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

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Chapter 1
Introduction

1.1 The importance of land use in integrated global change modeling

Land use plays an important role in the climate system (Feddema *et al.*, 2005). Many ecosystem processes are directly or indirectly climate driven, and together with human driven land use changes, they determine how the land surface will evolve through time (Claussen *et al.*, 2001; Brovkin *et al.*, 2006; Betts *et al.*, 2007) These 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). These biosphysical feedbacks on land use can be either positive or negative (Claussen *et al.*, 2001).

The carbon cycle is an important actor in the climate system and has been the focus of many studies (Cox *et al.*, 2000; Houghton, 2003a; Feddema *et al.*, 2005; Friedlingstein *et al.*, 2006; Findell *et al.*, 2007; Plattner *et al.*, 2008; Strassmann *et al.*, 2008). Changes in land use, primarily through conversion of undisturbed ecosystems to other forms of land use (such as deforestation for agriculture or grazing, logging activities, or infrastructure such as roads) result in GHG emissions and contribute also considerably to the cumulative carbon dioxide (CO_2) increase in the atmosphere. These carbon fluxes are still not well quantified in the global carbon budget (Pacala *et al.*, 2001), and uncertainties quantifying the impact of land use changes on the global carbon cycle lead to uncertainties in projections of atmospheric CO_2 and climate, and consequently, affect policy makers in establishing reasonable emission mitigation strategies.

Present day measurements of CO_2 cannot be used to verify global CO_2 emissions estimated from energy data, because the uptake of CO_2 by the land and ocean CO_2 sinks are not quantified with high enough accuracy. The Global Carbon Project (GCP, Le Quere et al (2009)) constructed a global CO_2 budget for each year during 1959–2008 and analysed the underlying drivers of each component. The global increase in atmospheric CO_2 was determined directly from measurements. CO_2 emissions from fossil fuel combustion were estimated on the basis of countries' energy statistics. CO_2 emissions from land-use change (LUC) were estimated using deforestation and other land-use data, fire observations from space, and assumptions on the carbon density of vegetation and soils and the fate of carbon. The time evolution of the land and ocean CO_2 sinks, however, cannot be estimated directly from observations. For these terms, state-of-the-art models were used on which the observed meteorological conditions of the past few decades were imposed (Le Quéré et al., 2009).

Therefore, the role of (historical) land use changes and their influence on the carbon cycle has received great attention in recent decades. In the past, emissions from land use changes have been estimated by a book-keeping method (Houghton *et al.*, 1983) that took into account temporal delays between carbon emissions and uptake after deforestation or abandonment of used land. This approach disregarded feedbacks between atmospheric CO_2, climate and carbon emissions from land use changes (Leemans *et al.*, 2002). To assess the effects of land cover changes on the climate system, models are required which are capable of simulating interactions between the involved components of the Earth system (land, atmosphere, ocean, and carbon cycle). Since driving forces for global environmental change differ among regions, a geographically (spatially) explicit modeling approach is called for, so that it can be incorporated in global and regional (climate and/or biophysical) change models in order to enhance our understanding of the underlying processes and thus improving future projections (Feddema *et al.*, 2005; Stendel *et al.*, 2006; Davin *et al.*, 2007; Plattner *et al.*, 2008; Strassmann *et al.*, 2008; Vavrus *et al.*, 2008).

Although estimates of historical CO_2 emissions from land use changes are uncertain (Ruddiman, 2003), many studies indicate that most land use changes are an important net source of CO_2 (DeFries *et al.*, 1999; Houghton, 1999; McGuire *et al.*, 2001; Pacala *et al.*, 2001; Houghton, 2003a). However, the exact contribution of land use changes to the global carbon cycle is still a major uncertainty (Houghton, 2003b; House *et al.*, 2003; Le Quéré et al., 2009; Houghton, 2010). Thus, there is a high scientific priority for a better representation of dynamic land use patterns into global (climate) change models in order to account for feedbacks and so reducing the uncertainty in future projections (Friedlingstein et al., 2006).

The required timescale of historical land use and land cover information is expanding towards the entire Holocene as this is essential to understand long-term relationships (e.g. time lags in the system) between land use and climate for future projections. Currently more and more models have attempted to characterize these long term land use time series (Vavrus *et al.*, 2008; Kaplan *et al.*, 2009; Ruddiman & Ellis, 2009; Gaillard *et al.*, 2010; Kaplan *et al.*, 2010). Besides that, many other studies use historical land use information in different ways; e.g. the recently developed Anthromes approach (Ellis & Ramankutty, 2008; Ellis et al., 2010), or the influence of global and regional land use change on biomass burning (Mouillot & Field, 2005; Marlon et al., 2008; Nevle & Bird, 2008). Furthermore, it serves as input for different disciplines such as macro-ecologists, helping them to understand the past dynamics of geographical ranges and species specific niches (Nogues-Bravo, 2009), determine the gain or loss in global biodiversity (Gaston et al., 2003; Gaston, 2006), or explore the human impact on several biodiversity issues (Cincotta et al., 2000; Goudie, 2006). Also various other examples exist of applications using historical land use changes such as historical water studies (Kummu et al., 2010), the changing role of biofuels in the world (Fernandes et al., 2007), historical emission inventories of GHG's (Van Aardenne et al., 2001), the Holocene methane budget (Houweling et al., 2008), or the global nitrogen and phosphorus balance for 1900 – 2050 (Bouwman *et al.*, 2011).

There are two different approaches concerning global historical land-use reconstructions; either by (dynamic) modeling or through combining statistical inventories with hind-casting techniques. The first group is represented by so-called Dynamic Global Vegetation Models (DGVMs), who are process based and look at the exchange of carbon, water, and vegetation dynamics to compute long historical transient time series of land use Since most of these DGVM's use biomes (envelopes of plant functional types), only natural vegetation patterns are modeled who lack human presence. These biomes are computed by models, which predict global patterns in vegetation physiognomy from physiological considerations influencing the distributions of different functional types of plant. Primary driving variables are temperature, precipitation, sunshine hours, humidity, incoming radiation and soil (water) characteristics. The model predicts which plant types can occur in a given environment, selects the potentially dominant types from among them, and biomes arise as combinations of dominant types (Sitch *et al.*, 2003; Hughes *et al.*, 2006; Zaehle *et al.*, 2007; Olofsson & Hickler, 2008)

The second group of historical land-use datasets use a mix of statistical data and hind-casting techniques, and they exist at different levels of detail, temporaly as well as spatially. Depending on the spatial and temporal scale, studies either rely completely on historical statistical data, or where data are limited or non-existing, hind-casting techniques and/or modeling techniques are applied. There are many local inventories available, such as the Burgundy region in France (Crumley, 2000) the Andean region in Colombia (Etter & Van Wyngaarden, 2000; Etter *et al.*, 2008), the Belgian Ardennes (Petit & Lambin, 2002), or Tibet (Ryavec, 2001). Such studies focus on relatively small regions, and use many archeological, historical, paleological and even photographical or oral history sources. At national scales studies exist for example for the USA (Maizel, 1998), Australia (AUSLIG, 1990), Japan (Himiyama, 1998), and China (Ge *et al.*, 2008), often not surprisingly countries with relative rich and well documented history archives. Such studies become scarcer at a larger regional/continental scale; e.g. Flint and Richards (1991) presented a land use change study for Southeast Asia for the period 1880 – 1990, based in inventory reports. Williams (2000) performed a literature study, and Kaplan et al. (2009) modeled (using also statistical data) historical land use changes for Europe.

1.2 Objectives

Global long term land use inventories are very rare. Therefore, the main objective of this thesis is to present a globally consistent spatially explicit database of historical populations and land use for the Holocene, useful for the scientific community, especially for integrated modeling of global (climate) change. While detailed snapshots of land use exist since the satellite era (Loveland & Belward, 1997; Bartholome & Belward, 2005), long term time series based on satellite imagery do not exist (yet). Land cover is defined as the observed (bio)phusical cover of the Earth's surface, while land use is considered as the arrangements, activities and inputs people undertake in a certain land type to produce, change or maintain it (GLP workshop, Vienna, 2008). Land cover may be observed directly in the field or by remote sensing, observations of land use and its changes generally require the integration of natural and social s. For example, areas covered by woody vegetation may represent an undisturbed natural shrubland, a forest preserve recovering from a fire (use = conservation), regrowth following tree harvest (forestry), a plantation of immature rubber trees (plantation agriculture), swidden agriculture plots that are in between periods of clearing for annual crop production, or an irrigated tea plantation (Ellis, 2010).

One of the first long time series of global land use changes covering the period 1850 – 1990 was presented by Houghton *et al*. (1983) who used a bookkeeping approach, and this was updated later on (Houghton, 1999; Houghton & Hackler, 2002). Klein Goldewijk and Battjes

(1995, 1997) started their inventory for the period 1890 – 1990, reporting cropland and pasture, and this was later expanded to the period 1700 – 2000 (Klein Goldewijk, 2001). Ramankutty and Foley (1999) also reported for that period, but only for croplands. Pongratz et al (2008) presented a reconstruction of global agricultural areas for the 800 – 2000 period and Klein Goldewijk et al (2011) expanded the time horizon covering the whole Holocene (10 000 BC – AD 2000). The work of Klein Goldewijk et al (2011) was partly used and expanded with future projections in its turn by Hurtt *et al* (2010) who present harmonized land use scenarios for 1500 – 2100 period, including shifting cultivation and primary and secondary use of ecosystems.

The first History of the Global Environment Database, on which the work in this thesis is based, (HYDE, version 1.0) included both general topics such as land use, population, livestock, gross domestic product (along with value added generated in industry and the service sector), and specific data on energy, the economy, atmosphere, oceans and the terrestrial environment. It was organized on a regional level and had no spatial resolution. It was updated in 1997 to version 1.1 (Klein Goldewijk & Battjes, 1995; Klein Goldewijk & Battjes, 1997). Most data were organized on the national and regional scale for a hundred year period (1890 – 1990).

Its successor, HYDE version 2.0 (Klein Goldewijk, 2001) was a consistent data set of historical land-use maps on a spatial resolution of 30 arc minutes, for the period 1700 – 2000. For simplicity reasons information was allocated in a Boolean way, meaning that whole grid cells were classified each time into a single category, no partial cover was possible. For non-agricultural ('natural') areas a static biome map was used (Prentice et al., 1992), under the assumption that natural vegetation had hardly changed by climate during the last three hundred years. One advantage was now that land use conversions such as deforestation could now be computed.

A major update (version 3.0) was presented in Klein Goldewijk & van Drecht (2006). With the main focus on population and land use modeling, this version included several improvements compared to its predecessor: (i) the HYDE 2.0 version used a Boolean approach with a 30 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 use; (iii) updated historical land-use data for the period 1700 – 2000; (iv) implementation of different allocation algorithms with time-dependent weighting maps for cropland and grassland used for livestock.

Finally, the current HYDE version 3.1 is an updated and internally consistent combination of historical population estimates and improved allocation algorithms with time-dependent weighting maps for cropland and grassland are implemented, while the period covered now is extended from 10 000 BC to AD 2000 (Klein Goldewijk *et al.*, 2010; Klein Goldewijk *et al.*, 2011). This version of the database and its applications is presented in this thesis.

1.3 Guide for readers

Chapter 2 focuses on of the most important drivers of land use change, namely population growth. For example Biggs and Scholes (2002) found almost a linear relationship between population growth an the expansion of agricultural land for South Africa from early 20th century up to the 1960s. Chapter 2 presents the most recent version of the HYDE 3.1 data base, using different demographic sources and describing the methodology to combine all the various inputs with specific algorithms in order to create gridded maps of population totals, population densities, and also an urban and rural distinction. And finally, for the first time a consistent time series of long term gridded historical built-up area is presented. The long term historical spatial population maps from Chapter 2 serve as an important (but not the only) input for the reconstruction of the historic land use maps. Chapter 3 describes how these gridded time series are computed, from the statistical input, to the algorithms, to the method and assumptions used in the process. Comparisons are made (where possible) with other studies and the different important historical land use trends/events through history are explained.

Chapter 4 deals with all the uncertainties involved in the chosen approach. A series of experiments have been set up, to quantify the role of these uncertainties in assessments of global change processes, through running a simplified version of the IMAGE model with historical HYDE data as input. By varying input parameters and assumptions while creating HYDE data, the implications for the resulting concentrations of resulting GHG's and carbon fluxes of IMAGE are assessed, thus demonstrating the sensitivity of an integrated assessment to historical land use data.

To demonstrate the potential use of this land use and population database, Chapter 5 presents an application called the Anthromes approach. This new conceptual framework is based on the idea that classical biomes (ecosystems defined by specific climate envelopes and soil characteristics), do not account for human presence and therefore human biomes were introduced (also called anthropogenic biomes, or "anthromes"). These anthromes were mapped for 1700, 1800, 1900 and 2000 using a rule-based anthrome classification model applied to gridded global data for human population density and land use, stemming from the HYDE 3.1 data base. The chapter describes that three centuries ago humans had already penetrated almost every habitable area. Deserts and tundra were then, and still are, the last places on Earth almost without hardly any human influence. But in 1700, there were lots of "semi-natural" land, marginally used by people. Nowadays this use has been largely increased and much of what remains is embedded within intensively used landscapes.

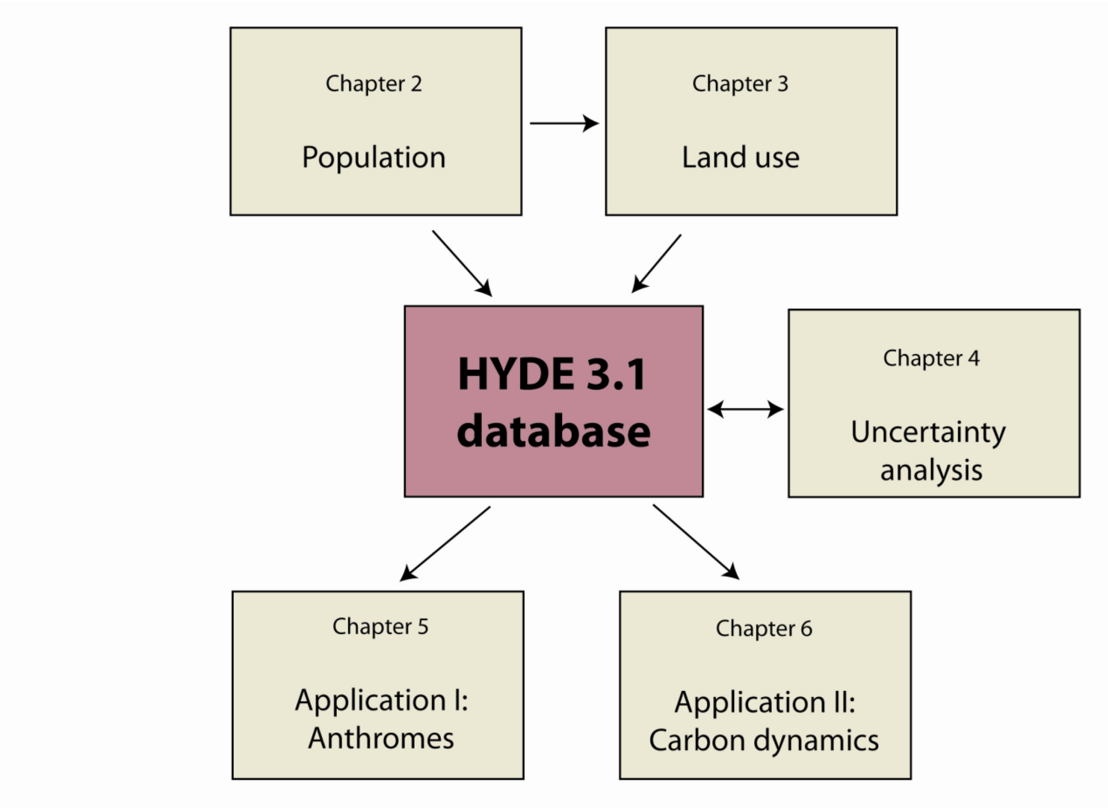

Figure 1. Layout of this thesis.

Chapter 6 illustrates another use of the data base for global change studies. It evaluates the impacts of anthropogenically-induced land use change on terrestrial carbon storage during the preindustrial Holocene. A new annually resolved inventory of anthropogenic land cover change from 8000 years ago to the beginning of large-scale industrialization (AD 1850) is presented, based on a simple relationship between population and land use observed in several European countries over preindustrial time, and together with an alternative scenario based on the HYDE land use database described in Chapter 3, a LPJ DGVM model combination is forced in a series of continuous simulations.

Chapter 7 synthesizes the thesis, and sketches the shortcomings, advantages and remaining scientific questions concerning the development of global scale historical land use data..

The database is freely available to the scientific community at http:/www.pbl.nl/hyde. Data from chapter 5 are available at http://ecotope.org/anthromes/v2/. Background data for chapter 6 can be found http://arve.epfl.ch/people/jedkaplan/.

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