Estimating historical changes in land cover:North American croplands from 1850 to 1992. GCTE/LUCC...

Article · September 1999

DOI: 10.1046/j.1365-2699.1999.00141.x

Navin Ramankutty
University of British Columbia - Vancouver

Global Ecology and Biogeography (1999) **8**, 381–396

GCTE/LUCC RESEARCH ARTICLE

Estimating historical changes in land cover: North American croplands from 1850 to 1992

NAVIN RAMANKUTTY and JONATHAN A. FOLEY *Climate, People, and Environment Program (CPEP), Institute for Environmental Studies, University of Wisconsin, 1225 West Dayton Street, Madison, Wisconsin 53706, U.S.A. e-mail:nramanku@students.wisc.edu*

ABSTRACT

1. We present a simple algorithm for reconstructing spatially explicit historical changes in croplands. We initialize our simulation with a satellite-derived characterization of present-day croplands *c.* 1992. This data set of croplands is then used within a simple model, along with historical cropland inventory data at the national and subnational level, to reconstruct historical crop cover. We present an annual data set of cropland areas in North America between 1850 and 1992, at a spatial resolution of 5 min ($\approx$10 km).

2. The reconstructed changes in North American crop cover are generally consistent with qualitative descriptions of change. Crop cover is initially concentrated in the eastern portions of the continent, and subsequently migrates westward into the Midwestern United States and the Prairie Provinces of Canada. We also see cropland abandonment in the eastern portions of the continent during the 20th century. The simulation, however, fails to characterize adequately the changes in crop cover in Mexico.

3. We also estimate the extent to which the different vegetation types of North America have been cleared for cultivation. We find that savannas/grasslands/steppes and forests/woodlands have undergone the most extensive conversion (1.68 and 1.40 million km^2 cleared, respectively, since 1850). We further discuss the wider implications of such large-scale changes in land cover.

Key words. Land use, land cover change, croplands, historical analysis, inventory data, agriculture, North America, spatially explicit model.

INTRODUCTION

The terrestrial biosphere provides many resources valuable to human societies, including food, fibre, and fresh water. Rapid population growth, combined with increasing per-capita resource consumption, has led to an increased consumption of natural resources, resulting in widespread modification of the Earth's land cover. The principal mode of anthropogenic land use has been clearing of natural ecosystems for agriculture. Across the globe nearly 18 million km^2, an area roughly the size of South America, is currently in some form of cultivation (Turner *et al.* 1993; Ramankutty & Foley, 1998). Much of this agricultural land has taken the place of forests, but also of grasslands and wetlands (Turner *et al.*, 1993). In North America, cropland area has increased 4-fold in the last 150 years, from roughly 50 million hectares in 1850 to 200 million hectares in 1980 (Richards, 1990).

Anthropogenic land use and land cover change can alter biogeochemical cycles of key significance, including the global cycles of water, carbon, and nitrogen (Houghton *et al.*, 1983; Postel *et al.* 1996; Vitousek *et al.*, 1997). For example, Houghton (1995) estimated that nearly 100 Gt-C have been released by land use activities between 1850 and 1980. By modifying important biophysical characteristics of the Earths surface, widespread land cover change can significantly influence the climate system. For example, Copeland *et al.* (1995) and Bonan (1997) have shown that the replacement of natural vegetation cover of the U.S.A. with modern vegetation cover in a climate model leads to significant changes in local climate. In addition, climate model simulations of complete deforestation in Amazonia indicate large changes in surface temperature, precipitation and evapotranspiration

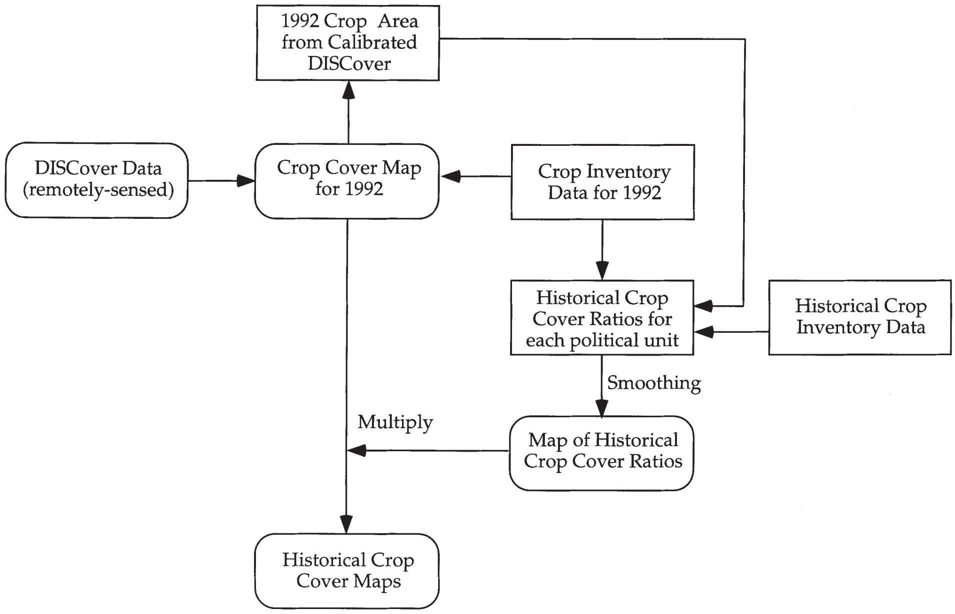


Fig. 1. Flowchart depicting the simple model reconstruction of historical crop cover. Boxes with sharp corners indicate data at the level of political units, while boxes with rounded corners indicate spatially explicit maps. A crop cover map for 1992 (5 min resolution) is first derived by calibrating the DISCover data set against crop inventory data for 1992 (Ramankutty & Foley, 1998). Then the ratio of crop cover in the past to the crop cover in 1992 is derived for each political unit, and then further converted to a spatial map (5 min resolution) and smoothed (see text for details). The resulting map is multiplied by the crop cover map for 1992 to derive historical crop cover maps (5 min resolution).

(Dickinson & Henderson-Sellers, 1988; Shukla *et al.* 1990).

Despite the increasing recognition that human land use and land cover change has been an important driver of global environmental change, there is a lack of adequate data on historical land use practices. To assess the impact of human activities on the global environment more accurately, it is imperative to develop accurate, geographically explicit data sets describing historical changes in land use and land cover.

In this study, we use a simple method to reconstruct historical land cover changes. We restrict our focus to permanent croplands, which are defined as the sum of arable lands (including land under temporary crops (double-cropped areas counted only once), lands with crop failure, land lying fallow or temporarily idle, cropland used temporarily for pasture, and land under market and kitchen gardens), and lands under permanent crops (including cocoa, coffee, and rubber plantations, and all other tree crops, except those grown for wood or timber) (FAO, 1995). We also restrict the focus of this study to the North American continent from 1850 to 1992, because it is the region with the best quality of historical inventory data, and because it has undergone extensive clearing for croplands in the last century.

RECONSTRUCTING HISTORICAL CROP COVER

Social scientists have traditionally collected data aggregated to the level of political units. This is necessarily so because such data are normally collected by an official government census organization. However, climate and ecological processes do not conform to political boundaries. Climatic data and biophysical data are normally presented as maps, which are spatially explicit representations. To study the human impacts on the environment, global climate models and global biosphere models have been developed that are also spatially explicit. However, in order to incorporate human activities into such models, much of the socio-economic data that represent these activities need to be 'spatialized'.

Several previous studies have attempted to reconstruct spatially explicit historical changes in land use and land cover. Esser *et al*. (1994) used a 'hindcast' modelling approach. Their simulation begins in 1980, with the Olson *et al.* (1983) data being used to represent crop cover. Then to estimate historical croplands, they took grid cells in or out of cropland within each country so that the total crop area for the country matched estimates from historical inventory data. Zuidema *et al*. (1994) developed a land cover change model as part of the IMAGE 2.0 model, wherein land-use demands are met by allocating land adjacent to existing agricultural land, and in regions with the highest potential crop productivity. Klein Goldewijk & Battjes (1997) also used the Olson *et al*. (1983) data to represent contemporary crop cover, and estimated the spatial distribution of agricultural land in 1890 by distributing estimates of country totals for 1890 within each country using current population density. Hall *et al*. (1995) developed a very elaborate land cover change model, GEOMOD, wherein several land-use rules are used, along with a map of relative crop suitability, to characterize the process of land conversion. Veldkamp & Fresco (1996) also developed a land cover change model, CLUE, similar to the GEOMOD and IMAGE 2.0 models, but their model has been calibrated over and applied to Costa Rica and China, and has not been extended to other regions.

All the aforementioned studies are characterized by four major limitations: (1) they use a Boolean representation of crop cover (each grid cell is completely occupied by either croplands or natural vegetation), rather than a continuous description wherein croplands occupy a certain fraction of each grid cell; (2) they are not initialized by an adequate representation of contemporary crop cover; (3) none of the studies have attempted to compile and use historical agricultural inventory data that are available at the national and subnational level from various sources; and (4) the more complex models (e.g. GEOMOD) use poorly validated assumptions.

In this study, we present an approach to estimating historical crop cover change, which although being simple, overcomes the limitations mentioned in the foregoing paragraph. We also use a hindcast modelling approach. First, a combination of satellite-based data and national/subnational cropland inventory data is used to obtain a reasonable characterization of the contemporary global crop cover (Ramankutty & Foley, 1998). This is then used within a simple land cover change model, along with historical cropland inventory data, to derive historical crop cover (Ramankutty & Foley, 1999). Figure 1 depicts the model used for reconstructing historical changes in crop cover.

A high resolution, global crop cover map for 1992 was initially derived by calibrating a satellite-derived land cover data set against a suite of national and subnational cropland inventory data. Specifically, we calibrated the crop cover categories of the DISCover land cover data set (a 1 km by 1 km resolution satellite-based global land cover data set; see Loveland & Belward, 1997) against cropland inventory data for 1992 (Ramankutty & Foley, 1998). The result of this procedure is a high-resolution (using a 5-min latitude/longitude grid) global map of crop cover for 1992. For each grid cell (with a location denoted by i, j), we denote the fraction of crop area for 1992 as $f_{CA}(i, j, 1992)$

To reconstruct historical changes in crop area (i.e. estimating $f_{CA}(i, j, t)$ where $t = 1850–1992$), we first compiled historical cropland inventory data at the national and subnational level (henceforth referred to as political unit level) from various sources (see Table 1). We adjusted the data to ensure consistency in definitions. We collected the data for different time periods, and then linearly interpolated them to get annual values between 1992 and 1850 (denoted as $A_I^t(k)$, where t is the year, and k is the political unit). These inventory data provide a constraint on the total amount of cropland within each political unit for the past.

To distribute this total crop area spatially within each political unit, we require some kind of land use model. The spatial distribution of croplands are influenced by both biophysical factors (e.g. climate, soils, topography, etc.) and socio-economic factors (e.g. market prices, access to markets, transportation costs, access to irrigation sources, government policies, etc.). It is possible to build a land use and land cover change model on lines similar to those mentioned earlier (Esser *et al*., 1994; Zuidema *et al*., 1994; Hall *et al*., 1995; Klein Goldewijk & Battjes, 1997; Veldkamp & Fresco, 1996). For instance, a map of land suitability for growing crops could be developed by incorporating climate information such as growing season length and moisture stress; soil information such as organic content, nitrogen density, pH, and soil texture; and topography. We could also parameterize the influence of infrastructure, such as irrigation sources, on the rate of change of crop cover. Such an elaborate model would

Table 1. Sources of historical cropland inventory data for North America

Region	Data source	Time period covered
States of the U.S.A.	U.S. Department of Agriculture (1992)	For 1945–92, approximately every 5 years
States of the U.S.A.	U.S. Bureau of the Census (1900, 1920, 1940, 1950)[1]	For 1850–1939, approximately every 10 years.
Provinces of Canada	A. Lupien (pers. comm., 1997)	1871–1991, every 10 years. We filled missing data in this time period using interpolation/extrapolation or using proportions from closest time period of data availability. We extrapolated data from 1871 back to 1850 using a cubic-spline fitting tool.
Regions of Mexico	Yates (1981), Houghton *et al.* (1991), FAO (1995)[2]	see footnote[2]
Central American countries	FAO (1995)	Annual for 1961–92 from FAO (1995). The 1850–1960 estimate is obtained by maintaining a constant ratio to the cropland area in Mexico.

[1] The following adjustments were made to the U.S. Bureau of the Census (BUCEN) data to ensure consistency in definitions (Ramankutty & Foley, 1999). (a) For 1929 & 1939, the BUCEN (1940) data listed only total amount of ploughable pastures, and not cropland used for pastures. To estimate this, using the USDA data of 1945 for each state, we calculated the ratio of total cropland (cropland harvested + crop failure + cropland idle/fallow + cropland used for pasture) to (cropland harvested + crop failure + cropland idle/fallow). We then applied this ratio to the BUCEN (1940) data of cropland harvested + crop failure + cropland idle/fallow for 1929 and 1939 to estimate the total amount of cropland. (b) For 1850–1920, the Bureau of the Census (1900, 1920) data only lists the category improved land. This was adjusted in two steps. Step 1: Bureau of the Census (1975) provides area of cropland harvested for the U.S. as a whole over 1850–1920. Using this, and the Bureau of the Census (1900, 1920) data on area of improved land, we estimated the ratio of cropland harvested to improved land for the U.S. as a whole to be 0.58–0.69 over 1850–1920, with the mean being 0.64. We applied the value of 0.64 to the Bureau of the Census (1900, 1920) data of improved land to estimate cropland harvested area for 1850–1992. Step 2: Bureau of the Census (1950) has data for each state of both harvested land and total cropland for 1944 and 1949. We calculated the ratio for each state, averaged over 1944 and 1949, of total cropland to harvested land. We applied these ratios to the results of step 1 to estimate total cropland data over 1850–1920. (c) Furthermore, for some states, there were no census data in the 19th century. For these states, we extrapolated the data backward from those available in later periods. In most cases, these extrapolations resulted in the crop areas falling off to zero, indicating that the lack of census information in those early time periods was probably due to lack of croplands. Also, we had to adjust some data for changes in political boundaries. We compiled data consistent with present-day boundaries, and adjusted historical data for states that split (Dakota Territory into North Dakota and South Dakota in 1890, Virginia into Virginia and West Virginia in 1863) using proportions in known time periods.

[2] Yates (1981) corrected the official statistics, and provided estimates for 1930–70, every decade, over 8 regions of Mexico. We first linearly interpolated this to get annual values. Between 1970 & 1992, we used the annual FAO (1995) statistics, corrected by the ratio of Yates (1981) data in 1960 to the FAO data in 1961; for regional information, we used the same proportions as Yates (1981) data from 1970 over 1970–92. For 1850, 1875, 1900, 1910 & 1920, we obtained data from Houghton *et al.* (1991) (digitized from his Fig. 1), and used linear interpolation to get annual values. For subnational information during 1850–1930, we used the same regional proportions as Yates (1981) for 1930. Thus our Mexican data are composites of estimates by FAO, Yates (1981), and Houghton *et al.* (1991).

seem to be appropriate for reconstructing historical changes in crop cover. However, the drivers of land-use and land-cover change are not sufficiently well understood (quantitatively) at continental scales to enable us to develop such a model from first principles. Furthermore, spatially explicit historical crop cover data do not exist to help calibrate an empirically based model. In this circumstance, employing the principle of Occam's razor, the simplest possible approach seems to be the most appropriate.

In this study, we use a simple model to transform political unit data into spatially explicit cropland data. Rather than develop an explicit model of land suitability for crops, we assume that the crop cover pattern in 1992 roughly represents the historical spatial patterns within each political unit. Thus, to simulate the historical crop cover distribution within each political unit, we simply maintain the same crop cover pattern as in 1992, multiplied by a factor so that the totals within each political unit match the historical inventory data (see Fig. 1). This assumption will not be appropriate for large countries with no subnational information. However, for North America, we have data at the subnational level for the United States, Canada, and Mexico.

The hindcast simulations are performed in a sequence, with the first one starting in 1992 and going back to 1991, the second starting in 1991 and going back to 1990, and so on, for every year back to 1850 (Fig. 2a,b). The methodology for executing the above mentioned procedure is outlined in more detail in Appendix 1.

CHARACTERIZING NATURAL VEGETATION COVER

To understand the environmental impacts of land cover change, it is imperative to know what types of natural vegetation have been cleared for croplands. Hence, by using a combination of the DISCover data set and the vegetation data set of Haxeltine & Prentice (1996) (referred to as HP hereafter), we have created a map of potential vegetation (i.e. vegetation that would most likely exist in the absence of human intervention) at 5 min resolution classified into fifteen vegetation types (Fig. 3; because the DISCover data poorly represents the distribution of wetlands, we ignore wetlands also and consider only upland vegetation). This procedure results in 'potential' vegetation, and not necessarily 'natural' (i.e. vegetation before European settlement) vegetation because human activities such as fire suppression have led to indirect changes in the natural vegetation cover by modifying the stages of succession at which plants exists.

We use the 1-km resolution DISCover data set, classified under the Olson Global Ecosystems (OGE) framework (Olson, 1994). We first reclassify the ninety-four OGE classes into fifteen potential vegetation classes (Fig. 3) and three additional classes – land-use, wetlands, and water. Then, within each 5-min resolution grid cell, we look for the dominant potential upland vegetation class (ignoring land use, wetlands, and water pixels), and assign that class as the potential vegetation for that grid cell (the two classes denoting 100% water are separately used to create a 5-min resolution land-water mask). All grid cells with >50% crop cover or <20% dominant potential vegetation (of all upland pixels) are then assigned the potential vegetation types from the HP data set. Prior to this, we interpolate the 0.5° resolution HP data set to a 5-min resolution, and further translate HP's eighteen biome types easily into our fifteen types. In addition, some climate rules are used to classify Tundra and Polar Desert, and to separate Tropical, Temperate and Boreal Forests/Woodlands. More details on the methodology can be found in Ramankutty & Foley (1999).

This approach to derive potential vegetation has several limitations. First, human activities are likely to have modified vegetation cover significantly without completely converting it (e.g. degradation of woodlands and savannas in Africa). Thus the vegetation type identified by the satellite data is not necessarily the potential vegetation. Secondly, it is likely that land cover classification data sets derived from remotely sensed data are unable to distinguish between some vegetation types; this will be evaluated during the validation phase of the DISCover data set. Despite these limitations, a combination of the DISCover data set and the HP data set yields a reasonable, high-resolution characterization of contemporary potential vegetation, which is also consistent with the source of our croplands data set.

RESULTS

Figure 2(a),(b) show our simulations of fractional crop cover for every two decades from 1850 to 1990. In 1850, crop cover in Canada was limited to the Grand Trunk and St. Lawrence regions; while in the United States, croplands were located to the east of the Mississippi. Subsequently, the agricultural frontier gradually migrated westward in the United States & Canada. Between 1850 and 1910, agriculture intensified in the Midwestern U.S.A., starting in Ohio and continuing westward into Indiana, Illinois, Missouri, northern Arkansas, eastern Oklahoma, and the Plain states. By 1910, the south-eastern U.S. states of Georgia, and the Carolinas were well developed, as was the Mississippi valley. The Prairie Provinces in Canada were starting to be developed around 1910. By 1950, crop areas peaked in United States, and then stabilized; while crop cover continued to increase in the Prairie Provinces of Canada. The intensively cultivated Corn Belt was very evident by 1950. Between 1890 and 1910, crop cover decreased in the New England region

(a)

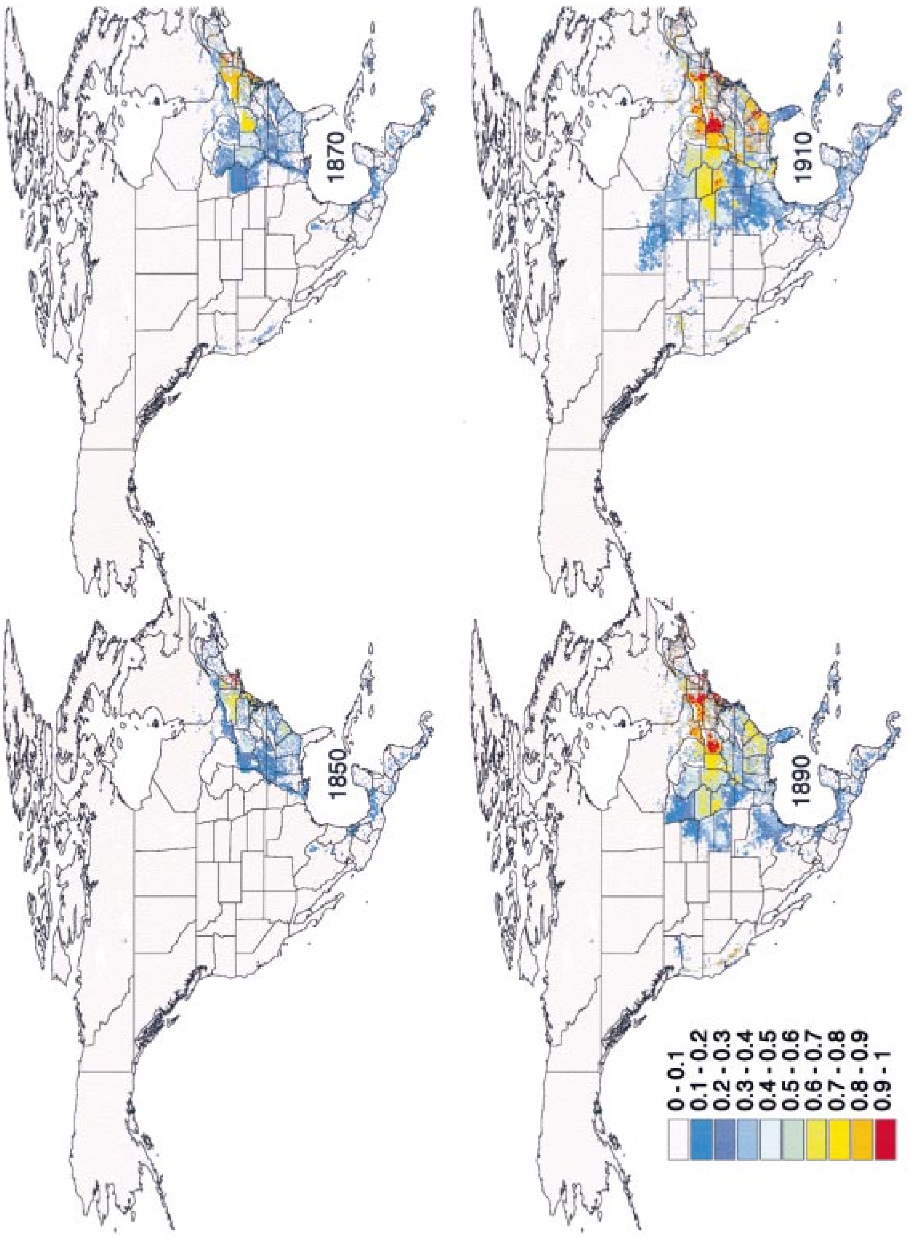

1870
1910
1850
1890
0 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
0.8 - 0.9
0.9 - 1

Fig. 2

(b)

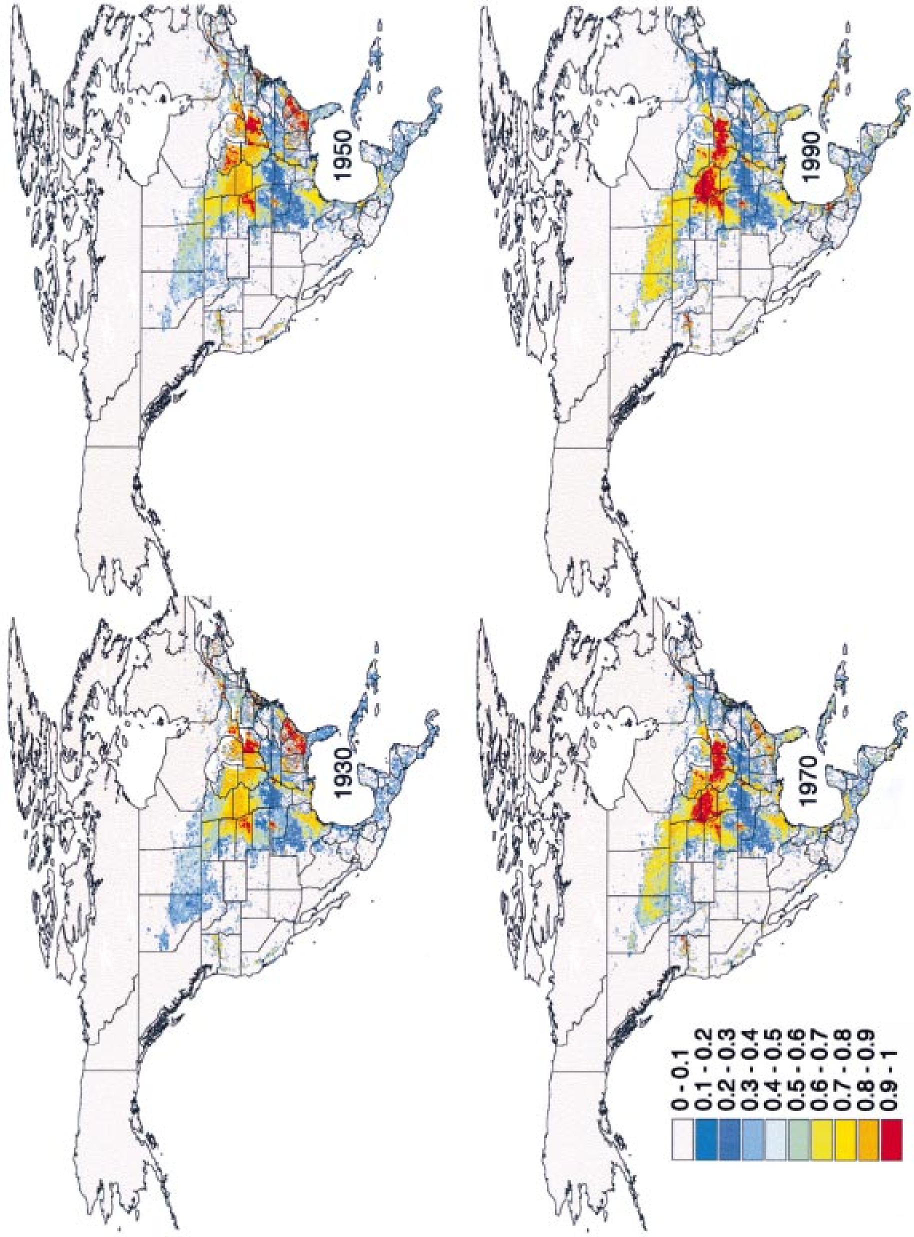

1950
1990
1930
1970
0 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
0.8 - 0.9
0.9 - 1

Fig. 2

of the United States. This marked the beginning of the general pattern of crop abandonment witnessed in the eastern portions of the continent during the 20th century. Between 1930 and 1990, cropland abandonment spread south into the Mid-Atlantic States, and then into the South-east.

A few studies have attempted to estimate the overall changes in presettlement vegetation cover by superimposing modern land cover maps over maps of potential natural vegetation (e.g. Klopatek *et al.*, 1979; Loveland & Hutcheson, 1995). We perform a similar analysis, but extend it further to provide a dynamic perspective from 1850 to 1992. Superimposing our maps of crop cover change over our map of potential vegetation, we estimate the changes in extent of the various vegetation types due to clearing for croplands. Figure 4(a) shows our estimated changes in area of the two biome types that have most extensively been cleared for croplands in North America. In this figure, for simplicity, we have combined all the forests/woodlands into one category, and the savannas with the grassland/steppe category. We also show the area of croplands, and the area of abandoned croplands in regions previously occupied by forests/woodlands and savannas/grasslands/steppes. About 1.68 million km^2 of original savannas/grasslands/steppes and 1.40 million km^2 of all 'original' forests/woodlands have been cleared since 1850 (original refers to the primary forest cover, excluding any potential regrowth since 1850). The largest changes have occurred in the grassland/steppe vegetation type (about a million km^2 cleared since 1850). This is consistent with our knowledge that prairies have been extensively cleared for crops in the Midwestern U.S.A. and in Canada. The major forest vegetation types affected are mixed forests (0.40 million km^2 cleared since 1850), temperate deciduous forests (0.42 million km^2 cleared) and temperate needleleaf evergreen forests (0.33 million km^2 cleared). Also, about 0.64 million km^2 of cropland areas have been abandoned in regions previously covered by forests/woodlands, and about 0.17 million km^2 in regions previously occupied by savannas/grasslands/steppes.

Figure 4(b) shows our estimate of the area of all original forests/woodlands (i.e. excluding potential regrowth due to abandonment of croplands since 1850) in the forty-eight conterminous states of the U.S.A., from 1850 to 1992. This figure shows the rapid clearing of original forests/woodlands in the United States since 1850. The figure also shows that a significant area of croplands have been abandoned in regions originally occupied by forests/woodlands. Since forests/woodlands are likely to have taken a long time to regrow, and to not have regrown everywhere, the actual forest/woodland area is likely to lie somewhere between our estimate of original forest/woodland area and our estimate of original forest/woodland area plus abandoned cropland areas in forests/woodlands. Also shown in Fig. 4(b) are two other independent estimates of forest area. The estimate from U.S. Department of Agriculture (1992) (including forested areas in parks, wildlife area, and other special-purpose use areas) is larger than our estimate of forests/woodland area. The differences are likely due to the use of different definitions of forests/woodlands. However, the U.S. Department of Agriculture (1992) (USDA, hereafter) estimate of the relative changes in forest/woodland area between 1945 and 1992 is similar to our estimates. The estimate from Williams (1989) (Table 13.3 of his book, adapted from Clawson (1979) and U.S. Forest Service (1982)), shows a very large increase in forest area from 1945 to around 1960; this large increase is not seen in either the USDA estimate or our own estimates. Figure 4(b) shows that the data of Williams after 1960 matches the USDA estimate including Alaska, suggesting that the large increase in the Williams (1989) data between 1945 and 1960 might be an artefact of including Alaska.

We further analyse our historical croplands data set in terms of the fractional area of croplands abandoned (Fig. 5). We estimate this quantity, for each grid cell, as the difference between the maximum extent of fractional cropland area and the extent of croplands in 1992 (top panel of Fig. 5). We also estimate the year at which the maximum cropland extent was attained (lower panel of Fig. 5). This clearly depicts the extensive abandonment of croplands in eastern North America. Cropland abandonment began in the mid to late 19th

Fig. 2. (*previous pages*) (a) Historical changes in North American crop cover 1850–1910. The data are at a resolution of 5 min, and are shown as the fraction of each 5 min grid cell in croplands. The outlines drawn on the map depict political units that correspond to the resolution of the inventory data. The abrupt transitions in crop area seen in some maps are artefacts of the discontinuous colour scheme used. (b) Historical changes in North American crop cover 1930–90. The data are at a resolution of 5 min, and are shown as the fraction of each 5 min grid cell in croplands. The outlines drawn on the map depict political units that correspond to the resolution of the inventory data. The abrupt transitions in crop area seen in some maps are artefacts of the discontinuous colour scheme used.

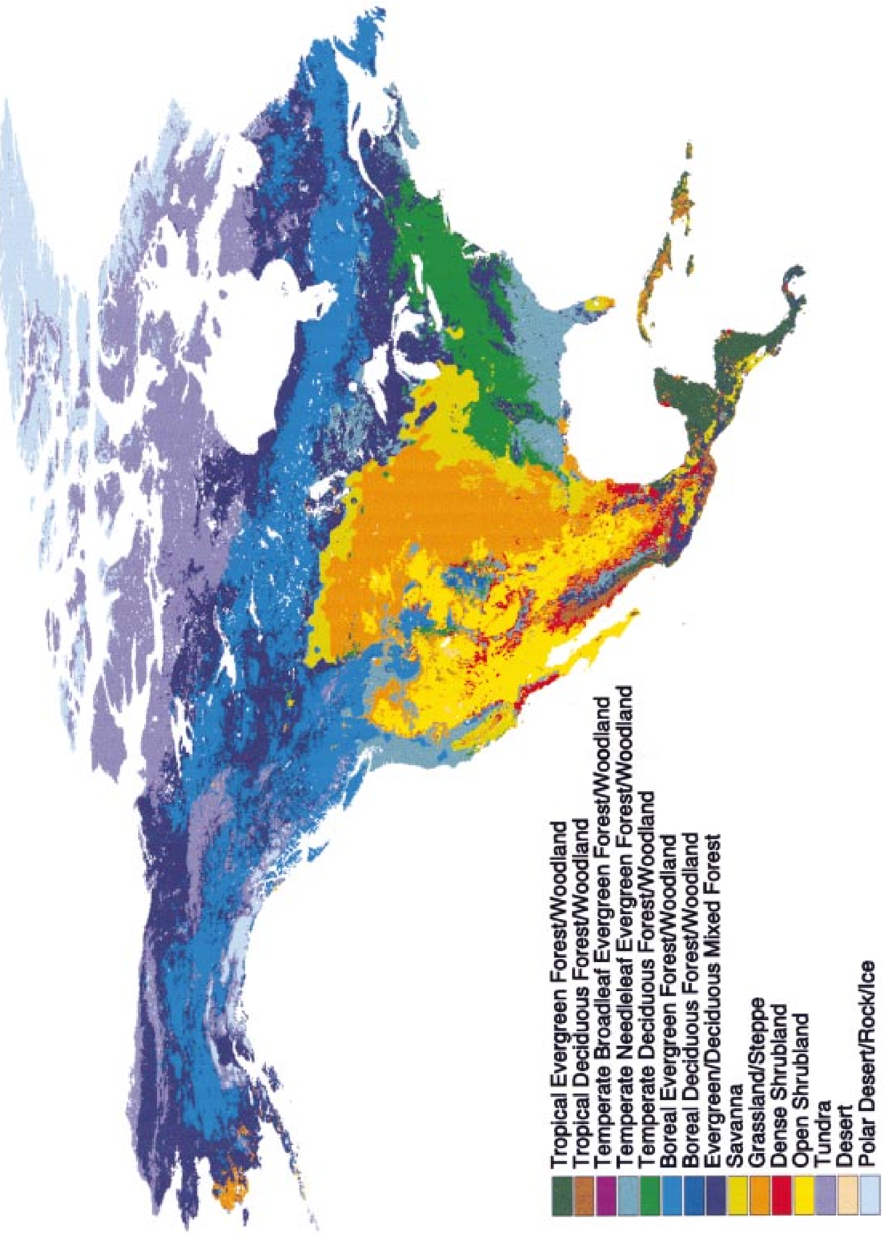
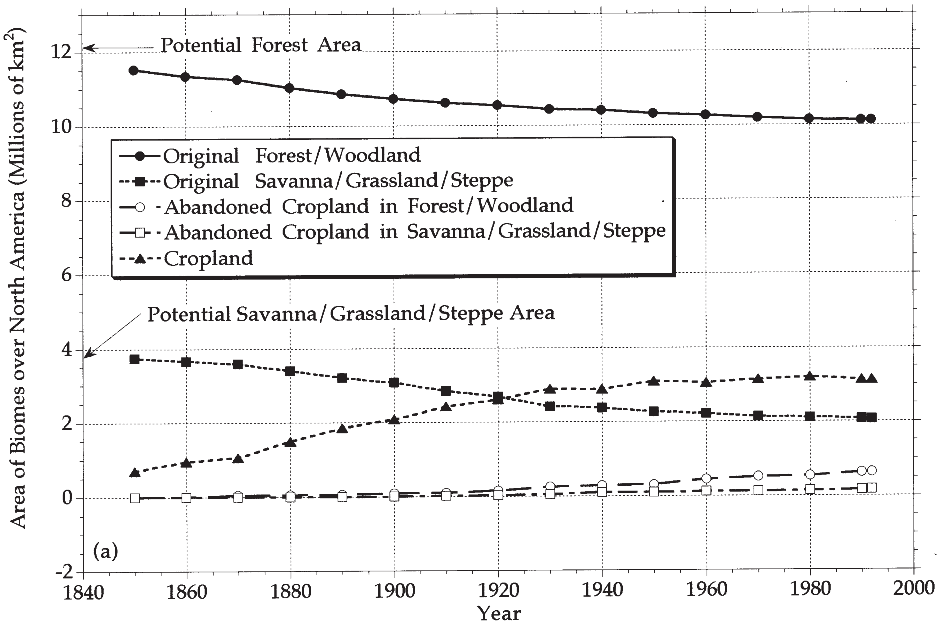


Fig. 3. Potential vegetation types, at a resolution of 5 min. The data set is derived using the 1 km DISCover land cover data set, with the regions dominated by land use being filled using the Haxeltine & Prentice (1996) potential vegetation data set.



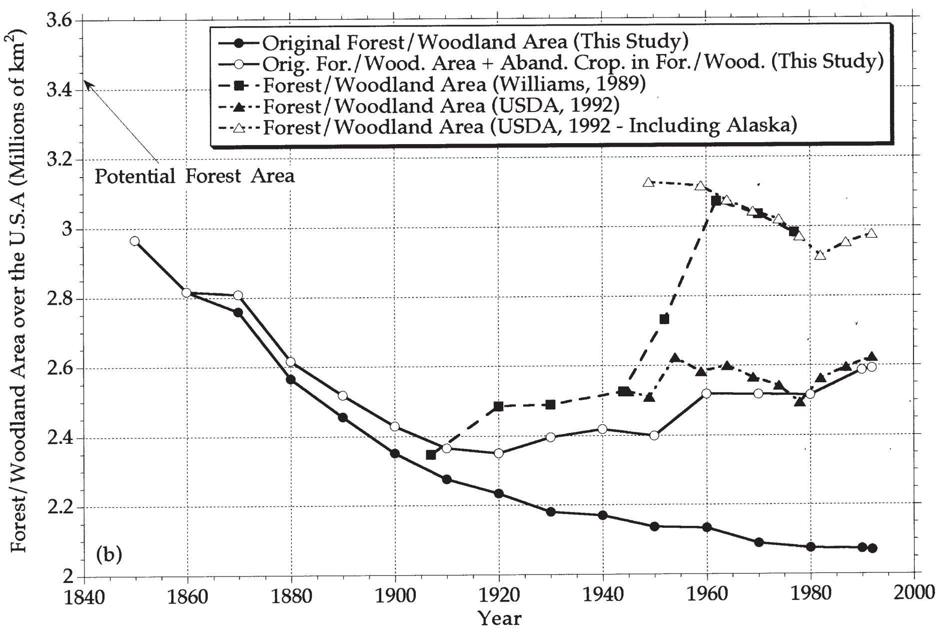


Fig. 4. Estimated changes in area of vegetation types. Fig. 4(a) (top panel): changes in area, over North America, of original forests/woodlands, original savannas/grasslands/steppes, croplands, and abandoned croplands in regions previously occupied by forests/woodlands and in regions previously in savannas/grasslands/steppes. Fig. 4(b) (lower panel): changes in forest area over the U.S.A., from this study as compared to two other independent estimates. See text for more detail.

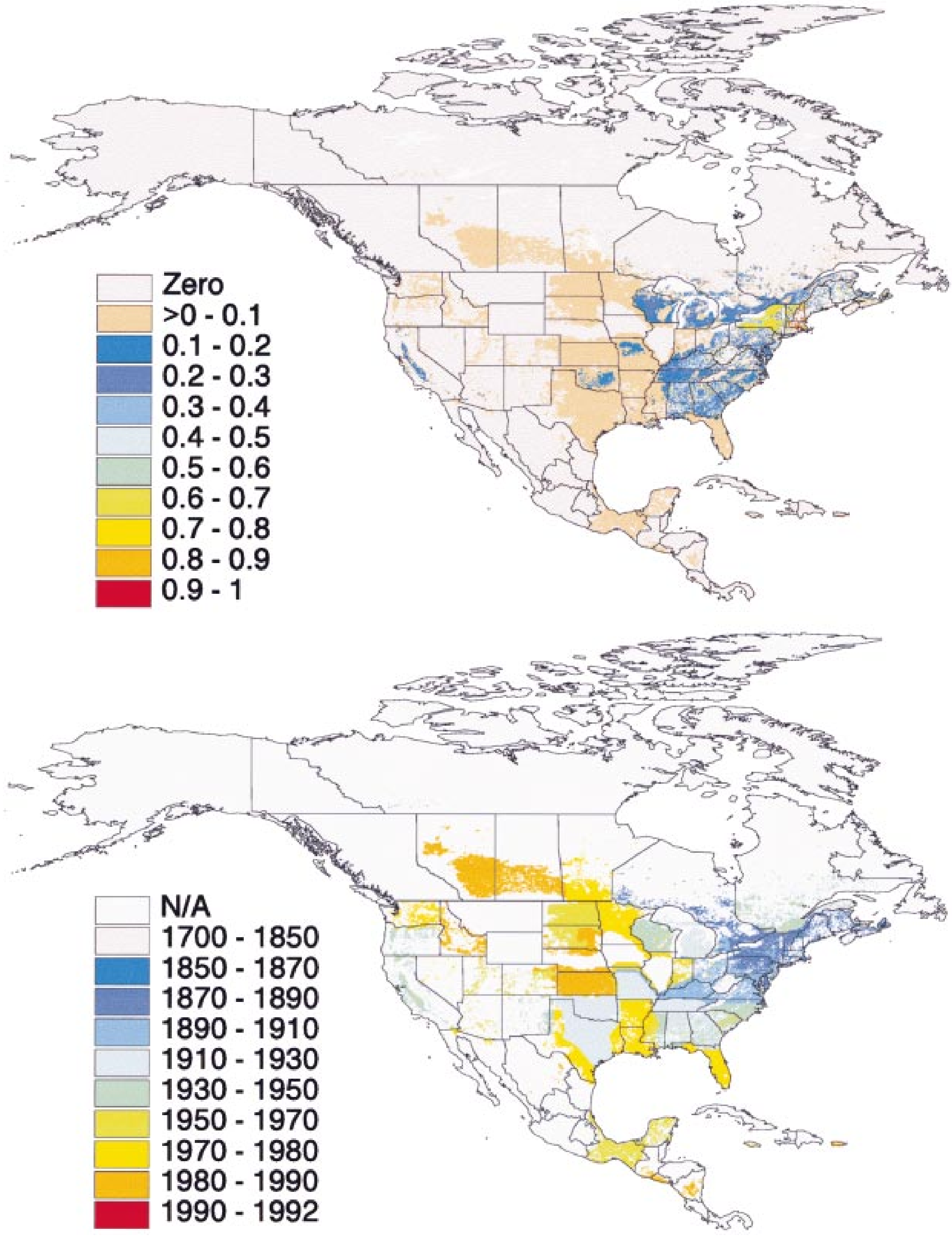


Fig. 5. Top panel: Abandoned cropland area, expressed as the proportion of a 5-min grid cell, estimated as the difference between the maximum cropland extent over the 1850–1992 period and the cropland extent of 1992. The zero value was defined using a threshold of 0.001. Bottom panel: Year at which the maximum cropland extent was attained. The N/A category indicates zero abandoned cropland area.

century in New England and the mid-Atlantic states, and in the early 20th century in other parts of eastern North America. The largest extent of abandonment occurred in New York State (roughly 60–70% abandonment), in the Mid-Atlantic States, and in the New England region of the U.S.A.

DISCUSSION

Because there are few historical maps of crop cover in North America, we have no direct means to validate our product. However, we have evaluated our 1992 cropland map against three other contemporary data sets and concluded that our product was in fair agreement over North America (Ramankutty & Foley, 1998). In the United States, our 1992 cropland distribution, as well as our estimated conversion rates over 1982–92, compare reasonably well to maps produced using county-level data by the National Resources Conservation Service of the U.S. Department of Agriculture (http://www.nhq.nrcs.usda.gov/land/index/cover_use.html). In addition, our data set over Canada compares reasonably well with a 1995 land cover map derived from satellite data (http://www.ccrs.nrcan.gc.c./ccrs/tekrd/rd/apps/em/cchange/lande.html). Furthermore, the DISCover land cover classification data set itself is being validated (http://keystone.geog.ucsb.edu/igbp.html). As with earlier efforts simulating large-scale land cover change, our study is also hampered by a lack of adequate validation. Future efforts may be directed toward a compilation and digitization of historical land cover maps in order to help evaluate simulated data sets.

In this study, we resort to comparing our simulated changes in crop area to qualitative descriptions of crop cover change found in the literature. It is interesting to consider additionally the processes that led to these changes. Many studies have described the historical changes in agriculture of North America (Bailey, 1909; Helfman, 1962; Menzies, 1973; Schlebecker, 1973; Schlebecker, 1975; Yates, 1981; Richards, 1990; Riebsame, 1990; Cronon, 1991; Meyer, 1995; U.S. Department of Agriculture, 1998). Based on these studies, we can summarise the historical changes in agriculture and the processes driving those changes in North America.

In the U.S.A., the Homestead Act of 1862 (wherein 160 acres of government land were given free to those settling and cultivating it for at least 5 years) led to a rapid settlement of public lands in the following decades. This was further stimulated by the end of the civil war and the disbanding of armies. The Great Plains region looked very promising to people who had lost everything they owned in the war. The increasing flow of immigration added further to the movement of people into the Midwest. Furthermore, the building of canals in the early 1800s, and subsequent expansion of railroads facilitated the rapid transport of goods to the market.

In the 1850s, corn and wheat belts began to develop. Wheat was constantly forced westward by the rising price of land and by encroaching corn areas. In the 1860s, the Corn Belt moved westward, and toward the end of the decade stabilized in its present area. Heavy agricultural settlement on the Great Plains began in the 1870s and 1880s. Dryland farming in the semiarid regions of the Midwest began in the 1880s. In 1902, the government passed a reclamation act to provide irrigation resources to small farmers, which further spurred the agricultural development of the Midwest. Since 1900, cropland area increased mostly in the Great Plains region, replacing grasslands. The period from 1898 to 1914 is sometimes known as the Golden Age of American Agriculture. By 1920, grain production had reached the most arid regions of the Great Plains and cotton had moved into western Texas and Oklahoma. Some states showed a reduction in crop acreage between 1930 and 1940, probably because of the dustbowl. Between the 1930s and the 1950s, the federal government sponsored large irrigation projects in the western states, leading to the subsequent agricultural development of California and other western states. Around the 1940s, crop acreage in the U.S.A. began to stabilize. In the 1960s, soybean acreage expanded in the Great Plains, as an alternative to other crops.

The early 20th century also saw the abandonment of croplands and regrowth of forests in the eastern portions of the U.S.A., starting in New England, followed by the Mid-Atlantic States, and more recently in the South-east. The abandonment of croplands in the eastern U.S.A. was partly due to competition from more fertile regions of the Midwest, and also due to competing demands on land within the east.

In Canada, the railways reached Winnipeg in 1885, and provided easy access to the prairies. Roughly a decade later, immigration into the Canadian West reached huge proportions. Innis (1935) observed that roughly one million settlers came to the Canadian West from the United States, and several thousand others from Europe. The Prairie Provinces had almost no crop cover in 1900, but was agriculturally developed by 1930.

In Mexico, corn and dry beans are the most widely cultivated crops. The Corn Belt runs across the great Central Plateau, from Zacatecas and San Luis Potosi in the north to Oaxaca in the south (Yates, 1981; U.S. Department of Agriculture, 1958). Our data for 1992 fails to capture this distribution of cropland in Mexico, except for the Gulf-south portion (Veracruz, Tabasco, Oaxaca, and Chiapas). This is possibly because of poor characterization of Mexican crop cover by the DISCover data set. Historical statistics also show that the most rapid increases in cropland between 1930 and 1970 occurred in the western portions of the country, and in the Gulf-south (Yates, 1981). Because our study fails to capture the correct distribution of crop cover in Mexico in 1992, we also fail to simulate the historical changes correctly.

SUMMARY AND CONCLUSIONS

In this study, we have presented a very simple approach for integrating spatially explicit remotely sensed data with agricultural inventory data at the political unit level. Because remotely sensed data on crop cover do not extend back into the past for more than a couple of decades, we have to rely on historical cropland inventory data. The reconstructed maps of North American crop cover change from 1850 to the present are in general agreement with qualitative descriptions of crop cover change in that continent. For instance, the westward migration of crop cover into the Great Plains region since the 1850s is simulated very well. Our simulation also shows the stabilization of crop cover around the 1940s in the U.S.A., and the abandonment of croplands in the eastern U.S.A. since the early 1900s. Our simulation of crop cover change over Canada is also reasonable. However, our simulation of Mexican crop cover change is incorrect, mainly due to the poor representation of contemporary crop cover in Mexico.

Combining the reconstructed changes in crop cover with a map of potential vegetation, we have also estimated the changes in different vegetation types due to clearing for croplands. This estimate shows a rapid decline in forests/woodlands and savannas/grasslands/steppes in North America since 1850. We also estimate a significant area of abandoned croplands in eastern North America, which could potentially have regrown back to natural vegetation. Over the United States, we have compared our estimates of changing forest/woodland cover, with independent estimates of changes in forest/woodland area. During 1945–92, our estimate shows reasonable agreement with the estimate from USDA, but not with the estimate of Williams (1989). The independent estimates of forest cover do not extend far enough into the past to make the comparisons more useful.

Our analysis of changes in forest area is based only on clearing for cultivation, and does not account for other land use practices. However, the most likely cause of forest loss in North America is probably cultivation. Given this caveat, our analysis, as well as the independent estimate from USDA, suggests that the regrowth of forests in the United States in the 20th century is quite small. This is in contradiction with the estimates of Williams (1989), which show a steep increase in forest areas between 1940 and 1960. This increase within the Williams (1989) dataset is commonly interpreted as regrowth of forests in the eastern U.S.A., but is more likely an artefact of including Alaska. This analysis has pertinence to the issue of carbon sequestration due to regrowing forests in eastern North America (Sedjo, 1992; Houghton, 1993; Fan *et al.*, 1998). If the data of Williams (1989) were accurate, then the estimate of carbon sequestration in the last century would be much larger than if our data or the estimate from USDA are used. This is particularly significant in the aftermath of the Kyoto protocol, whereby countries can reduce net emissions of carbon to the atmosphere either by limiting fossil fuel consumption or by increasing net carbon sequestration in terrestrial sinks (IGBP Terrestrial Carbon Working Group, 1998).

It is important to point out now that the outcome discussed above is a result of applying adjustments to the U.S. historical cropland inventory data to ensure consistent definitions. Uncorrected data over the U.S.A. generally show a decline in cropland area after 1940 (U.S. Bureau of the Census 1975). We believe that this decrease in cropland area is an artefact of the changes in definitions. In the census of 1945 and after, a separate category called ‘croplands used for pastures temporarily, ploughed within 7 years’ was included to indicate those croplands that were temporarily used as pastures as part of a long-term crop rotation. Prior to 1945, the agricultural census (of 1939 and earlier) only had a single category called ‘ploughable pastures’, which was much larger than the portion that was just temporarily used as pastures. The ploughable pastures data were included in the total crop area estimates prior to 1945, while only the portion that was ploughed within 7 years was included in 1945 and afterward, leading to an apparent decline in crop area between 1939 and 1945. The corrected total cropland data for the United States shows cropland rising almost linearly between 1850 and 1930, and then stabilising, showing no decline. Consequently, when the corrected crop area is subtracted from the potential forest areas, the estimated changes in forest area also do not indicate much potential regrowth after 1940 for the U.S.A. as a whole. However, our spatial estimates do show a significant abandonment of croplands in the eastern U.S.A. For the U.S.A. as a whole, the abandonment of croplands in the eastern portions is probably cancelled by an intensification of croplands in the western portions of the country. Clearly, much work remains to be done to quantify carefully the historical changes in land cover in eastern North America.

Our reconstructed data set of North American crop cover from 1850 to 1992 can be used within global climate models to study the impact of crop cover change on climate over the last century (e.g. Bonan, 1997). Our data set can also be used within global biosphere models (e.g. IBIS of Foley *et al*., 1996) to study the impact of land cover change on the carbon and hydrologic cycles (e.g. Costa & Foley, 1997). Furthermore, although our approach has been restricted to North America in this study, it could easily be extended to the global scale.

ACKNOWLEDGMENTS

We appreciate Nicholas Olejniczak's immense help with collecting the cropland inventory data, as well as the assistance of Amber Shavers and Catherine Mergen. We would like to thank Dr Pat Bartlein for providing us with the T_{min} data set, and Dr Colin Prentice for his very valuable input on the potential vegetation data set. We greatly appreciate Dr Jorge Sarmiento's suggestion that we include a spatial map of abandoned croplands in the paper. We would like to thank Mike Coe, Jeff Cardille, Veronica Fisher, and Chris Kucharik for their comments and technical assistance. The DISCover data set was obtained from the EROS Data Center. This work was supported by NASA's Office of Earth Science (through grant NAG5–3513 and by a NASA Earth System Science Fellowship) and the National Science Foundation (through grant ATM-9506588). In addition, this work was partially supported by the Climate, People, and Environment Program (CPEP) of the University of Wisconsin.

Note

A digital version of this croplands data set will be made available through our web site (http://cpep.meteor.wisc.edu) upon the publication of this paper.

REFERENCES

Bailey, L.H. (1909) *Cyclopedia of American agriculture: a popular survey of agricultural conditions, practices and ideals in the United States and Canada, Vol. IV – Farm and Community*, p. 628. Macmillan, London.

Bonan, G.B. (1997) Effects of land use on the climate of the United States. *Clim. Change,* **37,** 449–486.

Clawson, M. (1979) Forests in the long sweep of American history. *Science,* **204,** 1168–1174.

Copeland, J.H., Pielke, R.A. & Kittel, T.G.F. (1995) Potential climate impacts of vegetation change: a regional modeling study. *J. geophys. Res.* **101,** 7409–7418.

Costa, M.H. & Foley, J.A. (1997) The water balance of the Amazon basin: Dependence on vegetation cover and canopy conductance. *J. geophys. Res.* **102,** 23973–23990.

Cronon, W. (1991) *Nature's Metropolis: Chicago and the Great West*, p. 530. W.W. Norton & Company, New York.

Dickinson, R.E. & Henderson-Sellers, A. (1988) Modeling tropical deforestation: a study of GCM land-surface parameterizations. *Q.J. Roy. Meteor. Soc.* **114,** 439–462.

Esser, G., Hoffstadt, J., Mack, F. & Wittenberg, U. (1994) *High Resolution Biosphere Model. Documentation, Model, Version 3.0.* Justus-Liebeg University, Giessen, Germany.

Fan, S.M., Gloor, J., Mahlman, S., Pacala, J., Sarmiento, T., Takahashi, P. & Tans (1998) A large terrestrial carbon sink in North America implied by atmospheric and oceanic carbon dioxide data and models. *Science,* **282,** 442–446.

FAO (1995) *Land use, FAOSTAT-PC*, 19 pp. Food and Agriculture Organization of the United Nations, Rome.

Foley, J.A., Prentice, I.C., Ramankutty, N., Levis, S., Pollard, D., Sitch, S. & Haxeltine, A. (1996) An integrated biosphere model of land surface processes, terrestrial carbon balance, and vegetation dynamics. *Global Biogeochem. Cycles,* **10,** 603–628.

Hall, C.A.S., Tian, H., Qi, Y., Pontius, G. & Cornell, J.. (1995) Modelling spatial and temporal patterns of tropical land use change. *J. Biogeogr.* **22,** 753–757.

Haxeltine, A. & Prentice, C.I. (1996) BIOME3: an equilibrium terrestrial biosphere model based on ecophysiological constraints, resource availability, and competition among plant functional types. *Global Biogeochem. Cycles,* **10,** 693–709.

Helfman, E.S. (1962) *Land, people, and history*, p. 271. David McKay Company, Inc., New York.

Houghton, R.A. (1993) Is carbon accumulating in the northern temperate zone? *Global Biogeochem. Cycles,* **7,** 611–617.

Houghton, R.A. (1995) Land-use change and the carbon cycle. *Global Change Biol.* **1,** 275–287.

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 CO_2 to the atmosphere. *Ecol. Monogr.* **53,** 235–262.

Houghton, R.A., Lefkowitz, D.S. & Skole, D.L. (1991) Changes in the landscape of Latin America between 1850 and 1985. I. Progressive loss of forests. *Forest Ecol. Mgmnt,* **38,** 143–172.

IGBP Terrestrial Carbon Working Group (1998) The Terrestrial carbon cycle: implications for the Kyoto Protocol. *Science,* **280,** 1393–1394.

Innis, M.Q. (1935) *An economic history of Canada*, p. 302. Ryerson Press, Toronto.

Klein Goldewijk, C.G.M. & Battjes, J.J. (1997) A hundred year (1890–1990) database for integrated environmental assessments (HYDE, Version 1.1). *Report No* 422514002, 100 pp. National Institute of Public Health and Environmental Protection, Bilthoven.

Klopatek, J.M., Olson, R.J., Emerson, C.J. & Joness, J.L. (1979) Land-use conflicts with natural vegetation in the United States. *Environ. Conserv.* **6,** 191–199.

Loveland, T.R. & Belward, A.S. (1997) The IGBP-DIS global 1km land cover data set, DISCover: first results. *Int. J. Remote Sens.* **18,** 3289–3295.

Loveland, T.R. & Hutcheson, H.L. (1995) Monitoring changes in United States landscapes from satellite imagery: status and future possibilities. *Our living resources* (ed. by E.T. LaRoe, G.S. Farris, C.E. Puckett, P.D. Doran and M.J. Mac), pp. 468–473. National Biological Survey, Washington, D.C.

Menzies, M.W. (1973) Grain marketing methods in Canada —the theory, assumptions, and approach. *Am. J. Agric. Econ.* **91,** 791–799.

Meyer, W.B. (1995) Past and present land use and land cover in the USA. *Consequences*, **1,** 25–33.

Olson, J.S. (1994) Global ecosystem framework-definitions. *USGS EROS Data Center Internal Report*, p. 37. Sioux Falls, South Dakota.

Olson, J.S., Watts, J.A. & Allison, L.J. (1983) *Carbon in live vegetation of major world ecosystems*, p. 180. Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Postel, S.L., Daily, G.C. & Ehrlich, P.R. (1996) Human appropriation of renewable fresh water. *Science,* **271,** 785–788.

Ramankutty, N. & Foley, J.A. (1998) Characterizing patterns of global land use: an analysis of global croplands data. *Global Biogeochem. Cycles,* **12,** 667–685.

Ramankutty, N. & Foley, J.A. (1999) Estimating historical changes in global land cover: Croplands from 1700 to 1992. *Global Biogeochem. Cycles* (in press).

Richards, J.F. (1990) Land transformation. *The Earth as transformed by human action* (ed. by B.L. Turner, W.C. Clark, R.W. Kates, J.F. Richards, J.T. Mathews and W.B.Meyer), pp. 163–178. Cambridge University Press, Cambridge.

Riebsame, W.E. (1990) The United States Great Plains. *The Earth as transformed by human action* (ed. by B.L. Turner, W.C. Clark, R.W. Kates, J.F. Richards, J.T. Mathews and W.B. Meyer), pp. 561–575. Cambridge University Press, Cambridge.

Schlebecker, J.T. (1973) *The use of the land*, p. 218. Coronado Press, Kansas.

Schlebecker, J.T. (1975) *Whereby we thrive. A history of American farming, 1607–1972*, p. 342. The Iowa State University Press, Ames, Iowa.

Sedjo, R.A. (1992) Temperate forest ecosystems in the global carbon cycle. *Ambio,* **21,** 274–277.

Shukla, J., Nobre, C. & Sellers, P.J. (1990) Amazon deforestation and climate change. *Science,* **247,** 1322–1325.

Turner, I.I.B.L., Moss, R.H. & Skole, D.L. (1993) *Relating land use and global land cover change. A proposal for an IGBP-HDP Core Project.* IGBP Report no. 24, HDP Report no. 5. The International Geosphere-Biosphere Programme: A study of global change and the Human Dimensions of Global Environmental Change Programme, Stockholm.

U.S. Bureau of the Census (1900) *12th Census of the U.S.* U.S. Dept. of Commerce, Bureau of the Census, U.S. Govt.

U.S. Bureau of the Census (1920) *14th Census of the U.S.* U.S. Dept. of Commerce, Bureau of the Census, U.S. Govt.

U.S. Bureau of the Census (1940) *16th Census of the U.S.* U.S. Dept. of Commerce, Bureau of the Census, U.S. Govt.

U.S. Bureau of the Census (1950) *18th Census of the U.S.* U.S. Dept. of Commerce, Bureau of the Census, U.S. Govt.

U.S. Bureau of the Census (1975) *Historical statistics of the United States, colonial times to 1970.* U.S. Dept. of Commerce, Bureau of the Census, U.S. Govt.

U.S. Department of Agriculture (1958) *Agricultural geography of Latin America*, p. 96. Foreign Agricultural Service, United States Department of Agriculture.

U.S. Department of Agriculture (1992) *Major Land Uses (1945–92)*. Economic Research Service, United States Department of Agriculture. <http://mann77.mannlib.cornell.edu/data-sets/land/89003/>.

U.S. Department of Agriculture (1998) *A history of American agriculture 1776–1990*. Economic Research Service, United States Department of Agriculture. <http://www.usda.gov/history2/front.htm>.

U.S. Forest Service (1982) An analysis of the timber situation in the United States. 1952–2030. *Forest Resources Report No.* 23. GPO, Washington, D.C.

Veldkamp, A. & Fresco, L.O. (1996) CLUE-CR: an

integrated multi-scale model to simulate land use change scenarios in Costa Rica. *Ecol. Model.* **91,** 231–248.
Vitousek, P.M., Mooney, H.A., Lubchenco, J. & Melillo, J.M. (1997) Human domination of Earth's ecosystems. *Science,* **277,** 494–499.
Williams, M. (1989) Americans and their forests. *A historical geography*, p. 599. Cambridge University Press, Cambridge.
Yates, P.L. (1981) *Mexico's agricultural dilemma*, p. 291. The University of Arizona Press, Tucson.
Zuidema, G., van den Born, G.J., Alcamo, J. & Kreileman, G.J.J. (1994) Simulating changes in global land cover as affected by economic and climatic factors. *Water Air Soil Pollut.* **76,** 163–198.

APPENDIX I

From the calibrated DISCover data for 1992, $f_{CA}(i, j, 1992)$ we calculated the crop area over each political unit, denoted as $A_S^{1992}(k)$. This estimate does not exactly match that from the inventory data, i.e. $A_S^{1992}(k) \neq A_I^{1992}(k)$ (see Fig. 1 of Ramankutty & Foley, 1998). Because our simulations are initialized with the calibrated DISCover data, and because they do not exactly match the inventory data in 1992, we cannot use the historical inventory data directly as a constraint for the hindcast simultion. Instead, the target crop areas could be estimated by calculating anomalies of the inventory data relative to 1992, and then applying them to $A_S^{1992}(k)$. In this paper, we calculate target crop areas as a weighted average of the estimates based on using absolute anomalies and relative anomalies of inventory data. The estimates are made as follows:

$$A_S^{t_2}(k) = \alpha(k)\left[A_S^{t_1}(k)\frac{A_I^{t_2}(k)}{A_I^{t_1}(k)}\right] + (1-\alpha(k))[A_S^{t_1}(k) + (A_I^{t_2}(k) - A_I^{t_1}(k))],$$

where, t_1 = the starting time of simulation, and t_2 = the ending time of simulation. In the first simulation, $t_1 = 1992$, $t_2 = 1991$; in the second simulation, $t_1 = 1991$, $t_2 = 1990$, etc.

$A_I^{t_1}(k)$ = Crop area from inventory data for time t_1, for political unit k,

$A_I^{t_2}(k)$ = Crop area from inventory data for time t_2, for political unit k,

$A_S^{t_1}(k)$ = Crop area from calibrated DISCover data for time t_1, for political unit k,

$A_S^{t_2}(k)$ = Target crop area for the simulation for time t_2, for political unit k, and

$$a(k) = \min\left[1, \exp\left\{-0.5\left(\frac{A_I^{t_2}(k)}{A_I^{t_1}(k)} - 1.1\right)\right\}\right].$$

Thus, when $A_I^{t_2}(k)/A_I^{t_1}(k) \leq 1.1$, $\alpha(k) = 1$, and as $A_I^{t_2}(k)/A_I^{t_1}(k)$ became large, $\alpha(k) \to 0$.

In addition, we apply the following rules:

If $A_S^{t_1}(k) = 0$, then $\alpha(k) = 0$;
If $A_I^{t_1}(k) = A_I^{t_2}(k) = 0$ then $A_S^{t_1}(k) = A_S^{t_2}(k)$;
$\min(A_S^{t_2}(k)) = 0$.

Once the target crop areas are calculated for each political unit, we then derive a factor which, when multiplied by $A_S^{t_1}(k)$, gives us the crop area for time t_2, i.e.,

$$\phi(k) = \frac{A_S^{t_2}(k)}{A_S^{t_1}(k)}.$$

The values of $\phi(k)$ are then converted to a map at 5-minute resolution, by uniformly applying $\phi(k)$ within the political boundaries of each political unit k. Since $\phi(k)$ can change sharply across the boundary of the political units, we smooth the map of $\phi(k)$. The smoothing is done by successively applying a simple filter and then correcting the values so that the total target crop area of each political unit is conserved. Thus, historical fractional crop cover is estimated using the equation:

$$f_{CA}(i, j, t) = f_{CA}(i, j, t_1)\tilde{\phi}(k),$$

where $\tilde{\phi}(k)$ is smoothed version of $\phi(k)$.

As mentioned earlier, simulations are performed in succession. In the first simulation, $t_1 = 1992$, $t_2 = 1991$; in the second simultion, $t_1 = 1991$, $t_2 = 1990$; . . . , and in the final simulation, $t_1 = 1851$, $t_2 = 1850$.