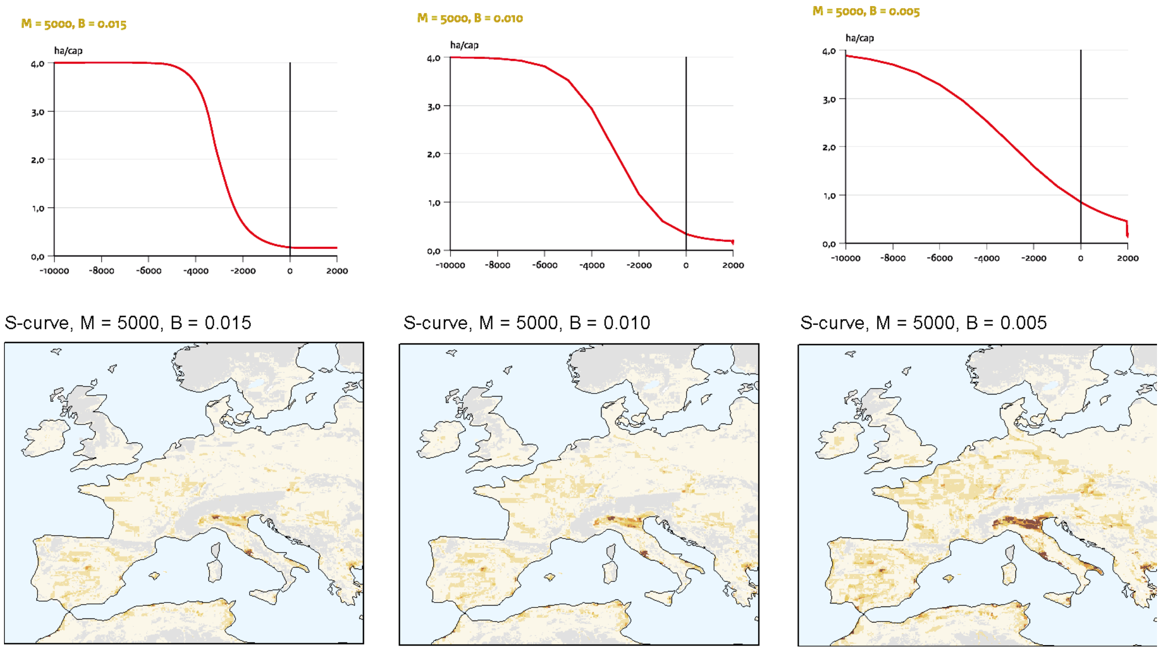


Figure 9. Example of three different B values in the S-curve for land use per capita. For Europe 0 AD.

The differences in B values can be interpreted as a proxy for a slower or faster rate of intensification. High values of B represent a fast intensification over time. Not surprisingly, the different shapes of the land-use curves per capita result in different estimates of total cropland and pasture areas for the various points in time that were analyzed.

4.7 Discussion

Synthesis of different types of uncertainty

The, mostly descriptive, analysis of different sources of uncertainty in the preceding sections has indicated that not all uncertainties can be quantified. For those sources of uncertainty for which the impacts on the land use reconstructions can be tested,Table 2, provides a summary and a comparison with other well-known global land use reconstructions. The very low numbers in the HYDE3.1 reconstructions, especially in the second lower population scenario, remain unrealistically low until AD 1000. This is simply a consequence of the chosen, rather straightforward mathematical approach. For example, when values in a region became negative (minus more than 100%) they were set to zero.

Table 2. Global historical estimates of total agricultural area (cropland and pasture), different hind cast scenarios (in million km^2).

	6000 BC	1000 BC	AD 1	AD 500	AD 800	AD 1000	AD 1100	AD 1400	AD 1500	AD 2000
HYDE 3.1 (baseline)	0.02	1.42	2.38	2.32	2.49	2.96	3.46	3.88	4.57	49.61
HYDE 3.1 1st lower	0.00	0.32	0.59	0.92	1.21	1.61	1.99	2.57	3.16	49.11
HYDE 3.1 1st upper	0.03	2.52	4.16	3.72	3.78	4.32	4.94	5.20	5.98	50.11

HYDE 3.1 2nd lower	0.00	0.00	0.00	0.00	0.00	0.26	0.51	1.26	1.75	48.62
HYDE 3.1 2nd upper	0.05	3.62	5.94	5.12	5.06	5.67	6.42	6.51	7.39	50.60
HYDE 3.1 (constant)	0.38	2.14	3.27	3.95	4.55	5.15	5.88	6.66	7.35	49.61
Lineair	0.74	3.89	5.20	5.53	5.98	6.64	7.49	7.81	8.49	49.61
S-curve	1.13	2.49	3.40	4.02	4.59	5.19	5.93	6.69	7.38	49.61
Concave-curve	0.95	6.65	9.60	10.21	11.07	12.63	14.57	14.60	16.12	49.61
Convex-curve	0.52	2.52	3.63	4.16	4.70	5.34	6.09	6.80	7.51	49.61
Pongratz et al (2008)					2.80		3.95	4.60		
Kaplan et al (2010)	1.86	8.71	13.60	15.30		18.00			23.00	
min	0.00	0.00	0.00	0.00	0.00	0.26	0.51	1.26	1.75	48.62
avg	0.44	2.78	4.23	4.56	4.00	5.64	5.30	5.80	7.79	49.62
max	1.86	8.71	13.60	15.30	11.08	18.00	14.59	14.62	23.00	50.82

Table 2 shows that it does matter which historical land-use per-capita relationship is assumed. For most time periods a factor 4 difference can be found in global agricultural land area between the baseline of HYDE 3.1 and the maximum value of the other variants. Differences with Kaplan et al. (2010) can be explained by the fact that they established a relationship between population density, development stage and deforestation in Europe. This relationship was then applied to the whole globe, probably resulting in an overestimation of historical land-use conversions. It is interesting to see that the estimates by Kaplan et al. are very close to the concave curve variant of the HYDE 3.1 land-use per-capita relationship. Pongratz et al. (2008) is close to the HYDE baseline, which is not surprising since Pongratz also used McEvedy and Jones (1978) data, as well as some of the data in older versions of the HYDE database. It debatable whether the 'start' value of 4 ha/cap in 10,000 BC is valid. Recent analysis of Chao (1986) and Bassino (2011) indicates that at least for some Asian countries a value of less than 1.0 ha/cap for cropland is much more realistic, over long time periods, back to AD 1. A similar value of 1 to 2 ha/cap for pastures might be appropriate, but also another much larger area for browsing, hunting and gathering activities (10-20 ha/cap) might be realistic, as suggested by Gregg (1988).

What are the main uncertainties?

The uncertainties are not evenly spread across continents and time. Most uncertain are the historical land-use estimates and the temporal development of the per-capita land-use quantities. Population numbers are also uncertain, but less so for specific regions, such as Europe, North America and Australia after AD 1700, and for China, for a period that goes back further in time. For Africa and, to a somewhat lesser extent, Latin America, population numbers as well as land-use statistics are most uncertain. Table 3 provides a summary of the evidence and expert interpretations, qualitatively indicating the uncertainties per region and per class.

Table 3. Qualitative judgement on the several uncertainties for the pre-FAO period, when statistics became available.

	North America		Latin America		Europe		Africa		Asia		Oceania	
	pre-ind.	ind	pre-ind.	ind	pre-ind.	ind	pre-ind.	ind	pre-ind.	ind	pre-ind.	ind
Population statistics	3	1	4	2	2	1	3	2	3	2	3	1
Weighing map & rules	2	2	2	2	2	2	3	3	2	2	2	2
Cropland statistics	4	1	4	3	3	2	5	5	3	2	4	2
Pasture statistics	4	2	4	3	4	2	5	5	4	3	4	2
Land use per capita curve	4	2	4	3	3	2	5	5	3	3	4	2

Note: Pre-Ind = pre-1700 AD period, Ind = 1700 – 1960 period;
Own jugdement of uncertainty classes; 1 = rather certain, 2 = not very certain, 3 = uncertain, 4 = very uncertain, 5 = totally uncertain.

Implications of uncertainties in land use reconstructions

Changes in land cover affect the climate system through impacts on biogeochemical processes (e.g. the emission of greenhouse gases) and biogeophysical changes, such as the modification of land surface albedo, evapotranspiration and surface roughness (Claussen *et al.*, 2001; Brovkin *et al.*, 2006; Betts *et al.*, 2007). Historical land-use reconstructions, therefore, are frequently used as input data to assessments of climate change based on land–climate interaction models. General circulation models (GCMs), used for studying the global climate, are too complex to do transient runs with a fully coupled land–atmosphere system. So, recently, a new class of Earth system models (ESMs), namely ESMs of intermediate complexity (EMICs; see Brovkin et al., 2006), emerged. These EMICs can assess the transient response of the climate system to different climate forcings on a much longer timescale than GCMs. Also, they are more computationally efficient without losing critical land–climate interactions. The results of these models in assessments of the impact of large-scale land-cover change on the Earth's climate vary from 'significant and large', to 'only local to the perturbation', or 'small enough to be ignored', according to the literature (de Noblet-Ducroudre & Pitman, 2007; Pitman *et al.*, 2009). The variation in these outcomes indicates that more investigation of the impact of historical land-use change on climate is needed.

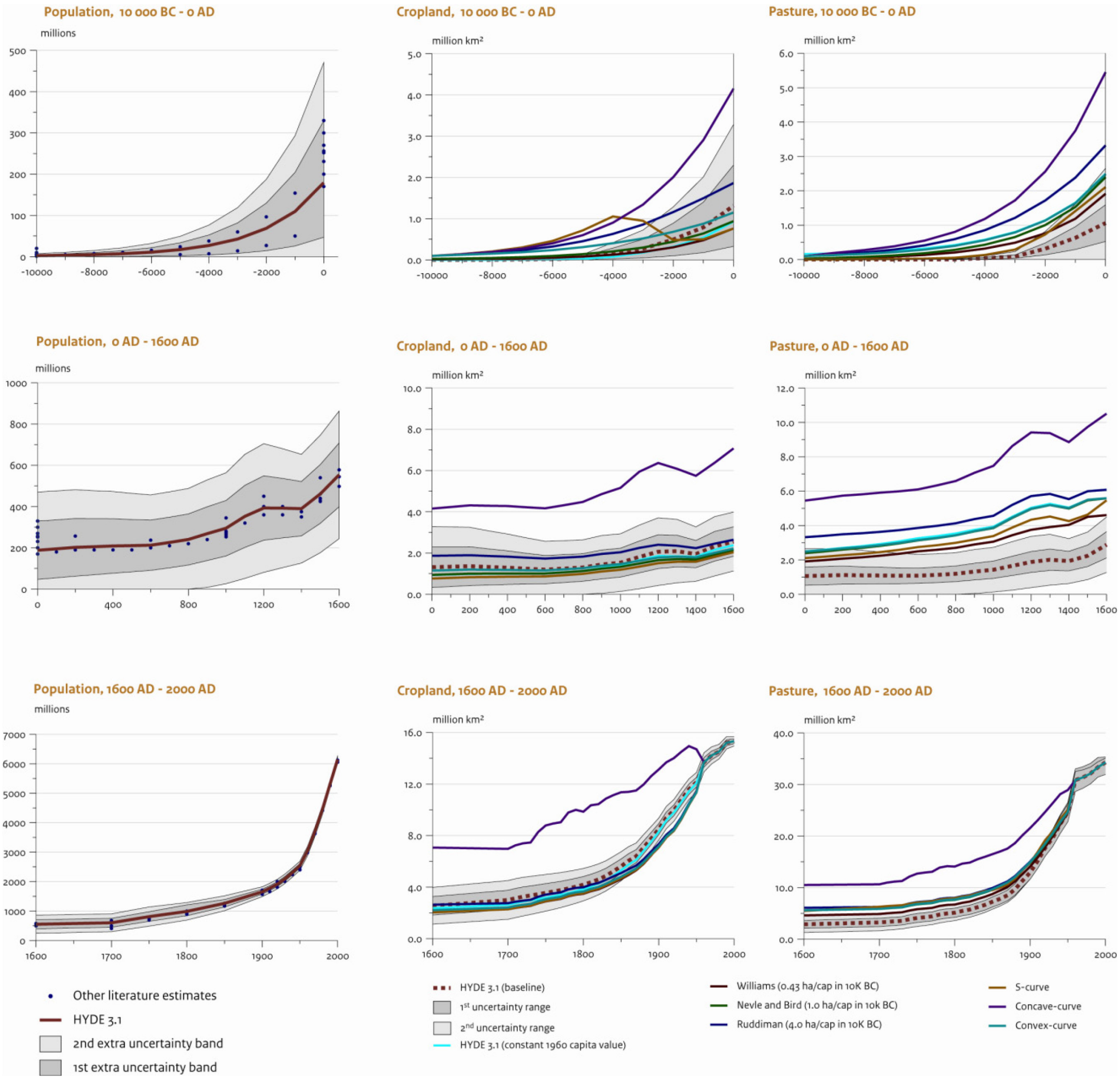


Figure 10. Summary of the estimated uncertainty bands in the HYDE 3.1 historical population and land use estimates.

Figure 10 summarizes the spread of estimates in the literature as well as the different assumptions in the model and parameters used on population and land use, for three different time periods. The dots represent other literature estimates.

Simulations of historical land-cover forcing suggest that the bio-geophysical effect of historical land-cover changes helps to clarify the observed changes in carbon and global temperature during the last centuries (Le Quéré et al., 2009; Friedlingstein *et al.*, 2010). Although most studies indicate global bio-geophysical cooling as a result of changes in land cover of between 0.13 and 0.25 °C since pre-industrial times, one of the major uncertainties in these results has been identified to be in the historical land-cover distribution (Pitman *et al.*, 2004; Brovkin *et al.*, 2006).

Carbon cycle

Crucial is how these historical land-use reconstructions are used in global integrated assessments; particularly crucial is the way in which land-cover changes are represented in the carbon cycle, and how conversions of natural ecosystems to cropland or pastures are handled. The role of historical and more recent land-use changes and their influence on the carbon cycle is receiving more and more attention. For example, the Global Carbon Project (GCP) has constructed and analyzed the global CO_2 budget of the last decades (Le Quéré et al., 2009). Atmospheric CO_2 was determined directly from measurements, but it was stated that the land and ocean CO_2 fluxes had not been quantified with high enough accuracy (Le Quéré et al., 2009). The CO_2 emissions from land-use change (LUC) were estimated using deforestation and other land-use data, because they could not be estimated directly from observations. For these terms, state-of-the-art models were used (Houghton *et al.*, 1983). In the past, emissions from land-use changes have been estimated by a bookkeeping method (Feddema *et al.*, 2005; Stendel *et al.*, 2006; Davin *et al.*, 2007; Plattner *et al.*, 2008; Strassmann *et al.*, 2008; Vavrus *et al.*, 2008) and more recently by global climate and/or biophysical change models (Houghton, 2003; House *et al.*, 2003; Le Quéré et al., 2009; Houghton, 2010). However, the exact contribution of land-use changes to the global carbon cycle remains a major uncertainty (Strassmann *et al.*, 2008; Pongratz *et al.*, 2011b; Stocker *et al.*, 2011b), not only in the distant past but also still for the present day.

Many studies have used the baseline version of HYDE 3.1 (or older HYDE versions) which is based on the assumption of an almost constant per-capita land use, which is likely to result in figures that are too low on historical land-use and subsequently in much lower land-use emissions (Pongratz *et al.*, 2011a; Stocker *et al.*, 2011a) . By applying these emission data – in combination with those on land-use changes – to the global carbon cycle has probably resulted in an underestimation of the land-use effect. Although Stocker et al. (2011a) experimented with higher estimates on land use per capita than those of the HYDE baseline, these were still based on an older baseline version of HYDE, which is regarded as being on the very low side (Diamond, 1997). Thus, when applying other, more plausible per-capita land-use scenarios in HYDE, resulting in higher Holocene land-use estimates, and subsequently in higher land-use emissions and a larger effect of land use on climate. However, this does not disprove the statement that 'early agricultural activities cannot explain the mid to late Holocene CO_2 rise of 20 ppm measured in ice cores' (Pongratz *et al.*, 2011a; Stocker *et al.*, 2011a), as at this point in time it is too early to make such a statement, given the many uncertainties in the historical land-use data.

Ways forward

With so many uncertainties in data, assumptions and parameters, and the absence of proper validation options, it seems nearly impossible to create a database on the historical population, cropland and pasture for the distant past with a somewhat reduced and quantified level of uncertainty. Given the high relevance and very frequent use of these data sets, this poses an important challenge to global change research. The currently available data sets, such as the HYDE database, should be seen as a start to estimations on historical land use, and not as the final product. By continually working with other disciplines, the database can be improved and uncertainties decreased. This may be achieved by a combination of multiple approaches, including (i) the collection of more empirical data. Local, small-scale case studies that may be synthesized through meta-analysis to determine critical parameters, such as data on historical land use per capita, as well as providing observations for validation of global reconstructions. Disciplines such as historical ecology can play an important role by making the many local case studies more accessible to other researchers. In addition to these small-scale case studies, alternative data should be considered, such as (ii) pollen records, tree-ring analysis and archeological evidence. These data not only provide evidence of the land use in a certain period, but may also provide some insight into the spatial differences in farming systems (e.g. Diamond (2010)). Gaillard *et al*. (2011) postulate that, for example, a new method to infer long-term records of past land cover from pollen data would enhance a more robust assessment of historical land-cover change on regional or continental scales. Finally, (iii) in addition to these bottom-up approaches, a more top-down approach includes improvement of modeling techniques and cross-comparison with atmospheric signals.

The above indicates that progress in reconstructing historical global land use can only be achieved by interdisciplinary co-operation in a wide range of disciplines, such as archeology, limnology, paleoecology, landscape ecology, social and economic history and historical geography.

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