

VU Research Portal

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

Klein Goldewijk, C.G.M.

2012

document version

Publisher's PDF, also known as Version of record

[Link to publication in VU Research Portal](#)

citation for published version (APA)

Klein Goldewijk, C. G. M. (2012). *(Looking) Back to the Future: A reconstruction of historic land use and its application for global change research*. [PhD-Thesis – Research external, graduation internal, Vrije Universiteit Amsterdam].

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

E-mail address:

vuresearchportal.ub@vu.nl

Chapter 7

Synthesis

The main objective of this thesis aims to address the following research questions:

- 1) Do historical data and census allow us to reconstruct a global coverage of historic population data ?
- 2) Can land use reconstructions be based on historic land use and population data? In other words, is there a (set of) simple rules or assumptions which can explain the historical land use patterns ?
- 3) What are the limitations and the uncertainty in such reconstructions ?
- 4) Can the thus produced data be used in global change research applications ?

The first research question is addressed in chapters 2 and 3, where the methodology is described how the database of historic land use, strongly based on population numbers, is made. The maps have been constructed by combining statistical data and a spatially explicit allocation routine, on a global 5 arc-minute resolution grid for the whole Holocene (10 000 BC to AD 2000). For practical reasons the temporal resolution differs during this period; 1000 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. Also, a simple method based on urban density curves was used to estimate built-up area in this period. These areas were excluded from the allocation of land use.

The second research question is addressed in chapter 4 where the approach of using a land use per-capita curve as a basis for estimating the historic human influence on the Earth' surface is discussed. The exact shape and magnitude of those curves is not well known and different shapes have been examined. The limitations and uncertainties from such an approach are also addressed in chapter 4, thus addressing research question 3. Historical land use (croplands, pasture and built-up land) is thus estimated by combining the absolute numbers of population with per capita land use estimates, and allocating the resulting total areas by means of weighted proxies for land use: population density, climate, distance to water, soil suitability and slope.

The development of land use and population databases, examples of their applications and their uncertainties are discussed in chapter 5 and 6 (research question 4). The objective of this synthesis chapter is to relate the different characteristics of this database and its use to the broader conception of human-environment interactions, to discuss the limitations of the database in the context of its applications and to sketch a perspective for the future development of this and similar databases of historic land use.

7.1 Human environment interaction theories

Human interactions with their environments have evolved over long time periods, and at least three major phases of development can be distinguished. The first phase is known as the Paleolithic or Human system (Ellis, 2011) and extends roughly the period 2.5 million years ago until 10 000 BC. In this first stage land use by humans emerges as a transformative

force on the terrestrial biosphere. The earliest major influence of humans on their natural environment started with the use of simple stone tools and later the use of fire (Goudsblom, 2002a; Ferretti *et al.*, 2005; Nevle & Bird, 2008; Nevle *et al.*, 2011). Fire had an immediate effect on land cover as it helped to open up natural savannas and grasslands and by doing so making it more favorable for hunting and gathering of roots and fruits (Denevan, 1992; Carcaillet *et al.*, 2002; Whitlock & Bartlein, 2003). The second phase of development begins roughly at 10,000 BC. A very important feature of this phase is that humans learned to domesticate plants and animals (the latter not only for food but also for labor). This process took place simultaneously in many different regions of the world, although varying in time. Gradually, people evolved towards a more sedentary existence and adapted new crops and animals. This transition from (mobile) hunting/gathering to sedentary farming is also often referred to as the “Neolithic Revolution” (Diamond, 1999; Goudsblom, 2002a). All these processes leading to social and cultural changes (more complex social systems evolved such as the city states and markets), leading to growth in population numbers. This phase is also referred to by some sociologists as ‘Agrarianization’ (Goudsblom, 2002a), while Ellis (2011) uses the term Neolithic or the Agricultural system. The third stage according to Ellis (2011) is the ‘Industrial system’, when humans began to use fossil fuel on a large scale. It started early in the 18th century AD in Europe and spread rapidly across the world, and led to a huge increase in welfare, hygiene, artificial fertilizer use, new technology and global markets, but also to severe pollution, degradation of land and decreases in natural resources and biodiversity. This phase is also often referred to as the ‘Industrial Revolution’, or the ‘Great Acceleration’ (Goudsblom, 2002b; Steffen *et al.*, 2004).

Regime shifts

In most historic and prehistoric contexts, agricultural systems have shifted into more intensive production systems before these “Malthusian events” occur. In several instances large steps forward in technology after stagnation are identified as leading to regime shifts. Well known examples are the genetically improved cultivars (e.g. rice) which resulted in the so-called ‘Green Revolution’. Also the large scale introduction and application of synthetic fertilizers boosted yields, which also lead to leaching of nitrate to ground and surface water in many areas (but that is another story). Together with changes in population numbers these shifts have a dominant impact on land use and land cover, albeit not always a positive one (Grigg, 1974, 1979, 1980, 1981).

Recent studies in ecology suggest that smooth changes in an internal process (feedback) or a single disturbance (external shocks) can trigger a completely different system behavior, leading to a regime shift and thus substantially lowering a carrying capacity of an ecosystem (Scheffer *et al.*, 2001; Beisner, 2003; Scheffer & Carpenter, 2003; Folke, 2004). However, regime shifts are defined in this thesis as ‘shifts in technical/social systems of production’. These shifts have played and will likely continue to play an important role in land use farming systems and their transitions, and have already had a major influence on the area requirements for agriculture per person. Together with changes in population numbers these regime shifts in farming systems are key driving forces behind long-term changes in land use and land cover. However, the occurrence of such regime shifts in time and space is difficult to trace and the quantification of their effects on land cover is very difficult (Scheffer & Carpenter, 2003; Lenton *et al.*, 2012).

The occurrence of regime shifts can also depend on the original natural productivity or carrying capacity of a particular region. Tribes living in regions with a low carrying capacity were already equipped to deal with meager life conditions, they knew very well how much could be taken from the land, and were forced to adapt to the circumstances and were therefore less vulnerable to extreme climate or other disruptive events (e.g. Aboriginals in Australia). This, in contrast of humans who lived in relative prosperous conditions, i.e. ecosystems with a high carrying capacity, who could not cope with sudden extreme events such as drought periods, because they never had to develop optimization strategies, e.g. Mayans in Central America (pers.comm. Bert de Vries).

Regime shifts mechanisms and motivations

Thomas Malthus (1766–1834) suggested that exponential population growth coupled with linear growth in resource productivity would inevitably lead to the most simple and catastrophic form of regime shift: the collapse of populations in the face of limited resources. Even when populations entered new habitats – such as the Americas at Malthus' time, or when recovering from wars and epidemic plagues – the growth of population would eventually reach the limit of the resource base and this would inevitably lead to an overshoot and thus collapse of the system (Malthus, 1798). This can be regarded as an *ecological* motivation. Although collapses have been documented and/or reconstructed from the past (e.g. Mayan, Inca, Aztec or Akkadian empires), most studies suggest that they are related to changes in climate (droughts), diseases and/or (internal) warfare (Sanchez-Albornoz, 1974; Mann, 2005; Beach *et al.*, 2009; Zhang *et al.*, 2011). Figure 1 depicts the possible regime shifts as population density increases as well as required resources per capita.

Ester Boserup (1910-1999) who proposed a more *technology* driven motivation and categorized a sequence of stages in agricultural development from hunter-gatherers, pastoralism, fallow (forest), bush fallow, short fallow with domestic animals, annual cropping with intensive animal husbandry, and multi-cropping with little animal food (Boserup, 1965). She presented evidence from many field studies to underpin her theory that land use intensifies with increasing population. In other words; population density determines agricultural methods, rather than agricultural technology determining population (via food supply, closely linked to carrying capacity). This process is still ongoing in many regions of the world. A nice example is the elaborate study of Codjoe and Bilsborrow (2011), who examined the role of population in agricultural practices in Ghana through a household survey of 504 households in 24 rural localities. They present evidence that although land use expansion occurred in both dry and derived savannah systems, no Malthusian impacts could be found, while Boserupian intensification was evident. Bill Ruddiman and others (Ruddiman & Thomson, 2001; Ruddiman, 2003; Ruddiman & Ellis, 2009) elaborated on Boserup's theory and applied it to (paleo)history. They argue that 'average land use per capita appears to have fallen from several ha per person in the middle Holocene to just tenth on one ha near the start of the industrial era' (Ruddiman & Ellis, 2009), which is consistent with Boserup. However, they do not know the exact shape of the land use per capita curve, nor the timing of the process.

Geertz (1963) described agricultural development in Indonesia during the last century and stated in his study on Indonesia that "as technical limits to productivity increase draw near

within a given technical systems (regime), productivity stagnates. This process of "agricultural involution", where the Javanese economy, faced with external pressure from the economic demands of the Dutch colonial regime and internal pressure from rapidly increasing population, intensified existing forms of agriculture rather than changing them. This involved putting even more labor into paddy field cultivation, increasing per hectare output while maintaining per capita output. According to Geertz this process was tied up with the development of sugar as a smallholder cash crop complementary with rice production (Geertz, 1963).

Weisdorf (2003) argued through *economic* motivation that the adoption of agriculture necessitated the introduction of non-food specialists. In hunter-gatherer societies every member was engaged in food provision, but the release of labor to non-food gathering activities slowly stimulated economic activities. They were faced with the costs of redistribution of labor, which led according to Weisdorf (2003) to a delay in the adoption of agricultural techniques. However, after a period of time it led to large steps forward in food acquirement technology – a Neolithic revolution – linked to a shift to farming.

The fore mentioned theories are based on many years of field work and numerous (local) case studies. However, there exist only few attempts to quantify those historical patterns of land use changes at a global scale (Ramankutty & Foley, 1999; Klein Goldewijk, 2001; Pongratz *et al.*, 2008). They can be seen as first approaches, but many uncertainties exist, leaving the resulting global and regional estimates of cropland and pastures with large upper and lower ranges, as clearly shown by Klein Goldewijk and Verburg (2012). In the light of Boserup's theory, different curves of the per capita land use estimate for the past are explored in this thesis for the process of agricultural intensification have been explored in this thesis (Chapter 4, figure 6).

Chapter 4 also shows that integrated global (climate) change modelers have to be aware that their choice of land use scenario is quite critical for the resulting emissions and carbon cycle. Both the assumptions concerning land use as well as how land use is represented in the calculation of carbon are essential because the land use practices have a major influence on the carbon emissions. Different forms of agricultural land use clearly have different impacts on carbon. I have not been able to really implement these trajectories except for the overall increase. Data on the exact triggers of regime shifts are missing and can therefore not being implemented. However, the experiments with the curves have shown the sensitivity of the approach.

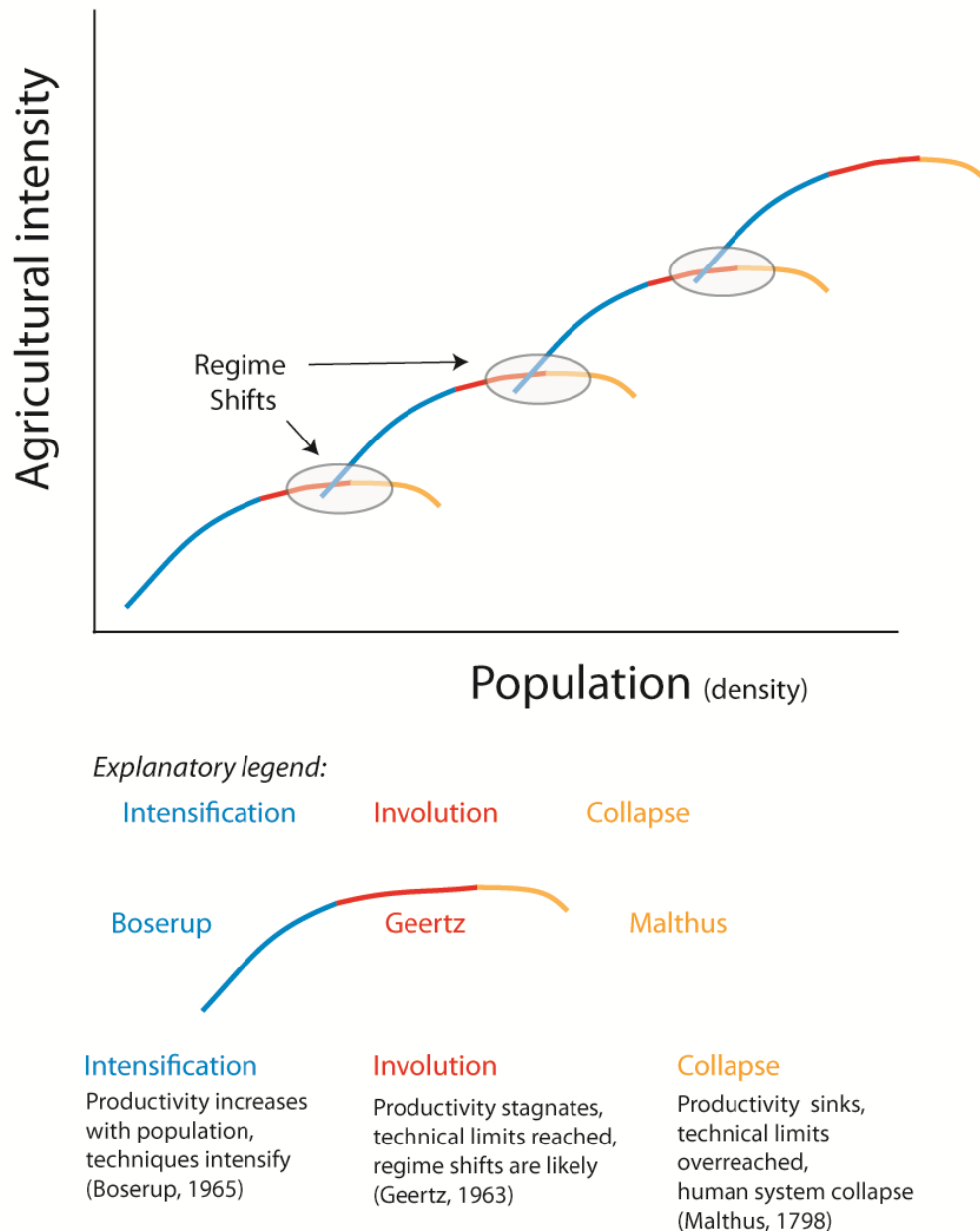


Figure 1. Regime shifts (original idea: Billie Turner II, adjusted from Erle Ellis, pers. comm 2012).

7.2 Added value to existing data

Global estimates of the historical areas of cropland and pasture land are rare and rather uncertain (Klein Goldewijk *et al.*, 2011). Different approaches were used in the available global estimates. Ramankutty & Foley (1998) calibrated the IGBP 1 km-resolution Global Land Cover Classification (GLCC) data set against cropland inventory data for 1992 to create a global map of cultivated land for 1992 (Ramankutty & Foley, 1998). Subsequently, they used a 'hindcast' modeling technique to extrapolate these data, using a compilation of historical cropland inventory data to create a spatial data set of croplands for the period 1700 to 1992 (Ramankutty & Foley, 1999). Others used a bookkeeping model with conversion rates of different land-cover types (including cropland and pasture) to estimate C fluxes (Houghton *et al.*, 1983; Richards, 1990; Houghton, 1999; Houghton & Hackler, 2002).

Pongratz et al (2008) reconstructed agricultural areas for the last millennium from AD 800 to 1992 by also using McEvedy and Jones (1978), combined with HYDE and other statistical sources.

The original HYDE 2 database (Klein Goldewijk, 2001) was a data base of historical land-use and population data of the 20th century on a spatial resolution of 30 arc-minutes. Much effort was put into bringing all the different data sources systematically to the same spatial and temporal level, and by doing so creating an internally consistent data set. The main focus was on land use and population, but other environmental variables were collected too, albeit on a less elaborate level. Most data were organized on the national scale for the period 1890 – 1990, and where available, for the period 1700 – 2000.

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

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

A major contribution of HYDE is that numerous historical data on population, built-up area, cropland and pasture of varying quantity and quality have been collected and streamlined into a consistent data base. With the population data from the United Nations World Population Prospects as a start (supplemented with many other historical population data sources), it serves as a central backbone for the land use part as well. Here, the data of the Food and Agricultural Organization (FAO) form the basis, and combined with many other land use data sources and the population data base, it resulted in a long term consistent population and land use data base on a high resolution 5 arc-minutes grid.

7.3 Applications

Climate change – carbon cycle

The HYDE data base has already been used in various studies concerning the effect of land use changes on carbon fluxes on CO₂ levels and climate and feedbacks in the climate system such as albedo, energy balance, radiative forcing, etc (Matthews *et al.*, 2004; Feddema *et al.*, 2005; Brovkin *et al.*, 2006; Friedlingstein *et al.*, 2006; Stendel *et al.*, 2006; Betts *et al.*, 2007; Bondeau *et al.*, 2007; Olofsson & Hickler, 2008; Pongratz *et al.*, 2009; Van Minnen *et al.*, 2009). Not only has it been used in studies of the past, but it has also been used for global change assessments, e.g. the Representative Concentration Pathway effort, where HYDE is used as major input for the 1500 – 2100 AD period in order to construct a consistent long term land use scenario for the 5th AR of IPCC (Hurtt *et al.*, 2011). It also has been used to

contribute to the Global Carbon Project (Le Quéré et al., 2009), by serving as input for historical (and current) carbon cycle analysis (Van Minnen *et al.*, 2009).

Other applications

HYDE has also been used in many other studies in different disciplines, table 1 lists a selection of applications in a chronological order..

Table 1 Overview of selected other applications of HYDE.

<i>Topic</i>	<i>Source</i>
Mappae Mundi, Humans and their habitats in a long-term socio-ecological perspective	De Vries and Goudsblom (2002)
Historical emissions of GHG's	Van Aardenne et al (2001), Lamarque et al (2010)
Habitat loss leading to species threat and extinction	Gaston et al (2003), Scharlemann et al (2004), Scharlemann et al (2010)
Black carbon, aerosols	Horowitz (2006)
Urban / built-up area	Potere and Schneider (2007)
Biomass burning	Mouillot and Field (2005), Marlon et al (2008) , Nevle and Bird (2008)
Biofuels	Fernandes et al (2007)
Historical methane budget	Houweling et al (2008)
Anthromes	Ellis et al (2010), see also chapter 5 of this thesis
Holocene carbon	Kaplan et al (2009), Kaplan et al (2011), see also chapter 6 of this thesis
Water scarcity	Scanlon et al (2007), Kummu et al (2010)
Transformation of the biosphere in the Anthropocene	Ellis (2011)
Plant biodiversity	Ellis et al (2012)

By bringing together multiple sources HYDE has increased the knowledge in historical data gaps but also improved the possibility for understanding historical interrelationships between population and land use over/between countries, regions and continents over time. And it can thus provide a framework for heuristic and speculative hypotheses about possible and yet unknown interactions (Wirtz & Lemmen, 2003; Ruddiman, 2007; Nevle & Bird, 2008; Ruddiman & Ellis, 2009).

7.4 Limitations of land cover reconstructions

There are several limitations to the use of population numbers and maps combined with per capita land use estimates and weighting maps to allocate land use across space. First of all, this approach relies heavily on gridded population density maps, under the assumption that agriculture is only possible where humans are resident. As a result, the temporal and spatial quality of input population density maps is very important. Because for many regions in the world, population statistics are very poor or absent, growth rates are used to inter- and

extrapolate between known data, introducing substantial uncertainty. For example, for 80 years, there has been a debate in the literature about pre-Colombian populations in the Americas, where estimates of total population for Latin America for the 15th century diverge from 12 to 100 million people (this thesis 39 million). Having chosen values for many countries and regions in compliance with as many literature sources as possible narrows this uncertainty a bit, but still most values for the New World before 1500 AD have to be regarded as 'educated guesses'. Recent studies (Heckenberger *et al.*, 2003; Mann, 2005) suggest that older estimates are on the low side and that much more humans must have lived there than previously thought, e.g. Denevan (1992) suggested 57 million for the Americas.

Secondly, the emergence of early subsistence farmers is not well known across the various regions of the world. How much area they used, when exactly the intensification processes took place, and over which period of time? Therefore, the shape of curves for land-use-per-capita back casting are highly uncertain and must therefore be considered as hypotheses awaiting testing. Careful examination of existing local case studies could enhance our knowledge on the temporal resolution and shape of regional intensification curves of agricultural land use per capita. The CLIO-INFRA project (<http://www.clio-infra.eu>) is an example of how social and economic historians and archeologists can contribute towards narrowing down some uncertainties in historical land use estimates. The project aims to collaborate with other institutes and many different disciplines, in order to link existing and create new datasets that together will enable new opportunities for data analysis and the testing of hypotheses from new economic theories.

Thirdly, there remains a lack of ability to compare model results with empirical data from paleo-ecological and/or historical/archeological studies. Gaillard *et al.* (2010) and Boyle *et al.* (2011) point out that "the existing anthropogenic land cover change scenarios show large discrepancies between them, and few cover time periods older than AD 800. When these scenarios are used to assess the impact of human land-use on climate, contrasting results are obtained". Often, this is a scale issue, many paleo-ecological and archeological studies are limited to local/point sources, or one moment in time, and investigators are usually reluctant to upscale their results to the regional, national or continental level, making it very hard to compare them to modeled results (Boyle *et al.*, 2011). The BIOME6000 project (Prentice *et al.*, 1996) was one of the first successful attempts to construct global historical global vegetation patterns, but still is was only for moments in time (6000 BC and 0 AD). A promising way forward is the LANDCLIM project (Gaillard *et al.*, 2010). It is a Model-Data comparison project, in which a so-called REVEALS (Regional Estimates of VEgetation Abundance from Large Sites) approach is used to infer long-term records of past land-cover from pollen data (Hellman *et al.*, 2008; Soepboer *et al.*, 2010).

Fourthly, spatially explicit population density maps can be improved by adding much more detailed historical city information. Books such as Raymond Chandlers 'Four thousand years of urban growth' have a vast amount of useful information about historical size and population of cities which can improve the urban/rural distinction in the HYDE population maps (Chandler, 1987).

Finally, a warning should be issued when using HYDE 3.1 data for integrated modeling of global change. Since HYDE 3.1 deals only with the expansion of agricultural activities, and this expansion can occur in many different natural land cover types, such as forests, grasslands, savanna, etc., HYDE cannot provide deforestation rates, nor does it present any data on land use change activities such as logging, shifting cultivation etc. Therefore, dynamic carbon cycle models should deal with such activities separately, such as Kaplan et al (2011) and Hurtt et al (2011), and therefore land use changes (and subsequently the resulting carbon fluxes) obtained by using HYDE 3.1 only should be regarded as a lower boundary.

7.5 Integrated assessments/global change research

Land use changes not only influence the climate system through biogeochemical processes by exchanging greenhouse-(GHG's) and other gases, pollutants and water vapor with the atmosphere (Betts, 2006; Brovkin *et al.*, 2006; Betts *et al.*, 2007), but also in a biophysical manner by affecting radiative forcing through a changing albedo or heat fluxes (Matthews *et al.*, 2003; Myhre & Myhre, 2003; Davin *et al.*, 2007; Pielke Sr *et al.*, 2011). Even the current Global Carbon Project states that the uncertainty on land use change emissions is the highest of any flux component of the global carbon budget (Le Quéré et al., 2009), which lays a burden on models who are trying to make sound projections for future climate policy. General Circulation Models (GCM's) run on supercomputers are far too complex to incorporate land use on a reasonable scale (time wise), in order to be used in future scenario studies. Therefore, a new class of Earth system models (ESM's) and ESM's of intermediate complexity (EMICs) emerged. These somewhat more simplified EMIC's are able to investigate the transient response of the climate system to different climate forcings on a much longer time scale than GCM's are capable of, because they are computationally more efficient without losing critical land-climate interactions. But still, there was a lack of good long-term historical land use reconstructions for global change modelers. Only one bookkeeping model existed (Houghton *et al.*, 1983), but it was not spatially explicit and not far enough back in time. This is important because uncertainty in global change models can be reduced by long time historic simulations. Reasoning is that if a model is capable to simulate the past correctly, it is a sign that the underlying processes are well understood, which increases the confidence for future projections. For that purpose historic spatially explicit land use data series are needed (Hurtt *et al.*, 2011). While many traditional input data of integrated assessments were quite rare and uncertain, new improved data were essential, and HYDE 3.1 can make an important contribution to this effort.

What are the implications for future global change research?

HYDE can contribute to a better understanding of human-environment interactions and the role of humans in earth system functioning. Questions such as 'Which elements of human-environment interactions observed in the past do also have a large impact on future land use?', "What are the land use consequences of trajectories according to the Boserupian theory as compared to the Malthusian assumption? "Which consequences will Boserupian intensifications have on future food production?" are highly relevant, also for future climate policy. To address these research questions, it is important to better understand which processes have driven the transformation of the Earth' landscapes.

Different theories exist about these processes. One can distinguish a sociological point of view, or an ecological point of view or a mixture of both. Or has there been a slow transformation from one into the other? For example, Goudsblom (2002a) advocates the sociological view and suggests that in early prehistory an increasing differentiation of humans occurred, in behavior, power, adaptation to changes, as compared to all closely related animals. Social learning is the crux – passing knowledge/technology over to others, with technology defined here as ‘harnessing various forms of matter and energy for human purposes’. Technology could not have developed without social organization. While currently humans can practice agriculture almost anywhere on the planet, if technology, capital and management are readily available. In short: ‘(actual) agriculture follows people’, even into the desert when irrigation schemes are provided, or into the pristine rainforests wherever massive clear cutting takes place.

A different and more ecology-based approach is from Wirtz and Lemmen (2003), who took as a starting point that the natural environment defines through the combination of climate, soil properties and other environmental variables the carrying capacity of an ecosystem or region. This carrying capacity steers to a great extent the number of people that can be sustained in a certain area, so one could say here that ‘people follow (the potential for) agriculture’.

The land use allocation scheme of HYDE reflects both theories in a way. HYDE starts in year 2000 with satellite imagery as the main ‘attractor’ for allocation of agriculture. In most populated places of the world one form or another of agriculture is practiced and, with the help of technology and modern management, the carrying capacity of many regions is dramatically raised. As the evidence from population and land use statistical data fades away in the (deep) past, we know with much less certainty where people lived and where agriculture emerged, nor can we answer the ‘what was first’ question: people or agriculture? The allocation rules change gradually in HYDE towards the past and other rules take over. Should they shift gradually towards the Wirtz and Lemmen (2003) approach, where climate, soil properties, distance to water and the main attractors for agricultural allocation are determinants? Or is Goudsblom’s theory the more valid one and should population maps be included in the allocation procedure? Probably, the HYDE approach as it is performed now is a mixture of both. It is beyond the scope of this research which approach gives a better agreement with empirical data found so far. The HYDE framework gives the opportunity to investigate the different assumptions in quantitative detail and, in this way, can support evidence in favor of one theory or the other or some balanced compromise.

Other disciplines could benefit from the HYDE database as well. There is a growing need for spatially explicit information for various about population density (e.g. in case of extreme weather, famines, local warfare, where do people live?). Combined with updated information about infrastructure, food producing areas, flooding areas, etc. this type of information/analyses could help policy makers to make a better judgment of the (potential) risk areas and the measurements to be taken.

In order to improve the HYDE and similar historic land use data bases, it is crucial that a multi disciplinary approach is sought with other fields of expertise. There is a vast amount of valuable information and expertise available, which information could be used to be

included and/or improve the population and land use estimates of HYDE. Research areas such as historical ecology, historical geography, (environmental) history, archeology, paleoecology, hydrology, renewable energy and limnology - to name a few – are just beginning to realize that they can contribute to future global change models and studies (Verschuren *et al.*, 2002; Gaillard *et al.*, 2010).

Also the socio-economic communities tend to expand their attention to spatially explicit modeling of demographic and economic indicators, for example Nordhaus (2006) presented a study where on a 1°x1° spatial grid the economic activity per unit area have been estimated on the basis of population density data and economic data at lower than national (state, province) level. One of the findings was that, whereas income (GDP per capita) tends to increase with distance from the equator, GDP is apparently higher in the temperate zones (5°-20°C). This spatially explicit thinking is crucial in integrated global assessments, where much information comes together and feedbacks in the systems can be addressed, to improve our understanding of the world we are living in. Nowadays we can tackle these issues on a global scale and from there we can incorporate local case studies.

This work can also contribute to various international research programs such as the Earth System Science Partnership (ESSP), a partnership of four international global change research programs (DIVERSITAS, IGBP, IHDP and WCRP) for the integrated study of the Earth System. Also important is that co-operation is sought and maintained with other disciplines and networks such as PAGES (Past Global Changes) and IHOPE (Integrated History and future Of the People on Earth) to share knowledge and gain more insight about the past and put it to use for a better (sustainable) future. HYDE is already endorsed by the Global Land Project (GLP), a joint research project for land systems for the International Geosphere-Biosphere Programme (IGBP) and the International Human Dimensions Programme (IHDP). A good effort could be the start of a 'Global land use data base portal', endorsed by PAGES/GLP. It should be a platform where global change modelers can contribute to and search for data sets. Ideally, this should be combined with similar efforts in the climate community (e.g. Global Historical Climate Network) and the socio-economic history community (CLIO-INFRA).

Finally, the essence of the work in this thesis is very nicely summarized by Costanza *et al* (2007):

“Integrated records of the co-evolving human-environment system over millennia are needed to provide a basis for a deeper understanding of the present and for forecasting the future. This requires the major task of assembling and integrating regional and global historical, archaeological, and paleoenvironmental records. Humans cannot predict the future. But, if we can adequately understand the past, we can use that understanding to influence our decisions and to create a better, more sustainable and desirable future”.

References

- Beach, T., Luzzadder-Beach, S., Dunning, N., Jones, J., Lohse, J., Guderjan, T., Bozarth, S., Millsbaugh, S. & Bhattacharya, T. (2009) A review of human and natural changes in Maya Lowland wetlands over the Holocene. *Quaternary Science Reviews*, 28, 1710-1724.
- Beisner, B. (2003) Beisner, B., et al. (2003) Alternative stable states in ecology. *Front. Ecol. Environ.* 1, 376-382 Beisner, B., et al. (2003) *Alternative stable states in ecology. Front. Ecol. Environ.* 1, 376-382 1, 376-382.
- Betts, R.A. (2006) Forcings and feedbacks by land ecosystem changes on climate change. *Journal De Physique. IV : JP* (ed by, pp. 119-142. Grenoble.
- Betts, R.A., Falloon, P.D., Klein Goldewijk, K. & Ramankutty, N. (2007) Biogeophysical effects of land use on climate: Model simulations of radiative forcing and large-scale temperature change. *Agricultural and Forest Meteorology*, 142, 216-233.
- Bondeau, A., Smith, P.C., Zaehle, S., Schaphoff, S., Lucht, W., Cramer, W., Gerten, D., Lotze-campen, H., Mueller, C., Reichstein, M. & Smith, B. (2007) Modelling the role of agriculture for the 20th century global terrestrial carbon balance. *Global Change Biology*, 13, 679-706.
- Boserup, E. (1965) *The Conditions of Agricultural Growth*, 1st edn. George Allen & Unwin Ltd, London.
- Boyle, J.F., Gaillard, M.-J., Kaplan, J. & Dearing, J. (2011) Modelling prehistoric land use and carbon budgets: A critical review. *Holocene*, 1-8.
- Brovkin, V., Claussen, M., Driesschaert, E., Fichefet, T., Kicklighter, D., Loutre, M.F., Matthews, H.D., Ramankutty, N., Schaeffer, M. & Sokolov, A. (2006) Biogeophysical effects of historical land cover changes simulated by six Earth system models of intermediate complexity. *Climate Dynamics*, 26, 587-600.
- Carcaillet, C., Almquist, H., Asnong, H., Bradshaw, R.H.W., Carrión, J.S., Gaillard, M.-J., Gajewski, K., Haas, J.N., Haberle, S.G., Hadorn, P., Müller, S.D., Richard, P.J.H., Richoz, I., Rösch, M., Sánchez Goi, M.F., Von Stedingk, H., Stevenson, A.C., Talon, B., Tardy, C., Tinner, W., Tryterud, E., Wick, L. & Willis, K.J. (2002) Holocene biomass burning and global dynamics of the carbon cycle. *Chemosphere*, 49, 845-863.
- Chandler, T. (1987) *Four thousand years of urban growth*, second edn. The Edwin Mellen Press, Lampeter.
- Codjoe, S.N.A. & Bilsborrow, R.E. (2011) Population and agriculture in the dry and derived savannah zones of Ghana. *Popul. Environ.*, 33, 80-107.
- Costanza, R., Graumlich, L., Steffen, W., Crumley, C., Dearing, J., Hibbard, K., Leemans, R., Redman, C. & Schimel, D. (2007) Sustainability or collapse: What can we learn from integrating the history of humans and the rest of nature? *Ambio*, 36, 522-527.
- Davin, E.L., de Noblet-Ducoudre, N. & Friedlingstein, P. (2007) Impact of land cover change on surface climate: Relevance of the radiative forcing concept. *Geophysical Research Letters*, 34
- de Vries, H.J.M. & Goudsblom, J. (2002) *Mappae Mundi, Human Society and their Habitats in a Long-Term Socio-Economic Perspective*, 1st edn. Amsterdam University Press, 368 pp.
- Denevan, W.M. (1992) The pristine myth: the landscape of the Americas in 1492. *Annals - Association of American Geographers*, 82, 369-385.
- Diamond, J. (1999) *Guns, Germs and Steel*. Norton Press, New York.
- Ellis, E.C. (2011) Anthropogenic transformation of the terrestrial biosphere. *Proceedings of the Royal Society a: Mathematical, Physical and Engineering Science*, 369, 1010-1035.
- Ellis, E.C., Antill, E.C. & Kreft, H. (2012) All is not loss: plant biodiversity in the Anthropocene. *PLoS ONE*, 7, e30535.
- Ellis, E.C., Klein Goldewijk, K., Siebert, S., Lightman, D. & Ramankutty, N. (2010) Anthropogenic transformation of the biomes, 1700 to 2000. *Global Ecology and Biogeography*, 19, 589-606.
- Feddema, J.J., Oleson, K.W., Bonan, G.B., Mearns, L.O., Buja, L.E., Meehl, G.A. & Washington, W.M. (2005) Atmospheric science: The importance of land-cover change in simulating future climates. *Science*, 310, 1674-1678.

- Fernandes, S.D., Trautmann, N.M., Streets, D.G., Roden, C.A. & Bond, T.C. (2007) Global biofuel use, 1850-2000. *Global Biogeochemical Cycles*, 21
- Ferretti, D.F., Miller, J.B., White, J.W.C., Etheridge, D.M., Lassey, K.R., Lowe, D.C., MacFarling Meure, C.M., Dreier, M.F., Trudinger, C.M., van Ommen, T.D. & Langenfelds, R.L. (2005) Unexpected changes to the global methane budget over the past 2000 years. *Science*, 209, 1714-1419.
- Folke, C. (2004) Regime shifts, resilience, and biodiversity in ecosystem management. *Annu. Rev. Ecol. Evol. Syst.*, 35, 557-581.
- Friedlingstein, P., Cox, P., Betts, R., Bopp, L., von Bloh, W., Brovkin, V., Cadule, P., Doney, S., Eby, M., Fung, I., Bala, G., John, J., Jones, C., Joos, F., Kato, T., Kawamiya, M., Knorr, W., Lindsay, K., Matthews, H.D., Raddatz, T., Rayner, P., Reick, C., Roeckner, E., Schnitzler, K.G., Schnur, R., Strassmann, K., Weaver, A.J., Yoshikawa, C. & Zeng, N. (2006) Climate-carbon cycle feedback analysis: Results from the C4MIP model intercomparison. *Journal of Climate*, 19, 3337-3353.
- Gaillard, M.-J., Sugita, S., Mazier, F., Kaplan, J.O., Trondman, A.-K., Brostroem, A., Hickler, T., Kjellstroem, E., Kunes, P., Lemmen, C., Olofsson, J., Smith, B. & Strandberg, G. (2010) Holocene land-cover reconstructions for studies on land-cover feedbacks. *Climate of the Past Discussions*, 6, 307-346.
- Gaston, K.J., Blackburn, T.M. & Klein Goldewijk, K. (2003) Habitat conversion and global avian biodiversity loss. *Proceedings of the Royal Society B: Biological Sciences*, 270, 1293-1300.
- Geertz, C. (1963) *Agricultural involution: the process of ecological change in Indonesia*, 4th edn. University of California Press, Ltd., Berkeley and Los Angeles, California, USA.
- Goudsblom, J. (2002a) Introductory overview: the expanding Anthroposphere. *Mappae Mundi, Humans and their habitats in a long-term socio-ecological perspective* (ed. by B. De Vries and J. Goudsblom), pp. 21-46. Amsterdam University Press, Amsterdam.
- Goudsblom, J. (2002b) The past 250 years: Industrialization and Globalization. *Mappae Mundi, Humans and their habitats in a long-term socio-ecological perspective* (ed. by B. De Vries and J. Goudsblom), pp. 353-378. Amsterdam University Press, Amsterdam.
- Grigg, D.B. (1974) *The Agricultural Systems of The World: An Evolutionary Approach*. Cambridge Univ. Press, New York.
- Grigg, D.B. (1979) Ester Boserup's theory of agrarian change: a critical review. *Prog Hum Geogr*, 3, 64-84.
- Grigg, D.B. (1980) *Population growth and agrarian change*. Cambridge University Press, Cambridge, UK.
- Grigg, D.B. (1981) The historiography of hunger: changing views on the world food problem 1945-1980. *Transactions Institute of British Geographers*, 6, 279-292.
- Heckenberger, M.J., Kuikuro, A., Kuikuro, U.T., Christian Russell, J., Schmidt, M., Fausto, C. & Franchetto, B. (2003) Amazonia 1492: Pristine Forest or Cultural Parkland? . *Science*, 301, 1710-1714.
- Hellman, S.E.V., Gaillard, M.-J., Brostrom, A. & Sugita, S. (2008) Effects of the sampling design and selection of parameter values on pollen-based quantitative reconstructions of regional vegetation: A case study in southern Sweden using the REVEALS model. *Vegetation History and Archaeobotany*, 17, 445-459.
- Horowitz, L.W. (2006) Past, present and future concentrations of tropospheric ozone and aerosols: Methodology, ozone evaluation, and sensitivity to aerosol wet removal. *Journal of Geophysical Research*, 111
- Houghton, R.A. (1999) The annual net flux of carbon to the atmosphere from changes in land use 1850-1990. *Tellus, Series B: Chemical and Physical Meteorology*, 51, 298-313.
- Houghton, R.A. & Hackler, J.L. (2002) Carbon Flux to the Atmosphere from Land-Use Changes: 1850 to 1990. In: *ORNL/CDIAC-131, NDP-050/R1* (<http://cdiac.esd.ornl.gov/ndps/ndp050.html>), p. 86. Carbon Dioxide Information Analysis Center, U.S. Department of Energy, Oak Ridge National Laboratory, Oak Ridge, Tennessee, U.S.A.

- Houghton, R.A., Hobbie, J.E., Melillo, J.M., Moore, B., Peterson, B.J., Shaver, G.R. & Woodwell, G.M. (1983) Changes in the Carbon Content of Terrestrial Biota and Soils between 1860 and 1980: A Net Release of CO₂ to the Atmosphere. *Ecological Monographs*, 53, 236-262.
- Houweling, S., van der Werf, G.R., Goldewijk, K.K., Röckmann, T. & Aben, I. (2008) Early anthropogenic CH₄ emissions and the variation of CH₄ and ¹³CH₄ over the last millennium. *Global Biogeochemical Cycles*, 22
- Hurt, G.C., Chini, L.P., Frolking, S., Betts, R., Feddema, J.J., Fischer, G., Hibbard, K.A., Janetos, A.C., Jones, C., Klein Goldewijk, K., Kindermann, G., Kinoshita, T., Riahi, K., Shevliakova, E., Smith, S., Stehfest, E., Thomson, A., Thornton, P., van Vuuren, D. & Wang, Y.P. (2011) Harmonization of land-use scenarios for the period 1500-2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands. *Climatic Change*, doi:10.1007/s10584-011-0153-2
- Kaplan, J.O., Krumhardt, K.M. & Zimmermann, N. (2009) The prehistoric and preindustrial deforestation of Europe. *Quaternary Science Reviews*, 28, 3016-3034.
- Kaplan, J.O., Krumhardt, K.M., Ellis, E.C., Ruddiman, W.F., Lemmen, C. & Klein Goldewijk, K. (2011) Holocene carbon emissions as a result of anthropogenic land cover change. *The Holocene*, 21, 775-791.
- Klein Goldewijk, K. (2005) Three centuries of global population growth: A spatial referenced population (density) database for 1700-2000. *Population and Environment*, 26, 343-367.
- Klein Goldewijk, K. (2001) Estimating global land use change over the past 300 years: The HYDE database. *Global Biogeochemical Cycles*, 15, 417-433.
- Klein Goldewijk, K. & van Dreht, G. (2006) *HYDE 3: Current and historical population and land cover*. In: Bouwman, A.F., Kram, T., Klein Goldewijk, K (eds). Integrated modelling of global environmental change. An overview of IMAGE 2.4. Netherlands Environmental Assessment Agency, Bilthoven, The Netherlands.
- Klein Goldewijk, K. & Verburg, P.H. (2012) Uncertainties in global-scale reconstructions of historic land use. *Landscape Ecology*, submitted
- Klein Goldewijk, K., Beusen, A., van Dreht, G. & de Vos, M. (2011) The HYDE 3.1 spatially explicit database of human induced land use change over the past 12,000 years. *Global Ecology and Biogeography*, 20(1), doi: 10.1111/j.1466-8238.2010.00587.x.
- Kummu, M., Ward, P.J., de Moel, H. & Varis, O. (2010) Is physical water scarcity a new phenomenon? Global assessment of water shortage over the last two millennia. *Environmental Research Letters*, 5, 034006.
- Lamarque, J.-F., Bond, T.C., Eyring, V., Granier, C., Heil, A., Klimont, Z., Lee, D., Liousse, C., Mieville, A., Owen, B., Schultz, M.G., Shindell, D., Smith, S.J., Stehfest, E., Van Aardenne, J., Cooper, O.R., Kainuma, M., Mahowald, N., McConnell, J.R., Naik, V., Riahi, K. & Van Vuuren, D.P. (2010) Historical (1850-2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: Methodology and application. *Atmospheric Chemistry and Physics*, 10, 7017-7039.
- Le Quéré et al. (2009) Trends in the sources and sinks of carbon dioxide. Global Carbon Project (2009) Carbon budget and trends 2008. *Nature Geoscience*, doi: 10.1038/ngeo689.
- Lenton, T., Livina, V., Dakos, V., Van Nes, E.H. & Scheffer, M. (2012) Early warning of climate tipping points from critical slowing down: Comparing methods to improve robustness. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 370, 1185-1204.
- Malthus, T.R. (1798) An essay on the principle of population, in Oxford World's Classics reprint. p61, end of Chapter VII In:
- Mann, C.C. (2005) *1491: New Revelations of the Americas Before Columbus* 1st edn. Vintage Books, New York.
- Marlon, J.R., Bartlein, P.J., Carcaillet, C., Gavin, D.G., Harrison, S.P., Higuera, P.E., Joos, F., Power, M.J. & Prentice, I.C. (2008) Climate and human influences on global biomass burning over the past two millennia. *Nature Geoscience*, 1, 697-702.

- Matthews, H.D., Weaver, A.J., Eby, M. & Meissner, K.J. (2003) Radiative forcing of climate by historical land cover change. *Geophysical Research Letters*, 30, 27-1.
- Matthews, H.D., Weaver, A.J., Meissner, K.J., Gillett, N.P. & Eby, M. (2004) Natural and anthropogenic climate change: Incorporating historical land cover change, vegetation dynamics and the global carbon cycle. *Climate Dynamics*, 22, 461-479.
- Mouillot, F. & Field, C.B. (2005) Fire history and the global carbon budget: A 1° x 1° fire history reconstruction for the 20th century. *Global Change Biology*, 11, 398-420.
- Myhre, G. & Myhre, A. (2003) Uncertainties in radiative forcing due to surface Albedo changes caused by land-use changes. *Journal of Climate*, 16, 1511-1524.
- Nevle, R.J. & Bird, D.K. (2008) Effects of syn-pandemic fire reduction and reforestation in the tropical Americas on atmospheric CO₂ during European conquest. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 264, 25-38.
- Nevle, R.J., Bird, D.K., Ruddiman, W.F. & Dull, R.A. (2011) Neotropical human-landscape interactions, fire, and atmospheric CO₂ during European conquest. *Holocene*, 21, 853-864.
- Nordhaus, W.D. (2006) Geography and macroeconomics: New data and new findings. *Proceedings of the National Academy of Sciences of the United States of America*, 103, 3510-3517.
- Olofsson, J. & Hickler, T. (2008) Effects of human land-use on the global carbon cycle during the last 6,000 years. *Vegetation History and Archaeobotany*, 17, 605-615.
- Pielke Sr, R., Pitman, A., Niyogi, D., Mahmood, R., McAlpine, C., Hossain, F., Klein Goldewijk, K., Nair, U., Betts, R., Fall, S., Reichstein, M. & Kabat, P. (2011) Land use/land cover changes and climate: Modeling analysis and observational evidence. *WIREs Clim Change*, in press
- Pongratz, J., Reick, C., Raddatz, T. & Claussen, M. (2008) A reconstruction of global agricultural areas and land cover for the last millennium. *Global Biogeochemical Cycles*, 22
- Pongratz, J., Raddatz, T., Reick, C.H., Esch, M. & Claussen, M. (2009) Radiative forcing from anthropogenic land cover change since A.D. 800. *Geophysical Research Letters*, 36
- Potere, D. & Schneider, A. (2007) A critical look at representations of urban areas in global maps. *GeoJournal*, 69, 55-80.
- Prentice, C.I., Guiot, J., Huntley, B., Jolly, D. & Cheddadi, R. (1996) Reconstructing biomes from palaeoecological data: a general method and its application to European pollen data at 0 and 6 ka. *Climate Dynamics*, 12, 185-194.
- Ramankutty, N. & Foley, J.A. (1998) Characterizing patterns of global land use: An analysis of global croplands data. *Global Biogeochemical Cycles*, 12, 667-685.
- Ramankutty, N. & Foley, J.A. (1999) Estimating historical changes in global land cover: Croplands from 1700 to 1992. *Global Biogeochemical Cycles*, 13, 997-1027.
- Richards, J.F. (1990) Land transformation. *The Earth as transformed by human action* (ed. by B.L.E.A. Turner), pp. 163-178. Cambridge University Press, New York.
- Ruddiman, W.F. (2003) The anthropogenic greenhouse era began thousands of years ago. *Climatic Change*, 61, 261-293.
- Ruddiman, W.F. (2007) The early anthropogenic hypothesis: Challenges and responses. *Reviews of Geophysics*, 45
- Ruddiman, W.F. & Thomson, J.S. (2001) The case for human causes of increased atmospheric CH₄ over the last 5000 years. *Quaternary Science Reviews*, 20, 1769-1777.
- Ruddiman, W.F. & Ellis, E.C. (2009) Effect of per-capita land use changes on Holocene forest clearance and CO₂ emissions. *Quaternary Science Reviews*, 28, 3011-3015.
- Sanchez-Albornoz, N. (1974) *The population of Latin America; a history*. University of California Press., Berkeley.
- Scanlon, B., Jolly, I., Sophocleous, M. & Zhang, L. (2007) Global impacts of conversions from natural to agricultural ecosystems on water resources: Quantity versus quality. *Water Resources Research*, 43, doi:10.1029/2006WR005486.
- Scharlemann, J.P.W., Green, R.E. & Balmford, A. (2004) Land-use trends in Endemic Bird Areas: global expansion of agriculture in areas of high conservation value. *Global Change Biology*, 10, 2046-2051.

- Scharlemann, J.P.W., Kapos, V., Campbell, A., Lysenko, I., Burgess, N.D., Hansen, M., Gibbs, H.K., Dickson, B. & Miles, L. (2010) Securing tropical forest carbon: the contribution of protected areas to REDD. *Fauna & Flora International, Oryx*, 44, 352-357.
- Scheffer, M. & Carpenter, S.R. (2003) Catastrophic regime shifts in ecosystems: Linking theory to observation. *Trends in Ecology and Evolution*, 18, 648-656.
- Scheffer, M., Carpenter, S.R., Foley, J., Folke, C. & Walker, B. (2001) Catastrophic shifts in ecosystems. *Nature*, 413, 591-596.
- Soepboer, W., Sugita, S. & Lotter, A.F. (2010) Regional vegetation-cover changes on the Swiss Plateau during the past two millennia: A pollen-based reconstruction using the REVEALS model. *Quaternary Science Reviews*, 29, 472-483.
- Steffen, W., Sanderson, A., Tyson, P.D., Jäger, J., Matson, P.A., Moore III, B., Oldfield, F., Richardson, K., Schellnhuber, H.J., Turner II, B.L. & Wasson, R.J. (2004) *Global Change and the Earth System: A Planet Under Pressure*. Springer-Verlag, Berlin Heidelberg New York.
- Stendel, M., Mogensen, I.A. & Christensen, J.H. (2006) Influence of various forcings on global climate in historical times using a coupled atmosphere-ocean general circulation model. *Climate Dynamics*, 26, 1-15.
- Van Aardenne, J.A., Dentener, F.J., Olivier, J.G.J., Goldewijk, C.G.M.K. & Lelieveld, J. (2001) A 1.0° - 1.0° resolution data set of historical anthropogenic trace gas emissions for the period 1890-1990. *Global Biogeochemical Cycles*, 15, 909-928.
- Van Minnen, J.G., Klein Goldewijk, K., Stehfest, E., Eickhout, B., van Drecht, G. & Leemans, R. (2009) The importance of three centuries of land-use change for the global and regional terrestrial carbon cycle. *Climatic Change*, 97, 1-22.
- Verschuren, D., Johnson, T.C., Kling, H.J., Edgington, D.N., Leavitt, P.R., Brown, E.T., Talbot, M.R. & Hecky, R.E. (2002) History and timing of human impact on Lake Victoria, East Africa. *Proceedings of the Royal Society B: Biological Sciences*, 269, 289-294.
- Weisdorf, J.L. (2003) Stone age economics: The origins of agriculture and the emergence of non-food specialists. In: *Discussion papers*, 03-34, University of Copenhagen, Denmark.
- Whitlock, C. & Bartlein, P.J. (2003) Holocene fire activity as a record of past environmental change. *Developments in Quaternary Sciences*, 1, 479-490.
- Wirtz, K.W. & Lemmen, C. (2003) A global dynamic model for the Neolithic transition. *Climatic Change*, 59, 333-367.
- Zhang, D.D., Lee, H.F., Wang, C., Li, B., Zhang, J., Pei, Q. & Chen, J. (2011) Climate change and large-scale human population collapses in the pre-industrial era. *Global Ecology and Biogeography*, doi:1466-8238.2010.00625.x.