



Land cover change over the last three centuries due to human activities: The availability of new global data sets

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Abstract

Land use and land cover change is an important driver of global change (Turner et al., 1993). It is recognized that land use change has important consequences for global and regional climates, the global biogeochemical cycles such as carbon, nitrogen, and water, biodiversity, etc. Nevertheless, there have been relatively few comprehensive studies of global, long-term historical changes in land cover due to land use. In this paper, we review the development of global scale data sets of land use and land cover change. Furthermore, we assess the differences between two recently developed global data sets of historical land cover change due to land use. Based on historical statistical inventories (e.g. census data, tax records, land surveys, historical geography estimates, etc) and applying different spatial analysis techniques, changes in agricultural land cover (croplands, pastures) were reconstructed for the last 300 years. The two data sets indicate that cropland areas expanded from 3–4 million km² in 1700 to 15–18 million km² in 1990 (mostly at the expense of forests), while grazing land area expanded from 5 million km² in 1700 to 31 million km² in 1990 (mostly at the expense of natural grasslands). The data sets disagree most over Latin America and Oceania, and agree best over North America. Major differences in the two data sets can be explained by the use of a fractional versus Boolean approach, different modelling assumptions, and inventory data sets.

Introduction

Since the beginning of civilisation, humans have deliberately managed and converted the landscape to derive valuable natural resources such as food, fiber, fresh water, and pharmaceutical products. As early as 1864, Marsh (1864) voiced concern about the deleterious consequences of human activities. Richards (1990) has estimated that over the last three centuries, roughly 1200 million ha of forests and woodlands have been cleared, grasslands and pastures have diminished by about 560 million ha (however, many grasslands have been converted to pastures), and cropland areas have increased by 1200 million ha (Richards, 1990). Presently, roughly 1800 million ha, an area roughly the size of South America, is in some form of cultivation (Turner et al., 1993).

Such large-scale changes in land use and land cover can have significant biophysical and biogeochemical consequences. For example, changes in surface reflectivity and water balance associated with land cover change can modify regional and global climates (Cope-land et al., 1996; Bonan, 1999). Land use change over the last 150 years has released almost half as much carbon as that from fossil fuel emissions (Houghton, 1999). Postel et al. (1996) and Vitousek et al. (1997) have reviewed the consequences of human activities for

the global cycles of water and nitrogen. The emerging understanding of the consequences of land use and land cover change has led to a growing demand for global spatially-explicit historical data on land use/land cover. Climate and ecosystem models, which need such spatially and temporally explicit data as inputs, can then be used to increase our understanding of the Earth system consequences.

This paper reviews the development of land use and land cover data sets at global scales. We first review the development of global data sets of present-day land cover. Such data sets were first developed in the early 1980s, as input data for models, to understand the climate and biogeochemical consequences of contemporary land cover, as opposed to a “natural” condition. However, there was a recognition that the temporal evolution of land cover change is important to understand as well, especially so with components of the ecosystem which evolve slowly, such as soil carbon dynamics. This led to the development of various historical land cover data sets that we briefly review in this paper. However, these previous efforts were at the local to regional scales. Recently, two efforts developed global, spatially-explicit, historical (for the last 3 centuries) data sets of land cover change due to land use. In this paper, we briefly present those data sets and provide an assessment of the differences between them.

Characterising the patterns of present-day global land use/land cover (ca. 1980–2000)

In the 1980s, the need for global land use/land cover data sets arose from the climate model community. Efforts were made to couple General Circulation Models (GCMs) with land use data in order to study the climatic impacts of land use changes through modifications of surface albedo, surface roughness, and surface water balance. One of the first such global land use data sets was presented by Matthews (1983), consisting of a land use/land cover data set on a $1^\circ \times 1^\circ$ latitude/longitude grid. It was constructed by combining numerous published sources and satellite imagery, resulting in a potential vegetation map and a separate land use map with five categories showing varying degrees of cultivation intensity. Olson et al. (1983, 1985) developed the 'Major World Ecosystem Complexes' map, which characterised the use and vegetative cover of the Earth's land surface on a $0.5^\circ \times 0.5^\circ$ latitude/longitude grid, in order to estimate carbon densities. The map distinguished 44 different land ecosystem complexes comprising seven broad groups, one of them being assigned to human activities. Wilson and Henderson-Sellers (1985) developed another land cover data base on $1^\circ \times 1^\circ$ latitude/longitude grid, describing several cropland and pasture types using information from the World Atlas of Agriculture and national atlases. Townshend et al. (1991) presented a comparison of the different data bases and their use. They concluded that until then, "compilers of the global estimates had to reclassify existing maps into a common scheme based on inherently incompatible classifications". They argued that remote sensing could provide a consistent depiction of the global land surface, although large uncertainties would still remain.

Recently, continuous global characterization of land cover has become possible with the use of improved remote sensing technology. Using the seasonal characteristics of land surface reflectances measured from satellites, two separate efforts have developed global land cover classification data sets. DeFries and Townshend (1994) from the University of Maryland (UMD) produced a global data set of 15 different land cover types at $1^\circ \times 1^\circ$ resolution by comparing AVHRR data with ground-based observations. More recently, Hansen et al. (2000), also from UMD, created a 1 km resolution land cover classification data set of 13 cover types (including a cropland category) by training AVHRR data against Landsat scenes. Another global land cover data set at 1 km resolution was created jointly by the United States Geological Survey's EROS Data Center, the University of Nebraska-Lincoln, and the European Commission's Joint Research Centre. The development of this DISCover data set was coordinated by the International Geosphere-Biosphere Programme's (IGBP) (Belward and Loveland, 1996).

These satellite-based efforts have provided a spatially and temporally consistent global land cover classification product. The previous efforts, although painstakingly

compiled, were a compilation of different maps that were inconsistent in terms of the definitions of land cover, and were from different periods in time. While the satellite-based efforts provided a very good baseline for present-day land cover, the next advancement in land cover change research required was the development of historical time trajectories of land cover change. However the earliest satellite to monitor the Earth's land surface was Landsat, launched in 1972. Prior to that, one has to rely on other sources of data, which do not give a global picture, and often are globally inconsistent. But such a historical perspective is vital to obtain a good understanding of land cover change.

New global data sets of historical land cover change

While several studies are compiling comprehensive data on historical land use and land cover change for different parts of the world (see Table 1), it will take a long time before they achieve the consistency in classification scheme and spatial coverage necessary to be aggregated into a consistent global product. The studies differ quite a lot in temporal scale – some only capture the last few decades, while others go back to the Middle Ages or even further back in time. Secondly, the local studies may not always be representative of the larger regions within which they exist. Furthermore, the studies are often not compatible in the land cover categories they consider. Finally, even if consistency can be obtained, the studies added together do not cover the whole globe.

An entirely new, and "top-down" approach needs to be taken to reconstruct a global scale historical land use product, even if it lacks the quality of the local/regional studies. In this regard, the availability of global remote-sensing based land cover products for the present-day has proven to be a major breakthrough. However, remotely sensed data exist only for the last two to three decades. For land use information further back in time, we necessarily have to rely on historical maps, aerial photographs, land surveys, and land cover census inventories. In this study, we present two approaches that combined contemporary remotely-sensed data of land cover with historical land cover inventory data to develop global data sets of historical land cover change due to land use.

Ramankutty and Foley (1998) used the IGBP 1 km-resolution Global Land Cover Classification (GLCC) data set and calibrated it against cropland inventory data for 1992 to create a continuous global data set of cultivated land for 1992. Then, Ramankutty and Foley (1999) used a "hindcast" modelling technique to extrapolate this data backwards in time by combining it with a compilation of historical cropland inventory data to create a data set of croplands from 1700 to 1992. Ramankutty and Foley (1999) also created a global potential natural vegetation data set of 15 different vegetation types by combining the GLCC data set with the Haxeltine and Prentice (1996) potential vegetation map. By overlaying the

Table 1. Examples of geographical explicit studies of historical land use

Authors	Spatial characteristics	Temporal characteristics
<i>Local/National level</i>		
White and Mladenoff (1994)	Northern Wisconsin, WI, USA	1860s, 1931, 1989
Bicik (1995)	Czech Republic	1845, 1948, 1990
Bork et al. (1998)	Germany	7th century–present
Cousins (2001)	South East Sweden	17th, 18th century, 1946, 1980
Crumley (2000)	Burgundy (France)	Iron Age–present
Himiyama (1992)	Japan	1850, 1900, 1980
Larsson and Frisk (2000)	Sweden	ca. 1700–present
Manies and Mladenoff (2000)	Sylvania Wilderness Area, MI, USA	pre-settlement
Odgaard and Rasmussen (2000)	Denmark	past 2 millenina
Petit and Lambin (2001)	Belgium Ardennes	1700–present
Serneels and Lambin (2001)	Mara region, Kenya	1975–present
<i>Continental level</i>		
Darby (1956)	Central Europe	900, 1900
Williams (2000)	Western Europe, reconstructed map	11th–13th century
AUSLIG (1989)	Australia, scale 1:20,000,000	pre-settlement (1780), 1980s
Maizel (1998)	Conterminous United States, county data	1850–1990
Richards and Flint (1994)	South East Asia	1880, 1920, 1950, 1970, 1980
<i>Global level</i>		
Richards (1990)	10 regions of the world	1700, 1850, 1920, 1950, 1980
Ramankutty and Foley (1999)	5 min. resolution	1700–1992
Klein Goldewijk (2001)	0.5 × 0.5 degree grid	1700–1990

croplands data set with the potential vegetation data set, one can estimate the extent to which different vegetation types have been converted to cultivation. Henceforth, this data set is referred to as the ‘RF’ data set (available from <http://www.sage.wisc.edu>).

The original work of Klein Goldewijk (2001) involved the construction of a History Database of the Global Environment, henceforth referred to as the ‘HYDE’ data set. HYDE was originally designed for testing and validation of the IMAGE model (Alcamo et al. 1998), because international reviews of IMAGE suggested that if the model makes projections for the next hundred years, it should at least be able to simulate the past century (Solomon, 1994).

In this study, HYDE used the potential vegetation data set of RF as a starting point, and allocated on top of this natural vegetation the historical inventory data on agricultural activities like cropland and pasture with historical population density maps as proxy for location. The assumption was made that where people lived for many centuries, agricultural activity is more likely in the proximity of urban centres than in remote areas. A Boolean approach was chosen, so each grid cell was, for simplicity, totally allocated to cropland, pasture or one of the potential land cover classes.

The historical population density maps were created by downscaling the population density map of Tobler et al. (1995) on the basis of historical total population numbers for (sub-) administrative units (the largest unit is the country level). Grid cells with the highest historical

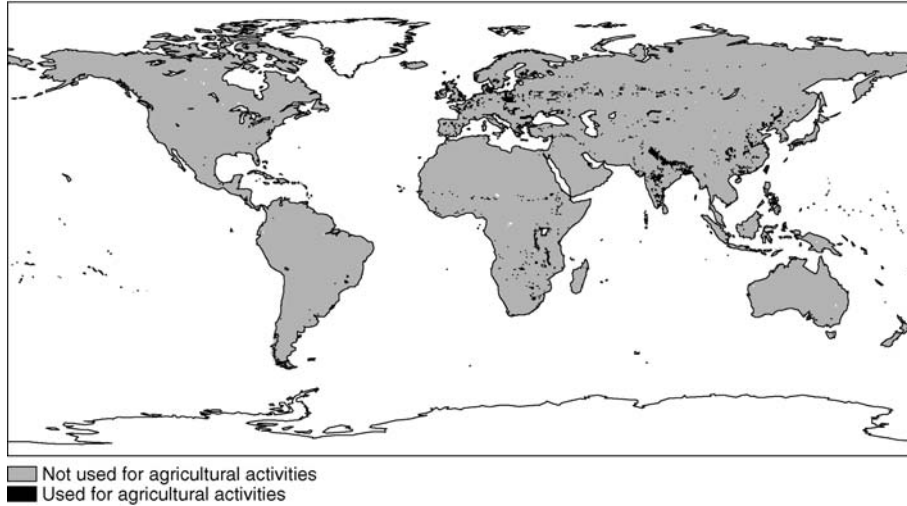
population density were classified as most likely available for agricultural expansion at that time. Thus, total population numbers per country (or per sub-administrative unit) are consistent with the statistics, while the density patterns reflect the current pattern. Reasoning for this approach is that towns/cities did not move spatially during the last 300 years so the distribution of the current density map is also valid for the historical time period. The approach for this study is described in detail in Klein Goldewijk (2001). Results are available on the website (<http://www.rivm.nl/env/int/hyde>).

Comparative analysis of the data sets

An important difference between the two datasets is that RF is a continuous data set describing the fraction of each grid cell in cropland, while the HYDE data set is Boolean (i.e., grid cells are classified as “cropland/no cropland”). To facilitate comparison, we first convert the RF data set to a Boolean version using the method described in McGuire et al. (2001). This is done by assigning Boolean values within contiguous boxes of the size of 6 degrees in latitude by longitude, until the total area in croplands within each 6 × 6 degree box is the same in both the Boolean and the continuous data set. Essentially, Boolean values of “cropland/no cropland” are allocated until the cropland area is conserved over large areas. We also modified our two spatial data sets to have a common grid by excluding Greenland (not included in the RF study) and Antarctica.

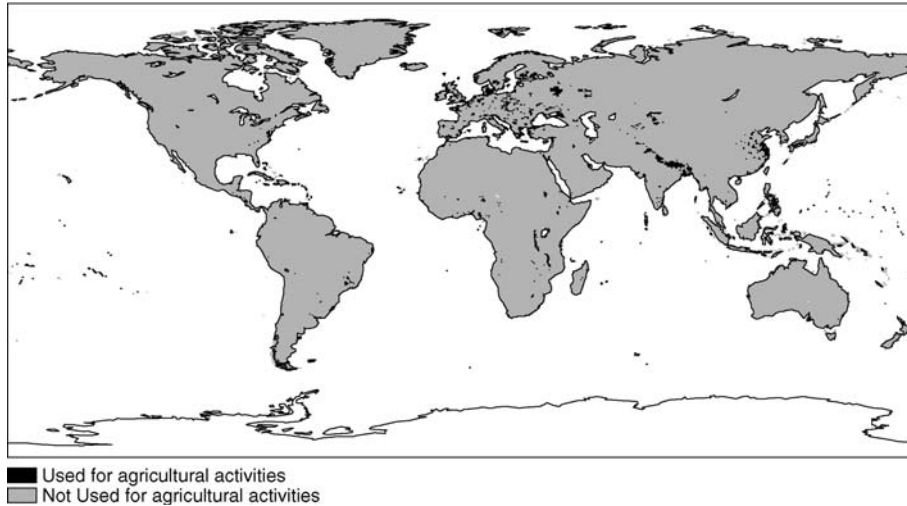
Cropland according to RF, year 1700

Boolean version



Cropland according to HYDE, year 1700

Boolean version



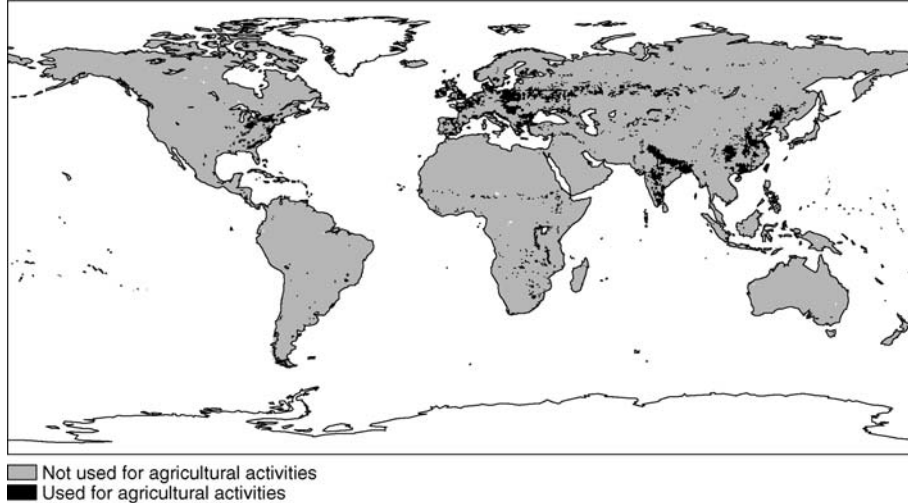
Before performing a detailed intercomparison between the HYDE and RF data sets, we should mention a strong caveat that the HYDE and RF data sets are not entirely independent. They have partially relied on each other concerning input data in their development and hence similarity in numbers does not necessarily indicate that we are confident about the extent of the different land covers. Another difference between the two new data sets is that the RF data set describes the historical changes in cropland areas only, while the HYDE database considers both croplands and pastures. Both the RF and HYDE databases use the same potential vegetation data set, hence it is not worthwhile intercomparing the natural vegetation types between RF and HYDE, although it would be worthwhile comparing our estimates of natural vegetation to other independent estimates. In this section, we first compare the RF and HYDE databases to other estimates of land cover change. We then make more detailed intercomparisons of the cropland changes described by the RF and HYDE data sets.

Regionally and globally aggregated data sets of land cover change are available from various sources (Richards, 1990; Houghton et al., 1983; Food and Agriculture Organization, 1996). As the new data sets presented in this paper are spatially explicit, while the others are not, we can only compare the data sets as global aggregates (Figure 1). The land cover categories are aggregated into larger, more general classes such as forests, grasslands, shrubland and others to facilitate comparison with other data sets. The forest category includes all the forest and woodland classes, while the grassland/pasture category also includes savanna and steppe. The category 'pasture' is only included in the HYDE data set, in Houghton et al. (1983) for 1983 and FAO (1996) for ca. 1990, while RF does not consider pastures and Richards (1990) does not distinguish between natural and grazed grasslands. Thus, we compare our estimates for 'grasslands plus pastures', and also compare pastures separately.

All data sets show croplands increasing from roughly 3–4 million km² in 1700 to 15–20 million km² in 1990 (mostly at the expense of forests), while grazing land area

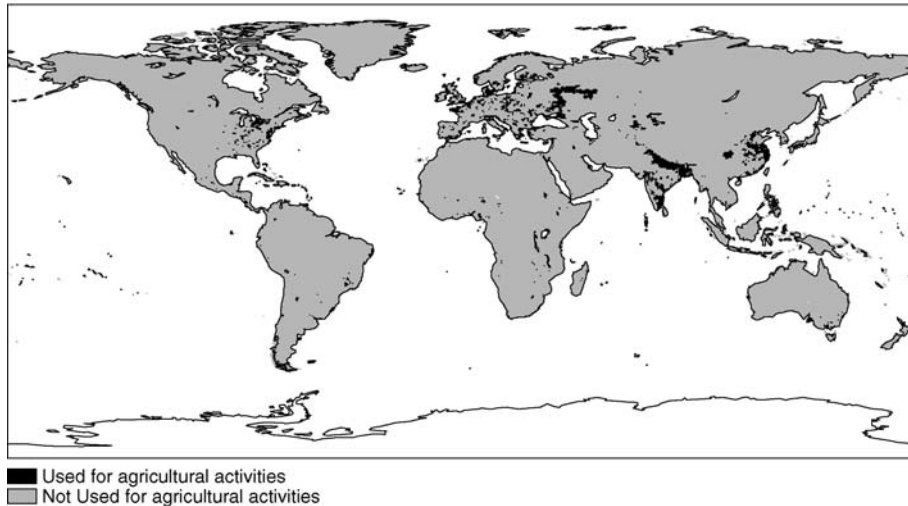
Cropland according to RF, year 1850

Boolean version



Cropland according to HYDE, year 1850

Boolean version



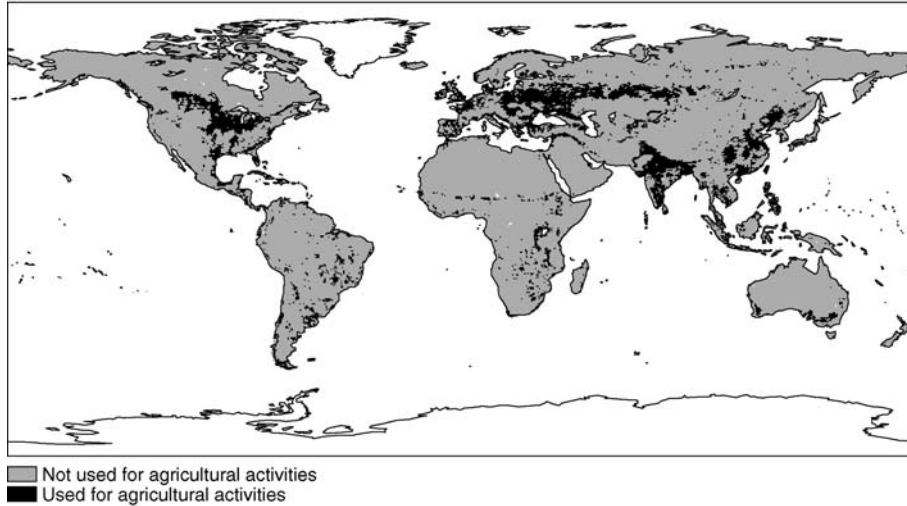
expanded from $\sim 4\text{--}5$ million km^2 in 1700 to $31\text{--}33$ million km^2 in 1990 (mostly at the expense of natural grasslands). RF has much greater cropland area than the other data sets and also larger cropland expansion. The larger cropland area in RF in 1990 is because of the inter calibration of satellite and statistical data, while the others rely on just statistical data. Forest area decreases from $50\text{--}62$ million km^2 in 1700 to $43\text{--}53$ million km^2 in 1990. Richards (1990) has roughly 20% greater forest cover than RF and HYDE. This is likely due to the use of different definitions for forest cover (i.e. distinction between forests and woodland, between closed and open forest canopies, whether degraded forests are included under forest cover, etc.). RF and HYDE estimate the bulk of their forest cover areas on the basis of satellite information (DISCover dataset), while Richards used census information from various sources. Grassland and pasture area is roughly twice as large in Richards (1990) than in RF or HYDE. Again, this could be due to the use of different definitions (depending on how

open shrubland, tundra, etc. are classified). However, the RF and HYDE estimates of ~ 30 million km^2 in 1700 is consistent with Matthews (1983). Richards (1990) shows very little change in grassland/pasture area. RF shows a decrease in grassland/pasture because some grassland is converted to cropland. HYDE shows an increase in grassland/pasture because of the conversion of ~ 4 million km^2 of forest to grazing land (e.g. Amazonian pastures for cattle ranching). The expansion of cropland and pastures areas took place mostly at the expense of temperate forest areas and grassland/steppe/savannah areas.

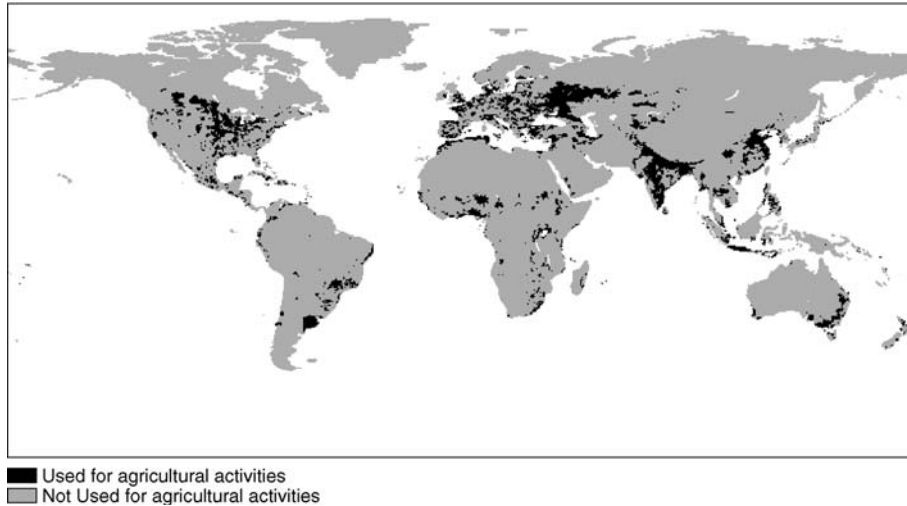
Plate 1. Historical cropland estimates of RF and HYDE for 1700, 1850 and 1990.

We now intercompare the spatially-explicit representation of croplands in the RF and HYDE data sets. Although there are differences, the RF and HYDE data sets are generally consistent in representing cropland change over the last 300 years (Plate 1). In 1700, both the RF and HYDE databases show little cropland in the

Cropland according to RF, year 1990
Boolean version



Cropland according to HYDE, year 1990
Boolean version



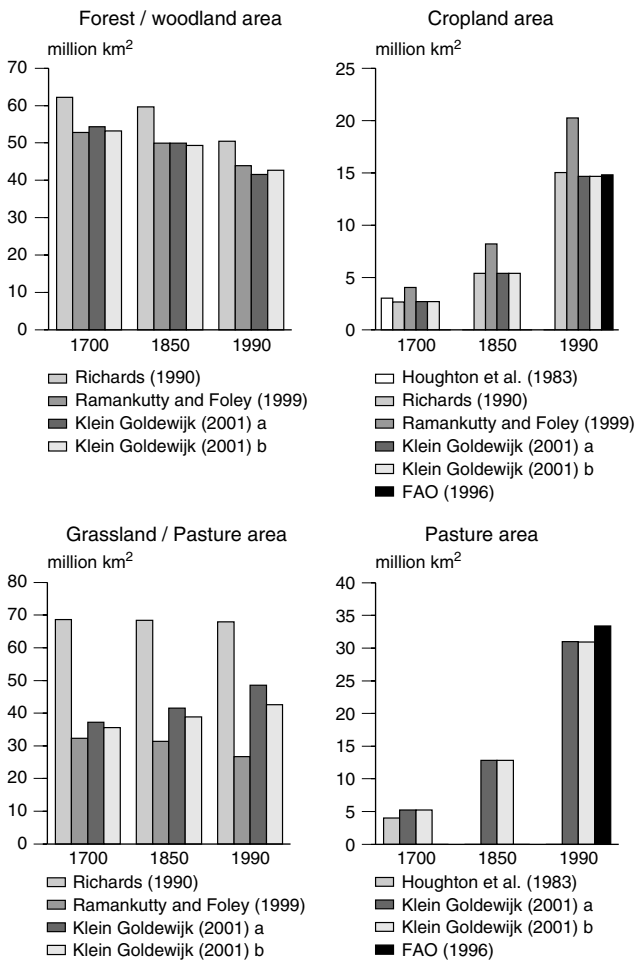
New World. At this time, most of the cropland is found in the Indus valley, scattered parts of Europe and Africa, and in Eastern China. By 1850, croplands are found in the eastern seaboard of North America. Croplands expand further in Europe and China by 1850. Between 1850 and 1990, croplands of North America have migrated westward, with abandonment in the eastern seaboard. South America has croplands in the Pampas region of Argentina and in Southeast Brazil by 1990. Croplands are found in central East Africa (Lake district), the Sahel, eastern part of South Africa, and Southwest and -East Australia, thus capturing the major agricultural areas of the world. Between 1850 and 1990, there is also further expansion of croplands in Europe, and the Former Soviet Union.

Nevertheless, although there is general agreement, significant differences exist between the two data sets. Croplands in the RF data set extend further east in the Former Soviet Union. The HYDE data set does not represent croplands in Manchuria, while RF does. In

South America, the croplands from the RF data set is scattered, while in HYDE, it is located in southeast Brazil and the Pampas. Croplands in eastern Australia extend further north in HYDE than in RF.

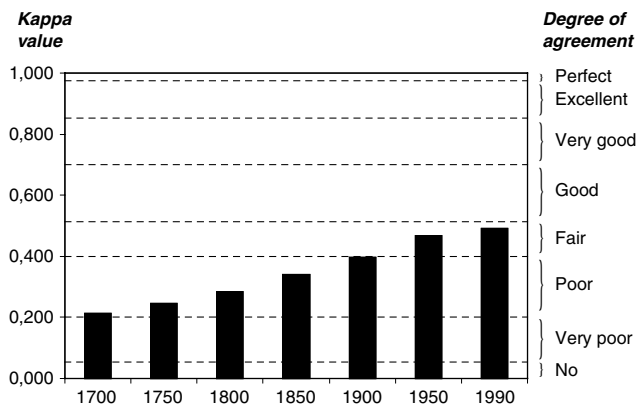
Spatially-explicit land cover data can be statistically compared by using the Kappa (κ) statistic (Cohen, 1960; Monserud, 1990; Monserud and Leemans, 1992). The Kappa statistic has been described by Monserud and Leemans (1992) as an objective tool for comparing global vegetation maps. In this study, the Kappa statistic is used to look at the level of agreement for the 'cropland' category over time. Figure 2 presents the Kappa statistics between the RF and HYDE data sets for the period 1700–1990.

Following the methodology of Landis and Koch (1997) the 'degree of agreement' for the cropland areas in the RF and HYDE data sets range from 'Poor' ($\kappa = 0.213$) in 1700 to 'Fair' ($\kappa = 0.491$) in 1990. The agreement is weak because although there seems to be a relative agreement visually, the pixel-by-pixel agreement



Note: - Klein Goldewijk (2001) a: run with potential vegetation from BIOME1 model (Prentice et al. 1992)
 - Klein Goldewijk (2001) b: run with potential vegetation of Ramankutty and Foley (1999)
 - Data from Richards (1990) for 1990 refer to 1980

Figure 1. Chart of other estimates of global land use.



Note: The 'Degree of agreement' classification is based on Landis and Koch (1977).

Figure 2. Kappa statistics for cropland areas of the RF and HYDE study.

is rather poor because of the patchy distribution of croplands in both data sets. Also, although some areas overlap, there are relative large areas where cropland has been distributed differently (e.g. Russia, China). Although many cropland pixels in the HYDE data set

are geographically located close to the RF ones, kappa value is low because it does not capture neighbourhood pixel agreement. Not surprisingly, the degree of agreement increases over time because the quality of the base census data is higher in more recent time periods and also derived from similar sources (e.g. FAO).

The analysis using Kappa statistics compares our two data sets at 0.5 degree resolution in latitude by longitude. However, to check whether our data sets are generally consistent over larger regions, even if there isn't pixel-by-pixel agreement, we now intercompare our data sets after aggregation to coarser resolution grids. In particular, we aggregated the two data sets to resolutions of 2 × 2 degree, 4 × 4 degree, and 6 × 6 degrees in latitude by longitude. This aggregation resulted in continuous data sets at the coarser resolution, as we calculated the total area of all Boolean 0.5 degree cropland pixels within each larger resolution grid cell, and divided it by the total area of the larger resolution grid cell. We calculated correlation coefficients between the two data sets for the whole globe, and over 6 major continental regions, and over time (Figure 3). The results show that our data sets agree best over North America in the recent time periods, while they disagree most over Latin America and Oceania. The agreement over Africa, especially in the 18th and 19th centuries, improves dramatically as we move to coarser resolutions. This shows that although pixel-by-pixel agreement is poor over Africa, there is general agreement on the continental scale. However, this does not indicate better data quality but rather that both HYDE and RF used the same source of data to reconstruct changes over Africa. In all cases, the agreement generally improves over time, and this is most dramatic over Latin America and Oceania. In those two regions, the correlation coefficient is often negative in the 18th century, because there is very little cropland at that time, and the few existing points are spatially located in different regions in the two data sets in the 18th century. In both regions, the small spatial extent of croplands also leads to a decrease in correlation coefficient with coarser resolution, because there are fewer points at the coarser resolution. This intercomparison exercise shows that future development of the global land use data sets should focus on independently verifying data quality over Latin America and Oceania.

Discussion and conclusions

There has been a growing recognition that global land use and land cover change is an important driver of global change. There have been estimates of the magnitude of land cover change at continental scales. Nevertheless, spatially-explicit global land use data sets, describing the changes at regular time intervals, have been absent until recently. Such data sets are critical for evaluating the consequences of land cover change within global climate and ecosystem models.

In this study, we present two new global data sets of historical land use and land cover change. Both data sets

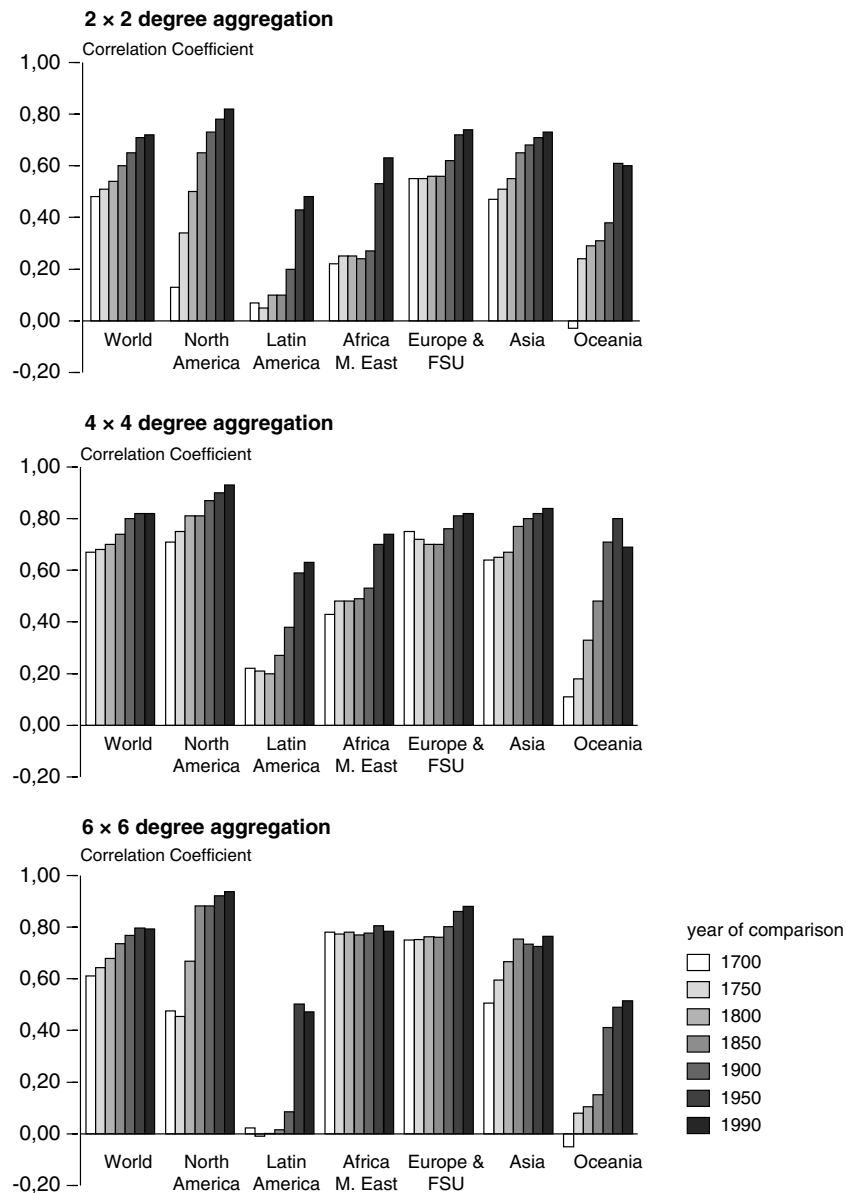


Figure 3.

describe the changes in agricultural land from 1700 to the present. By overlaying the land use data sets over a potential vegetation data set, we have also estimated the changes in extent of natural vegetation due to clearing for agriculture.

The new data sets describe the patterns of agricultural expansion in general agreement with the patterns of economic development and European settlement. Nevertheless, although there is “broad brush” consistency, there are significant differences in spatial patterns and magnitudes of change. This inconsistency can largely be attributed to the following causes: (1) Use of different assumptions about spatial patterns – RF used remotely-sensed data to spatialize inventory data, while HYDE used population density to spatialize data; (2) differences in statistical inventory data; (3) use of Boolean versus continuous description of the landscape which makes direct comparison difficult.

The two global data sets presented here provide a good basis for use in studies of global change, however, there is room for considerable improvement. The data sets were developed with the view of having a “first-cut” database, even if the quality were poor. But the intention is also to open a dialogue with the global change community to develop new methods and techniques and to compile data sets from different parts of the world to help develop improved global data sets of land use and land cover change.

As mentioned earlier in this paper, many local and regional data sets of historical land use change exist. Unfortunately, there are still many gaps in these databases. A globally co-ordinated effort needs to be made to collect historical maps, aerial photographs, land surveys, tax records, etc. These data further need to be digitally compiled to ensure consistency in definitions of land cover, and with some evaluation of the quality.

The effort by Richards and Flint (1994) is an excellent example of the type of work required in the rest of the world. New methods for reconstructing historical land use change need to be explored. For example, the BIOME 300 project, a joint LUCC-PAGES initiative (Leemans et al., 2000) was initiated to reconstruct historical land use/land cover data sets for the last 300 years using data from several disciplines such as paleo data from pollen records. The participation of scientists from around the world with expertise in their own particular regions of study is required in these global efforts.

Even for the present-day, the extent of agricultural land is uncertain. For example, several studies have asserted that the cultivated land area in China has been underreported (Frolking, 1999; Heilig, 1999; U.S. Department of Agriculture, 1991). In 1990, the FAO reports 15 million km² of global cropland, while the satellite-census intercalibrated RF data set estimates 18 million km² of cropland. Although the quality and resolution of remotely-sensed data is getting better, they still don't have sufficient spatial and temporal coverage to accurately identify land use (Landsat data have high spatial resolution, but low temporal resolution, while AVHRR and MODIS data have high temporal resolution, but low spatial resolution). While the IGBP 1 km resolution GLCC data base identified croplands and cropland/natural vegetation mosaics, it was unable to distinguish pastures from natural grasslands. Future efforts in remote sensing and remote-sensing based land cover classification systems have to pay greater attention to the explicit identification of land use patterns.

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References

- Alcamo J., Leemans R. and Kreileman G.J.J., (eds.), 1998: *Global Change Scenarios of the 21st Century*. Pergamon, Tarrytown, New York.
- Belward A.S. and Loveland T.R., 1996: The DIS 1 km land cover data set, In: *The International Geosphere-Biosphere Programme: A Study of Global Change (IGBP) of the International Council of Scientific Unions. Global Change Newsletter 27*: 7–8.
- Bicik I., 1995: Possibilities of Long-Term Human-Nature Interaction Analysis: The Case of Land-Use Changes in the Czech Republic. In: Simmons I.G. and Mannion A.M. (eds.), *The Changing Nature of the People-Environment Relationship: Evidence from a Variety of Archives*. pp. 47–60, Faculty of Science, University of Prague, Prague.
- Bonan G.B., 1999: Frost followed the plow: impacts of deforestation on the climate of the United States, *Ecological Applications 9*(4): 1305–1315.
- Bork H.-R., Bork, H., Dalchow C., Faust B., Piorr H.-P. and Schatz Th., 1998: *Landschaftsentwicklung in Mitteleuropa. Wirkungen des Menschen auf Landschaften*, 328 pp., Gotha (Klett-Perthes).
- Cohen J., 1960: A coefficient of agreement for nominal scales, *Educational and psychological measurement XX*(1): 37–46.
- Copeland J.H., Pielke R.A. and Kittel T.G.F., 1996: Potential climate impacts of vegetation change: A regional modeling study, *Journal of Geophysical Research 101*: 7409–7418.
- Crumley C., 2000: From Garden to Globe: Linking Time and Space with Meaning and Memory. In: Roderick J. McIntosh, Joseph A. Tainter, and Susan Keech McIntosh (eds.), *The way the wind blows: climate, history, and human action*, pp. 193–208. *Columbia Series in Historical Ecology*, William Balee and Carole L. Crumley (Series eds.), Columbia University Press, New York.
- Cousins S.A.O., 2001: Land-cover transitions based on 17th and 18th century cadastral maps and aerial photographs, *Landscape Ecology 16*(1): 41–54.
- Darby C., 1956: The clearing of the woodland in Europe. In: Thomas W.L. (ed.), *Man's role in changing the face of the Earth*. Chicago University Press, based on: O. Schlüter: 1951, *Die Siedlungsräume Mitteleuropas in frugeschichtlicher Zeit, Part I, Forschungen zur Deutschen Landeskunde*, Vol. 61, Hamburg.
- DeFries R.S. and Townsend J.R.G., 1994: Global land cover: Comparison of ground-based data sets to classifications with AVHRR data. In: Foody G. & curran R. (eds.), *Environmental Remote Sensing from Regional to Global Scales*. pp. 84–110, John Wiley, New York.
- Food and Agriculture Organization, 1996: *FAOSTAT*, Food and Agric. Organization of the U.N., Rome, <http://apps.fao.org/>.
- Frolking S., Xiao X.M., Zhuang, Y.H., Salas, W. and Li C.S., 1999: Agricultural land-use in China: a comparison of area estimates from ground-based census and satellite-borne remote sensing, *Global Ecology and Biogeography, 8*(5): 407–416.
- Hansen M.C., DeFries R.S., Townshend J.R.G. and Sohlberg R., 2000: Global land cover classification at 1 km spatial resolution using a decision tree classifier, *International Journal of Remote Sensing, 21*: 1331–1365.
- Haxeltine A. and Prentice C.I., 1996: BIOME3: An equilibrium terrestrial biosphere model based on ecophysiological constraints, resource availability, and competition among plant functional types, *Global Biogeochemical Cycles 10*(4): 693–709.
- Heilig G.K., 1999: Can China feed itself? – A system for evaluation of policy options, International Institute for Applied Systems Analysis, http://www.iiasa.ac.at/Research/LUC/ChinaFood/index_m.htm.
- Himiyama Y. (ed.), 1992: *Atlas of Land Use Change in Modern Japan*. Hokkaido University of Education, Asahikawa.
- Houghton R.A., Hobbie J.E., Melillo J.M., Moore B., Peterson B.J., Shaver G.R. and 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*(3): 235–262.
- Houghton R.A., 1999: The annual net flux of carbon to the atmosphere from changes in land use 1850–1990. *Tellus, Ser. 51B*: 298–313.
- Klein Goldewijk K., 2001: Estimating global land use change over the past 300 years: the HYDE database, *Global Biogeochemical Cycles 15*(2): 417–433.
- Landis J.R. and Koch G.G., 1977: The measurement of observer agreement for categorical data, *Biometrics 33*: 169–174.
- Larsson L.-I. and Frisk M., 2000: Bringing the past to life, *GEOEurope*, December 2000, p. 40–41.
- Leemans R., Klein Goldewijk K. and Oldfield F., 2000: Developing a fast-track global database of land-cover history. *LUCC Newsletter No. 5*, 6–7.
- Maizel M., White R.D., Root R., Gage S., Stitt S., Osborne L. and Muehlbach G., 1998: Historical interrelationships between population settlement and farmland in the conterminous United States, 1790–1990. In: Sisk T.D. (ed.) *Perspectives on the Land Use History of North America: A Context for Understanding Our Changing Environment*. U.S. Geological Survey, Biological Resources Division, Biological Science Report, USGS/BRD/BSR 1998-0003.
- Manies K.L. and Mladenoff D.J., 2000: Testing methods to produce landscape-scale presettlement vegetation maps from the U.S. public land survey records, *Landscape Ecology 15*(8): 741–754.

- Marsh G.P., 1864: *Man and Nature*. 656 pp., Charles Scribner, New York.
- McGuire A.D., Sitch S., Clein J.S., Dargaville R., Esser G., Foley J., Heimann M., Joos F., Kaplan J., Kicklighter D.W., Meier R.A., Melillo J.M., III B.M., Prentice I.C., Ramankutty N., Reichenau T., Schloss A., Tian H., Williams L.J., and Wittenberg U., 2001: Carbon balance of the terrestrial biosphere in the twentieth century: analyses of CO₂, climate and land-use effects with four process-based ecosystem models., *Global Biogeochemical Cycles*, **15**: 183–206.
- Matthews E., 1983: Global vegetation and land use: new high-resolution data bases for climate studies. *Journal of Climate and Applied Meteorology* **22**: 474–487.
- Monserud R.A., 1990: Methods for comparing global vegetation maps, Report WP-90-40, IIASA, Laxenburg.
- Monserud R.A. and Leemans R., 1992: Comparing global vegetation maps with the Kappa statistic, *Ecological Modelling* **62**: 275–293.
- Odgaard B.V. and Rasmussen P., 2000: Origin and temporal development of macro-scale vegetation patterns in the cultural landscape of Denmark, *Journal of Ecology* **88**(5).
- Olson J.S., Watts J.A. and Allison L.J., 1983: Carbon in live vegetation of Major world ecosystem complexes. Environmental Sciences Division Publication 1997, 164 pp. Oak Ridge Natl. Lab., Oak Ridge, Tenn.
- Olson J.S., Watts J.A. and Allison L.J., 1985: Major world Ecosystem Complexes Ranked by Carbon in Live Vegetation: A Database. ORNL/CDIAC-134, NDP-017. Carbon Dioxide Information Analysis Center, U.S. Department of Energy, Oak Ridge National Laboratory, Oak Ridge, Tennessee, U.S.A. (Revised 2001).
- Postel S.L., Daily G.C. and Ehrlich P.R., 1996: Human appropriation of renewable water. *Science* **271**: 758–788.
- Prentice I., Cramer C.W., Harrison S.P., Leemans R., Monserud R.A. and Solomon A.M., 1992: A global biome model based on plant physiology and dominance, soil properties and climate. *Journal of Biogeography* **19**: 177–134.
- Ramankutty N. and Foley J.A., 1998: Characterizing patterns of global land use: an analysis of global croplands data. *Global Biogeochemical Cycles* **12**(4): 667–685.
- Ramankutty N. and Foley J.A., 1999: Estimating historical changes in global land cover: croplands from 1700 to 1992. *Global Biogeochemical Cycles* **13**(4): 997–1027.
- Richards J.F., 1990: Land transformation, In: Turner II B.L. et al. (eds.), *The Earth as Transformed by Human Action*. pp. 163–178, Cambridge Univ. Press, New York.
- Richards J.F. and Flint E., 1994: Historic land use and carbon estimates for South and Southeast Asia 1880–1980, Data set NDP-046 CDIAC/ORNL, Carbon Dioxide Information Analysis Center, Oak Ridge Natl. Lab., Oak Ridge, Tenn.
- Tobler W., Deichmann U., Gottsegen J. and Maloy K., 1995: The global demography project, *Tech. Rep. TR-95-6*, National Center for Geographic Information and Analysis (NCGIA), Santa Barbara, California.
- Townshend J., Justice C., Li W., Gurney C. and McManus J., 1991: Global land Cover classification by remote – Present capabilities and futher possibilites. *Remote Sensing of Environment* (**35**): 253–255.
- Turner B.L., Clark W.C., Kates R.W., Richards J.F., Mathews J.T. and Meyer W.B., 1990: *The Earth as Transformed by Human Action*, pp. 713, Cambridge Univ. Press, New York.
- Turner II, B.L., Moss R.H. and Skole D.L., 1993: Relating land use and global land-cover change: A proposal for an IGBP-HDP core project, pp. 65, International Biosphere-Geosphere Program: A study of global change and the human dimensions of global environmental change programme, Stockholm.
- U.S. Department of Agriculture, 1991: *China Agriculture and Trade Report*. Economic Research Service, U.S. Department of Agriculture.
- Vitousek P.M., Mooney H.A., Lubcheno J. and Mellilo J.M., 1997: Human domination of Earth's ecosystems. *Science* **277**: 494–499.
- White M.A. and Mladenoff D.J., 1994: Old-growth forest landscape transitions from pre-European settlement to present, *Landscape Ecology* **9**(3): 191–205.
- Williams M., 2000: Dark ages and dark areas: global deforestation in the deep past. *Journal of Historical Geography* **26**(1): 28–46.
- Wilson M. F. and Henderson-Sellers A., 1985: A global archive of land cover and soils data for use in general circulation climate models. *Journal of Climatology* **5**: 119–143.