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

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Summary

Context

As long as humans have been present on the Earth, they have been altering the global landscape. These historical changes in land use, primarily conversion (deforestation) of undisturbed ecosystems to other forms of land use (cropland, grazing land), have contributed considerably to the cumulative carbon dioxide (CO_2) increase in the atmosphere. The earliest major influence of humans on their natural environment started with the domestication of fire. This first stage is defined as the 'Paleolithic' system. Over time, humans learned to make and use tools, and plants and animals were domesticated. This transition from a hunterer/gatherer system towards a more sedentary agricultural system is often referred to as the second phase; 'Agrarianization' or the 'Neolithic system/ Neolithic Revolution'. It lead to more complex social systems, such as the city states and markets, and all this lead to a steadily growth in population numbers. Finally, the third stage or the 'Industrial system' arrived when humans began to use fossil fuels at a large scale. This lead not only to a huge increase in welfare, hygiene, artificial fertilizer, new technology and global markets, but also to pollution, degradation of land and decreases in natural resources and biodiversity. This phase is also often referred to as the 'Industrial system/Revolution', or the 'Great Acceleration'.

Land use changes not only influence the climate system through biogeochemical processes by exchanging greenhouse- and other gases, pollutants and water vapor with the atmosphere, but also in a biophysical manner by affecting radiative forcing through a changing albedo or heat fluxes. General Circulation Models (GCM's) run on supercomputers are far too complex to incorporate land use on a reasonable scale (timewise), 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, 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.

This thesis describes a database (and some applications) of a historic land use data base named HYDE; the History Data base of the Global Environment.

The HYDE Data Base

Population has been and still is an important driving force in Earth' history, so Chapter 2 describes the population part of the HYDE data base. Total and urban/rural population numbers are computed on the basis of numerous statistical sources and growth rates, and population densities and fractions (incl. built-up area) are derived. The period covered is the

Holocene, roughly the period 10 000 BC to AD 2000 with a spatial resolution of 5 arc minutes longitude/latitude grid.

The resulting maps have been constructed by combining statistics and a spatially explicit allocation routine, on a global 5 min 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 over past times. These areas were excluded from the allocation of land use.

With a total global population increase from 2 to 6145 million people over that time span, resulting in a global population density increase of < 0.1 cap/km^2 to almost 46 cap/km^2 and a urban built-up area evolving from almost zero to 0.5 million km^2 (still only <0.5% of the total global land surface, but having tremendous impact through the demand of food, services, building materials, etc), it is clear that this must have had, and will continue to have profound influence on the Earth's environment and its associated (climate) change.

Chapter 3 presents a methodology for estimating the development of global historical agriculture over time. The approach uses statistical data and a simple land use per-capita curve as a base for estimating the historic human influence on the Earth' surface. The exact shape and magnitude of those curves is not well known and different shapes have been examined. 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 allocate the resulting total areas with the weighted proxies of population density, climate, distance to water, soil suitability and slopes.

Results show that cropland occupied roughly less then 1% of the global ice-free land area for a long time period until AD 1000, quite similar like the area used for pasture. In the centuries that followed the share of global cropland increased to 2% in 1700 (ca. 3 million km^2), and 11% in 2000 (15 million km^2), while the share of pasture area grew from 2% in 1700 to 24% in 2000 (34 million km^2) These profound land use changes have had, and will continue to have quite considerable consequences for global biogeochemical cycles and subsequently global climate change.

Uncertainties

There are still many uncertainties in the role of current and historic land use in the global carbon cycle as well as in other dimensions of global change. Although databases of historic land use are frequently used in integrated assessments and climate studies, the databases are subject to major uncertainties that are not often addressed. This chapter 4 examines a number of the most important uncertainties related to the process of reconstructing historical land use. We discuss the origin of different types of uncertainty and the sensitivity of the land use reconstructions to these uncertainties. The results indicate that uncertainties not only arise due to large temporal and spatial variation in historic population data but, especially, also related to the assumptions on the relationship between population and land use. Especially here, improved empirical data to better specify and validate the assumptions of the population-land use relationships and accounting for the spatial and temporal variation in this relationship could reduce uncertainties in the final databases. Such empirical evidence could be derived from local case studies conducted in disciplines such as landscape ecology, environmental history, archeology or paleoecology. By better understanding of the underlying processes it is possible to substantially improve historical land use reconstructions.

Applications

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 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 more intensively used landscapes.

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 (KK10 scenario), and together with an alternative scenario based on the land use database of Chapter 3 (HYDE), a LPJ DGVM model combination is forced in a series of continuous simulations. Based on two different land use scenario's the outcome of the study indicates a wide range of land use emissions and subsequently land use per capita curves. By 3000 BC, cumulative carbon emissions caused by anthropogenic land cover change in our new scenario ranged between 84 and 102 Pg, translating to ca. 7 ppm of atmospheric CO_2. By AD 1850, emissions were 325-357 Pg in the new scenario, in contrast to 137-189 Pg when driven by HYDE. While we cannot close the carbon budget in this study, simulated cumulative anthropogenic emissions over the preindustrial Holocene are consistent with the ice core record of atmospheric $\delta^{13}CO_2$ and support the hypothesis that anthropogenic activities led to atmospheric CO_2 concentrations at a global level warmer than it otherwise would be. It also demonstrates that the hypothesis is very sensitive to the land use scenario chosen, especially the magnitude of the historical land use per capita.

The HYDE data base has also been used in various other studies concerning the effect of land use changes on carbon fluxes on CO_2 levels and climate and feedbacks in the climate system. Furthermore, it has been used in global change assessments, e.g. the Representative Concentration Pathway effort, where HYDE is used as major input for the AD 1500 – 2100 period in order to construct a consistent long term land use scenario for the 5th AR of IPCC and contributed to the Global Carbon Project. Finally, HYDE has already demonstrated its usefulness and in applications in studies of historical emissions of GHG's, habitat loss leading to species threat and extinction, black carbon and aerosols, urban / built-up area, biomass burning, biofuels, historical methane budget, water scarcity and global N and P balances.

Synthesis

In this thesis, the development of land use and population databases, their application and their uncertainties have been discussed. 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.

The approach uses a land use per-capita curve as a basis for estimating the historic human influence on the Earth' surface. The exact shape and magnitude of those curves is not well known and different shapes have been examined. 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.

A theoretical framing is discussed of the different theories for the development of land use (intensity) over time. First, the technological motivated intensification theory of Boserup is described, where productivity increases with population growth and techniques intensify. Secondly, the economical motivated theory of Weisdorf is discussed, who argued that the adoption of agriculture necessitated the introduction of non-food specialists. This lead to a redistribution of labor, and subsequently delaying new techniques, but eventually to (large) steps in food acquiring technology, linked to regime shifts. This delay is described by the theory of Geertz, who 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" lead to more intensification by putting even more labor into paddy field cultivation, increasing per hectare output while maintaining per capita output. The third motivation is an ecological one, described by Malthus. He 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. 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.

The fore mentioned theories are based on many years of field work and numerous (local) case studies. However, there have been a few approaches to quantify those historical patterns of land use changes at a global scale. 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. 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 are essential as well as how land use is represented in the calculation of carbon 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.

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. While many traditional input data of integrated assessments were quite rare and uncertain, new improved data were essential, and HYDE can make an important contribution to this effort.

In order to improve the HYDE and similar historic land use data bases, it is crucial that co-operation 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. Research areas such as historical ecology, historical geography, (environmental) history, archeology, paleoecology, hydrology, renewably energy and limnology - to name a few – are just beginning to realize that they can contribute to future global change models and studies.