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# Estimating historical changes in global land cover: Croplands from 1700 to 1992

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**Abstract.** Human activities over the last three centuries have significantly transformed the Earth's environment, primarily through the conversion of natural ecosystems to agriculture. This study presents a simple approach to derive geographically explicit changes in global croplands from 1700 to 1992. By calibrating a remotely sensed land cover classification data set against cropland inventory data, we derived a global representation of permanent croplands in 1992, at 5 min spatial resolution [Ramankutty and Foley, 1998]. To reconstruct historical croplands, we first compile an extensive database of historical cropland inventory data, at the national and subnational level, from a variety of sources. Then we use our 1992 cropland data within a simple land cover change model, along with the historical inventory data, to reconstruct global 5 min resolution data on permanent cropland areas from 1992 back to 1700. The reconstructed changes in historical croplands are consistent with the history of human settlement and patterns of economic development. By overlaying our historical cropland data set over a newly derived potential vegetation data set, we analyze our results in terms of the extent to which different natural vegetation types have been converted for agriculture. We further examine the extent to which croplands have been abandoned in different parts of the world. Our data sets could be used within global climate models and global ecosystem models to understand the impacts of land cover change on climate and on the cycling of carbon and water. Such an analysis is a crucial aid to sharpen our thinking about a sustainable future.

## 1. Introduction

Humans have always depended on the terrestrial biosphere for deriving valuable resources such as food, fiber, and fresh water. However, over the last three centuries, with an exponentially rising human population and increasing per capita consumption of resources, there has been widespread modification of the Earth's biosphere and atmospheric composition. There has been increasing recognition of these changes and the consequent environmental damage, as well as of the rapid depletion of natural resources. Vast differences in resource consumption between different parts of the human population have further aggravated this situation. *Wackernagel et al.* [1997], for example, estimated that an average American today uses roughly 10.3 ha of land to produce all the resources consumed and assimilate all the generated waste, and an average Italian uses roughly 4.2 ha, while an average Indian uses only 0.8 ha and a Bangladeshi uses only 0.5 ha. Thus, in addition to population growth, differences in economic development, political structure, societal culture, and values also play a large role in consumption of natural resources.

However, while we recognize the need to minimize human impact on the environment, we also recognize the fundamental need of every individual to access the natural resources. This dilemma has led to much thought in recent decades, and the new concept of "sustainable development" points the way toward a solution. However, there is much debate and controversy from local to international levels over how sustainability can indeed be achieved. To implement this concept, one first needs to identify and quantify the stock of natural resources, and then needs to estimate how much of it has been depleted and modified over the course of human history. To make intelligent choices for the future, we need to have a better understanding of the past.

The recognition of global human impact on the environment is not a recent idea. As early as 1864, *Marsh* [1864], recognized the deleterious consequences of human activity on the Earth's landscape. More recently, *Thomas* [1956] lent further credence to the notion that one of the most obvious global changes in the last three centuries has been the direct human modification and conversion of land cover. *Turner et al.* [1990] have made an excellent attempt at documenting some of these historical changes.

Recently, efforts have been made to quantify the nature and extent of these anthropogenic changes of land cover at a global scale. The primary mode of human land use has been the conversion and modification of natural ecosystems for agriculture. Over the last three centuries, roughly 12 million km$^2$ of forests and woodlands have been cleared, grasslands and pastures have diminished by about 5.6 million km$^2$ (however, many grasslands have been converted to pastures), and cropland areas have increased by 12 million km$^2$ [*Richards*, 1990]. Currently, roughly 18 million km$^2$, an area roughly the size of South America, are in



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some form of cultivation [*Turner et al.*, 1993; *Ramankutty and Foley*, 1998]. Such large-scale changes in land cover can have important biophysical consequences and biogeochemical consequences. For instance, climate model simulations by *Dickinson and Henderson-Sellers* [1988] and *Shukla et al.* [1990] have shown that complete deforestation of the Amazon basin can lead to large changes in surface temperature, precipitation, and evapotranspiration. *Copeland et al.* [1996] and *Bonan* [1997] have shown that the replacement of natural vegetation cover over the United States by modern vegetation cover leads to large changes in regional climate. *Houghton et al.* [1983] and *Houghton and Hackler* [1995] have estimated a large release of $CO_2$ from the terrestrial biosphere due to historical land use and land cover change. *Postel et al.* [1996] and *Vitousek et al.* [1997] have published excellent reviews of the consequences of human activities for the global cycles of water and nitrogen.

Despite the recognition that large-scale changes in land use and land cover have occurred over the last few centuries and that these can have very important consequences for "environmental health" and for sustainability of natural resources, there have been few attempts to quantify these historical changes at a global scale in a spatially explicit fashion. We therefore need to develop geographically explicit data sets of historical land use and land cover change, and we further need to access the consequences of these changes on the Earth system using biophysical and biogeochemical models. This study is an attempt to make progress in this direction.

In this study, we reconstruct a spatially explicit global data set of croplands from 1992 to 1700. Our method for historical reconstruction uses a simple algorithm which links contemporary satellite data and historical cropland inventory data. We first derived a spatially explicit cropland data set for 1992 by calibrating a satellite-derived land cover classification data set against cropland inventory data for 1992 [*Ramankutty and Foley*, 1998]. We then use this data set within a simple land cover change model, along with historical cropland inventory data, to derive spatially explicit maps of historical croplands. Although the primary mode of historical land use has been conversion of natural vegetation to croplands, other forms of land use such as grazing, shifting cultivation, afforestation, urbanization, and land degradation have also been major players in the last century. These other forms of land use change can have important biophysical and biogeochemical consequences as well at the regional and global scale. Future efforts should focus on deriving historical data sets of these land use and land cover change practices.

The data set is restricted to a representation of "permanent croplands" (i.e., excluding shifting cultivation), which follows the Food and Agriculture Organization (FAO) definition of "arable lands and permanent crops." According to *Food and Agriculture Organization* [1995], "*Arable land* refers to land under temporary crops (double-cropped areas are counted only once), temporary meadows for mowing or pasture, land planted to market and kitchen gardens (including cultivation under grass), and land lying fallow or idle temporarily (less than five years).", and "*Land under permanent crops* refers to land cultivated with crops that occupy the land for long periods and need not be replanted after each harvest, such as cocoa, coffee and rubber; it includes land under shrubs, fruit-trees, nut trees and vines, but excludes land under trees grown for wood or timber."

## 2. Methods for Characterizing Modern Crop Cover

We now have the capability to observe land cover remotely from space using satellite sensors. Several satellite sensors are in operation today, collecting data at various resolutions [*Skole*, 1994]. The higher-resolution sensors such as the Landsat Thematic Mapper and Spot, with 10-30 m resolutions, have too much information to compile at a global scale. Continental to global-scale data sets are normally derived using the Advanced Very High Resolution Radiometer (AVHRR) sensor, with resolution of the order of 1-4 km. Recently, several global-scale land cover classification data sets have been derived using the AVHRR data [*Koomanoff*, 1989; *DeFries and Townshend*, 1994; *Loveland and Belward*, 1997; *DeFries et al.*, 1998; *Hansen et al.*, 1999]. However, these global data sets need to be tested more widely and calibrated against other sources of information such as ground-based data.

In a previous study, *Ramankutty and Foley* [1998] reconciled a satellite-derived land cover data set against census data. They derived a high-resolution, global crop cover map for 1992 by calibrating the cropland categories of the DISCover land cover data set (a 1 km resolution satellite-based global land cover data set [see *Loveland and Belward*, 1997] against cropland inventory data for 1992. This product is a 5 min resolution (in latitude and longitude) global data set representing the fraction of each grid cell occupied by crops in 1992 (let us denote this by $f_{CA}(i,j,1992)$ for each grid cell in location $i,j$). In this paper, we have further made some minor updates to our 1992 fractional croplands data. *Ramankutty and Foley* [1998] used adjusted FAO data from *Alexandratos* [1995] for 91 developing countries. Since the publication of that paper, we noticed that the adjustments were unreasonable for some large countries like Brazil. For instance, in 1990, the FAO data give a total cropland area in Brazil of 52 Mha (which is comparable to Brazilian census data estimates of 52 Mha in 1985 and 42 Mha in 1995-1996), while the adjusted data from *Alexandratos* [1995] gives an area of 89 Mha. This estimate from Alexandratos seems to be too high (M. Costa, personal communication, 1998). Hence we have revised our 1992 cropland inventory data to use the original FAO data, and we have also corrected some errors in the data for former Yugoslavia. We recalibrated the DISCover data against the revised cropland inventory data (Plate 1). The major difference between this new version and the version of *Ramankutty and Foley* [1998] is a decrease in crop cover in South America.

The cropland map of 1992 is consistent with our knowledge of agricultural geography. It clearly depicts those regions of the world with intense cultivation (e.g., North American corn belt, European wheat-corn belt, eastern China, Ganges floodplain, southeastern India, etc.). It also depicts those regions which are less intensely cultivated (the Pampas region of Argentina, the wheat growing regions of southern Australia, etc., as well as regions surrounding the most intensely cultivated places), including regions characterized by subsistence agriculture such as Africa.

## 3. Methods for Characterizing Natural Vegetation Cover

To increase our understanding of land use practices and to better understand the environmental consequences of cultivation, it would be useful to compare our croplands map to a global map of natural vegetation. To facilitate such an analysis, we derive a global map of natural vegetation at a 5 min resolution classified into 15 vegetation types (Plate 2). This data set is derived mainly from the DISCover land cover data set, with the regions dominated by land use filled using the vegetation data set of *Haxeltine and Prentice* [1996] (Figure 1). Thus our natural vegetation data set is consistently derived from the same source, the DISCover data, as our croplands data set.

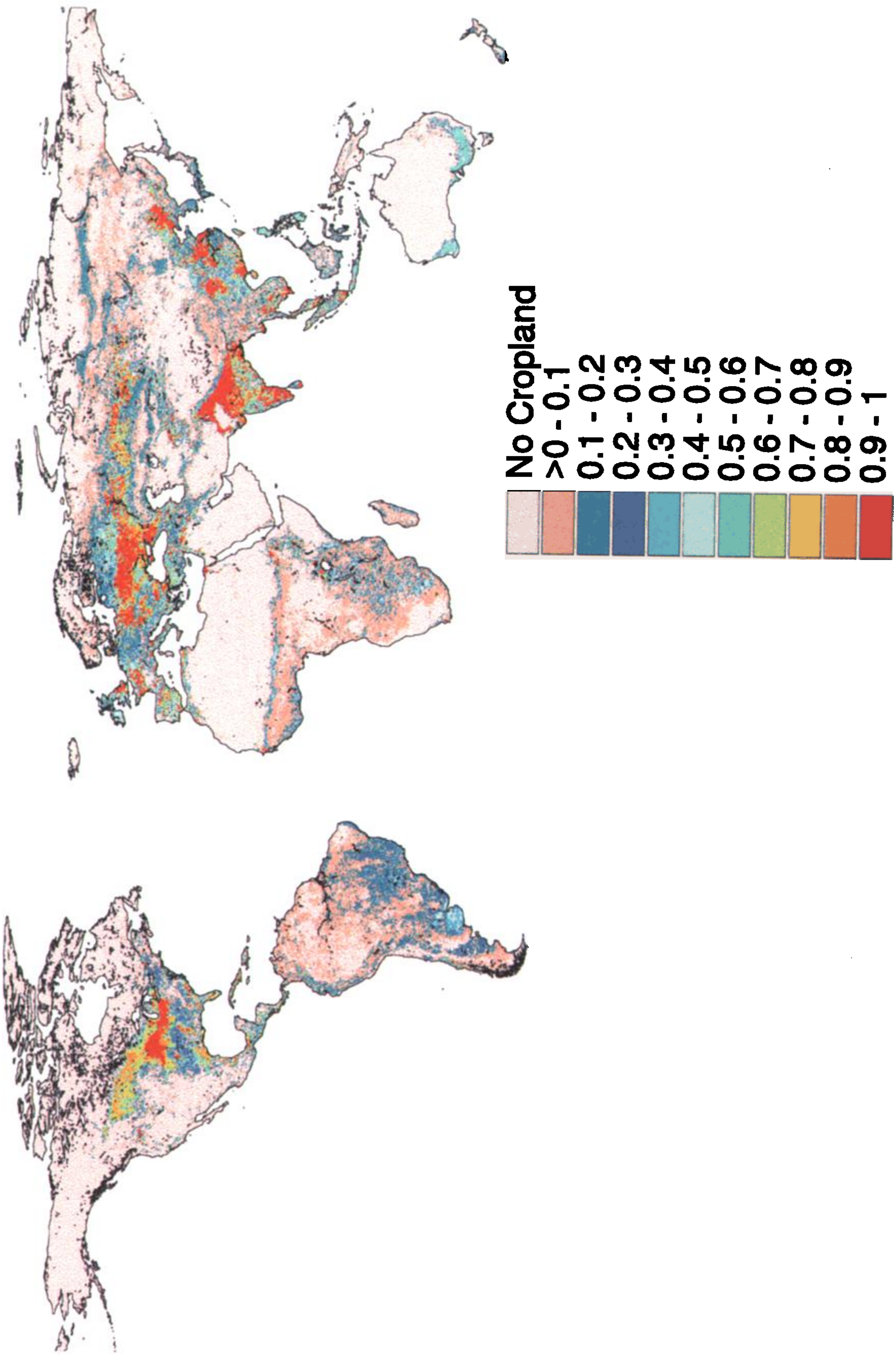



**Plate 1.** Global fractional cropland area at 5 min resolution. This is an updated version of the data set presented by *Ramankutty and Foley* [1998].


**Plate 2.** Global potential vegetation types at 5 min resolution

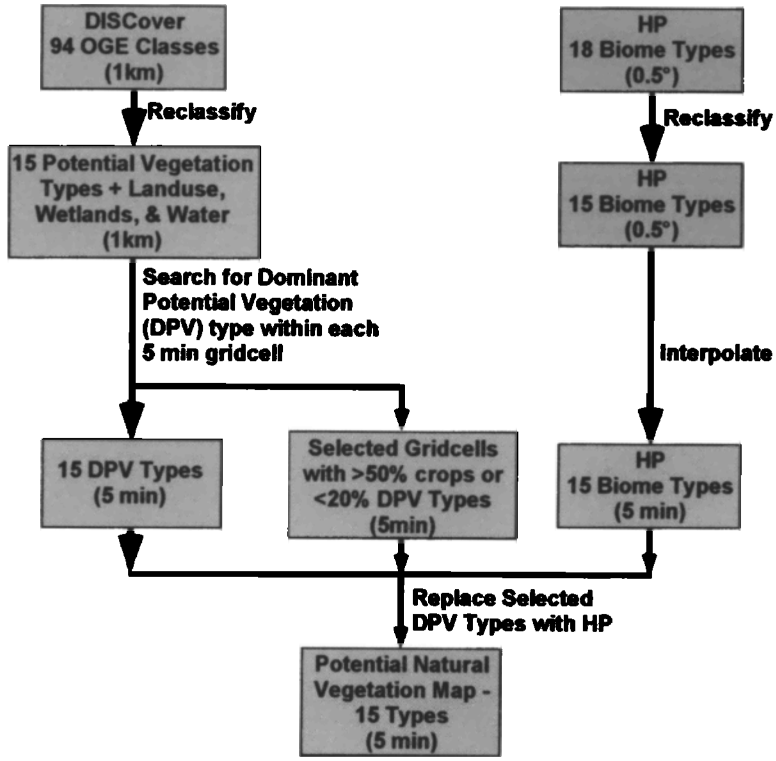



**Figure 1.** Algorithm for deriving potential natural vegetation. Within each 5 min grid cell of a global grid, we search for the dominant potential vegetation (DPV) type among each 1 km resolution vegetation type from the DISCover data set. Here we considered only upland vegetation and ignored wetlands. In those 5 min grid cells that are dominated by land use, we replace the DPV class by the potential vegetation types given by the *Haxeltine and Prentice* [1996] data set. In addition certain rules are employed during these transformations, which are described in the text.

This data set does not necessarily represent the world's natural preagricultural vegetation. Rather, it is representative of the world's "potential" vegetation (i.e., vegetation that would most likely exist now in the absence of human activities). In regions not dominated by human land use, our vegetation types are those currently observed from a satellite. This differs from presettlement natural vegetation to the extent that vegetation types have changed because of changing environmental conditions such as climate and $CO_2$ concentrations. Furthermore, human activities such as fire suppression have modified the stages of succession at which the mosaic of vegetation communities exist. In regions dominated by land use, our vegetation types are from the *Haxeltine and Prentice* [1996] data set (HP hereafter), which is based primarily on the vegetation map of *Melillo et al.* [1993], with further modifications from *Matthews* [1983], *Olson et al.* [1983], *Isachencko et al.* [1990], and *Kuchler* [1964]. The vegetation types in HP follow the *Kuchler* [1964] definition of potential natural vegetation, "the vegetation that would exist today if Man were removed from the scene and if the resulting plant succession were telescoped into a single moment." Thus the influence of disturbances are not accounted for in the HP data set.

To derive this potential vegetation data set, we use the 1 km resolution DISCover data classified under the Olson Global Ecosystems (OGE) framework [*Olson*, 1994]. Of the 94 OGE classes, 19 denote some degree of land use, and 12 denote some type of wetlands or land-water fringe. We first reclassify the 94 OGE classes into 15 potential vegetation types and 3 additional classes, land use, wetlands, and water (see Table 1). Because wetlands are still poorly characterized in the DISCover data, we decided to ignore them and consider only upland natural vegetation. Within each 5 min resolution grid cell, we search among the 1 km pixels for the dominant potential upland vegetation class (ignoring the land use, wetlands, and water classes) and assign that to be the potential vegetation for that 5 min grid cell (we also use the two classes denoting 100% water to create a land-water mask at 5 min resolution). Even in regions with substantial land use, there is often some remnant natural vegetation at 1 km resolution that helps us identify the potential vegetation type. In some grid cells, two types share the dominant potential vegetation class, or no potential vegetation class exists In such cases, we iteratively extend the search to include adjacent 1 km pixels, until we find a dominant potential vegetation class within a slightly expanded grid cell. This procedure gives us a preliminary map of the dominant potential upland vegetation at 5 min resolution. However, this preliminary data set has several problems in the regions dominated by land use; often the remnant vegetation is not representative of the potential vegetation, and furthermore, extrapolations from pixels that are far away yield wrong results. Thus we further refine this data set by using the HP data to fill in the regions dominated by land use.

To determine the grid cells that need correction, we calculate the percentage of crop cover, wetlands, water, and the dominant potential vegetation within each 5 min grid cell. We flag all the grid cells with >50% crop cover or <20% dominant potential vegetation of all upland pixels. All the flagged grid cells are then assigned the potential vegetation types from the HP data. We

**Table 1.** Deriving the Potential Vegetation Data Set

| Biome Type | DISCover-OGE Classes |
|---|---|
| 1) Tropical Evergreen Forest/Woodland | 28, 29, 33, 34 |
| 2) Tropical Deciduous Forest/Woodland | 32, 90 |
| 3) Temperate Broadleaf Evergreen Forest/Woodland[1] | 6, 79, 89[1] |
| 4) Temperate Needleleaf Evergreen Forest/Woodland[2] | 20, 22, 27, 77[2] |
| 5) Temperate Deciduous Forest/Woodland[3] | 5, 25, 26[3] |
| 6) Boreal Evergreen Forest/Woodland[2] | 3, 21, 62[2] |
| 7) Boreal Deciduous Forest/Woodland[3] | 4[3] |
| 8) Mixed Forest | 17, 18, 23, 24, 54, 60, 61, 63, 78 |
| 9) Savanna[4] | 43, 91[4] |
| 10) Grassland/Steppe[4] | 2, 7, 40, 41, 42, 87[4] |
| 11) Dense Shrubland[4] | 16, 46, 47, 48, 59, 88[4] |
| 12) Open Shrubland[4] | 11, 51, 52[4] |
| 13) Tundra | 9, 53, 64 |
| 14) Desert[5] | 8, 50, 71, 80, 81, 82, 83, 84[5] |
| 15) Polar desert/Rock/Ice | 12, 49, 69, 70, 86 |
| Land use | 1, 10, 30, 31, 35, 36, 37, 38, 39, 55, 58, 76, 92, 93, 94 |
| Wetlands | 13, 44, 45, 65, 66, 67, 68 |
| Water | 14, 15, 73, 74, 75 |

Classes ignored: 19, 56, 57, 85. The climate data are the following: (1) Absolute minimum temperature, $t_{min}$ (°C): Dataset at 0.5° resolution in latitude by longitude was provided by Pat Bartlein (persn. commn.); we interpolated these further to a 5 min resolution and (2) growing Degree Days calculated on a 5°C base, $GDD_5$ (days-°C): Calculated from the 0.5° resolution Cramer and Leemans data set of monthly averaged temperatures; and futher interpolated to a 5 min resolution. The climatic zone rules are the following: If $t_{min} > 0$°C, then zone = tropical; else if $t_{min} > -45$°C and $GDD_5 > 1200$, then zone = temperate; else zone = boreal. The override is described as follows: A few grid cells in North America, in the Ozark plateau, were changed manually from tropical deciduous to temperate deciduous forests/woodlands.

Overriding climatic rules:

[1] If biome 3 occur in the tropical zone, it is reclassified as biome 1, and if it occurs in the boreal zone, it is reclassified as biome 6.

[2] If biome 4 or 6 occurs in the tropical zone, it is reclassified as biome 1; if it occurs in the temperate zone it is reclassified as biome 4; and if it occurs in the boreal zone if is reclassified as biome 6.

[3] If biome 5 or 7 occurs in the tropical zone, it is reclassified as biome 2; if it occurs in the temperate zone, it is reclassified as biome 5, and if it occurs in the boreal zone it is reclassified as biome 7.

[4] If biome = 9, 10, 11, or 12 and $GDD_5 < 350$, then Biome = 13.

[5] If biome = 14 and $GDD_5 < 350$, then Biome = 15.

translate HP's 18 biome types easily into our 15 types prior to assigning them to the flagged grid cells. However, if both HP and DISCover identify a forest type in a flagged grid cell, the specific forest type is determined by the DISCover data because we believe that the DISCover data set identifies forest type (e.g., tropical evergreen, temperate needleleaf evergreen, etc.) more accurately than HP. In addition, some climate rules are used to classify Tundra and Polar Desert, and to separate Tropical, Temperate and Boreal Forests/Woodlands. The OGE legend identifies only tropical types and none of the other climatic zone definitions. We retain the "tropical types" in the data and separate the others based on a superimposed definition of climatic zones. Finally, an overriding correction is applied to reassign some tropical deciduous forest pixels in the Ozark plateau of North America to temperate deciduous forests/woodlands.

There are several limitations to this approach of deriving potential vegetation. First, it is likely that human activities have significantly modified (without completely converting) vegetation cover (e.g., degradation of woodlands and savannas in Africa). Hence, the dominant potential vegetation in a grid cell, as identified by the satellite data, is not necessarily the natural vegetation. Second, of course, the source satellite data itself may have problems in distinguishing between different vegetation types, which will need to be addressed as part of the validation of the DISCover data set. Furthermore, we need to include the caveat that we have used the HP data set to fill in the regions dominated by land use. The use of a different potential vegetation data set might affect our results. Despite these limitations, the DISCover data set, filled with the HP data set in regions dominated by land use, gives us a reasonable, high-resolution characterization of contemporary potential vegetation, which is also consistent with the source of our croplands data set.

## 4. Methods for Reconstructing Historical Crop Cover

With the advent of remote sensing, it is now possible to monitor the changes in land cover consistently from space. However, remotely sensed data is available only for the last two decades and is therefore not very useful to study changes in land cover on very long timescales. Therefore we have to rely on alternative sources of historical information such as socioeconomic data collected by census organizations at the level of political units (e.g., states, provinces, etc.). However, to understand the influence of land use and land cover change on the terrestrial biosphere, we need geographically explicit data in order to account for the heterogeneity in climate, soils, vegetation cover, and croplands within political units. Hence we need to develop a method to "pixelize" the socioeconomic data.

Several studies in the past have attempted to reconstruct spatially explicit historical changes in land use and land cover. *Esser et al.* [1994], for example, used the *Olson et al.* [1983] global land cover data to represent crop cover in 1980. Then they used an estimate of clearing probabilities to allocate land in each grid cell, until the total crop area for the country matched country-

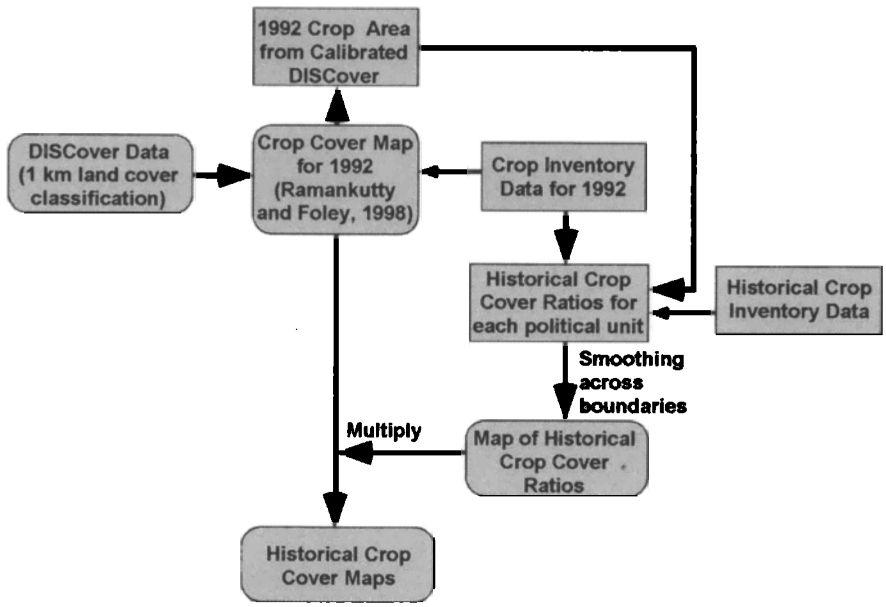



**Figure 2.** Algorithm for reconstructing historical crop cover maps. Boxes with sharp corners indicate data at the level of political units, while boxes with rounded corners indicate spatially explicit maps. A crop cover map for 1992 is first derived by calibrating the DISCover data set against crop inventory data for 1992 [*Ramankutty and 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 and smoothed across the boundaries of political units. The resulting map is multiplied by the crop cover map for 1992 to derive historical crop cover maps.

level estimates from a historical cropland inventory data set. Another land cover change model, by *Zuidema et al.* [1994], allocates new agricultural land adjacent to existing agricultural land, the adjacent lands with highest potential crop productivity are allocated first. *Klein Goldewijk and Battjes* [1995] also used the *Olson et al.* [1983] data to represent contemporary crop cover; then, within each country, they distributed historical country-level cropland estimates on the basis of population density. *Hall et al.* [1995], in their elaborate land cover change model called GEOMOD, used several land-use rules to characterize the process of land conversion. GEOMOD also used a map of relative crop suitability to guide the land allocation process. *Veldkamp and Fresco* [1995] also developed an elaborate land cover change model, Conversion of Land Use and its Effects (CLUE), which is similar to the GEOMOD model; however, CLUE has been calibrated over and applied to Costa Rica and China alone and has not been extended to other regions.

All the aforementioned studies are characterized by at least one of four major limitations:

1 They all use a Boolean representation of croplands (each grid cell is either completely occupied by croplands or not at all), rather than a continuous representation allowing croplands to occupy a certain fraction of each grid cell. Simulations of carbon or water balance using a Boolean representation of croplands will experience abrupt shifts when a grid cell comes into or leaves cultivation.

2 They are initialized using an inadequate representation of contemporary crop cover. The global data sets of *Esser et al.* [1994] and *Klein Goldewijk and Battjes* [1995] have used the *Olson et al.* [1983] database, which has spatially inconsistent sources of data and is not well tied to a particular year.

3 The assumptions made in the more complex models such as GEOMOD are poorly validated In the absence of information, it seems inappropriate to use anything more than the simplest possible assumptions.

4. None of the studies have attempted to extensively compile historical agricultural inventory data at the national and subnational level. Although there is little documentary evidence on historical land cover change, we believe that it is prudent to utilize whatever data is available to the fullest possible extent rather than simply rely on model assumptions.

In this study, we present a simple approach to estimate historical crop cover change that overcomes the above limitations We first obtained a reasonable characterization of global croplands for 1992 as described in section 2. Then, we compile an extensive database of historical croplands at the national and subnational (state, province, etc.) level (henceforth referred to as "political unit" level) (see appendix A). The data is collected for 339 countries at the national level and for 8 countries at the subnational level, consistent with present-day political boundaries The 1992 croplands data set is then used as an initial condition for a simple land cover change model, which runs backward in time-generating historical land cover maps, using the historical crop inventory data as a constraint for each political unit (Figure 2). In other words, the land cover change model is merely a simple algorithm for spatially distributing the historical cropland inventory data within each political unit.

To spatially distribute the cropland inventory areas within each political unit, one could build an elaborate land use and land cover change model. Such a model would necessarily have to be empirical (like GEOMOD or CLUE) because our current understanding of the dynamics of land use and land cover change on a global scale does not permit us to build a model based on first principles. For instance, one could construct a map of land suitability for growing crops using climate information (e g , length of the growing season for cultivation and moisture stress),

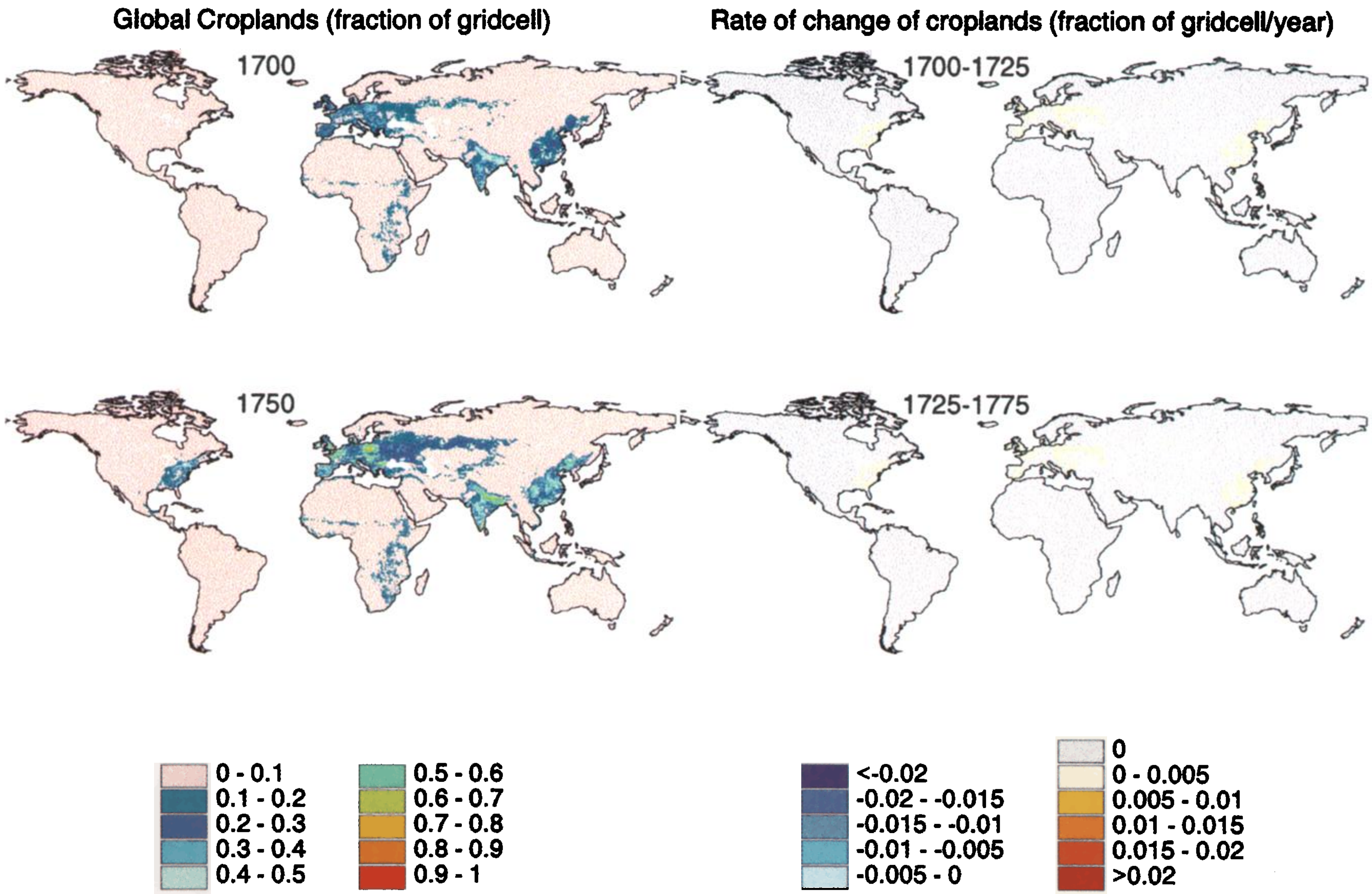



**Plate 3.** (left) Global historical cropland areas from 1700 to 1992; (right) rate of change of cropland areas calculated over various time intervals during the 1700-1992 time period. The data set is shown at 0.5° resolution. Often, the abrupt transitions seen in cropland areas are an artifact of the discontinuous color scheme used

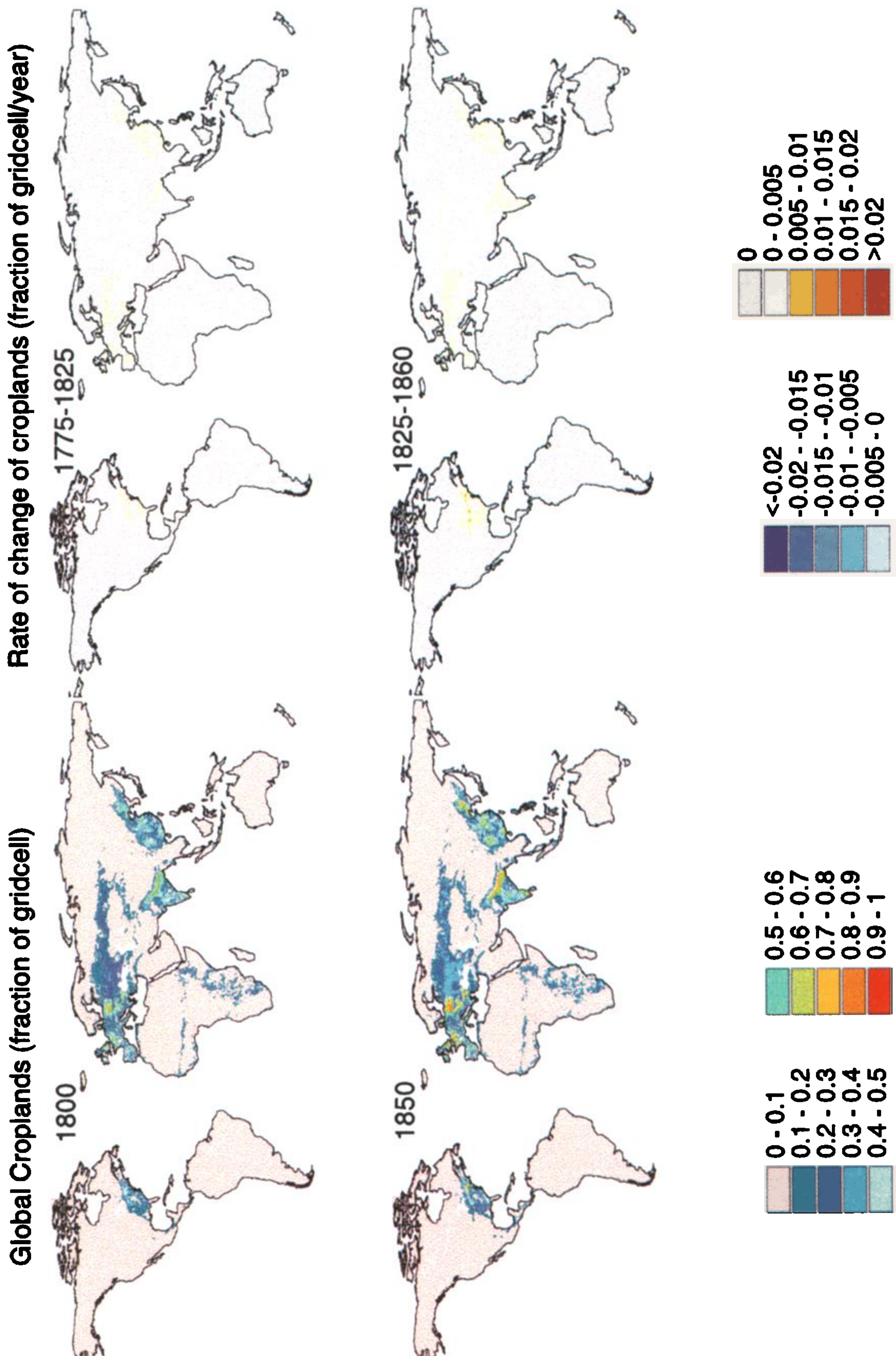
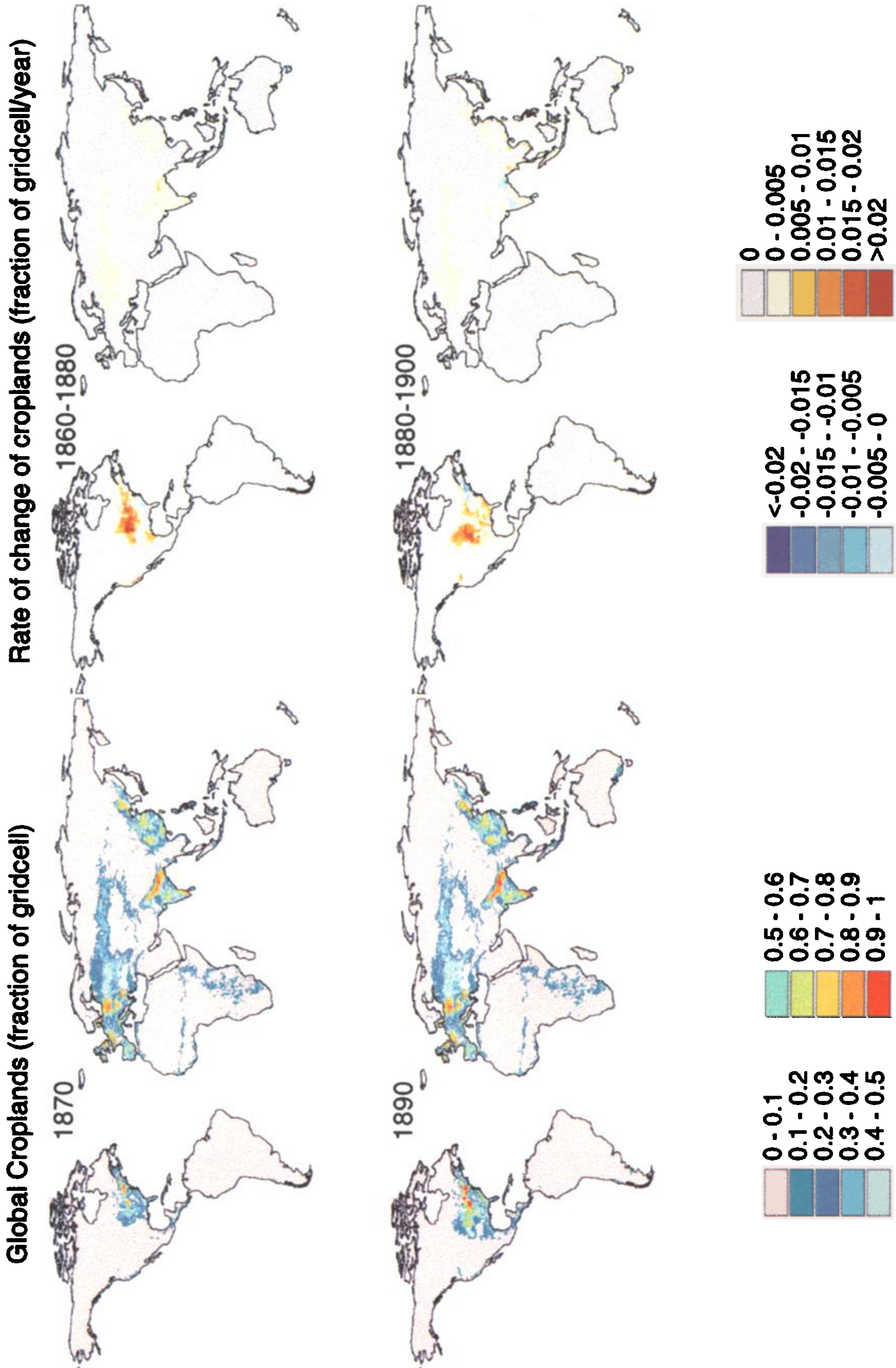



**Plate 3.** (continued)

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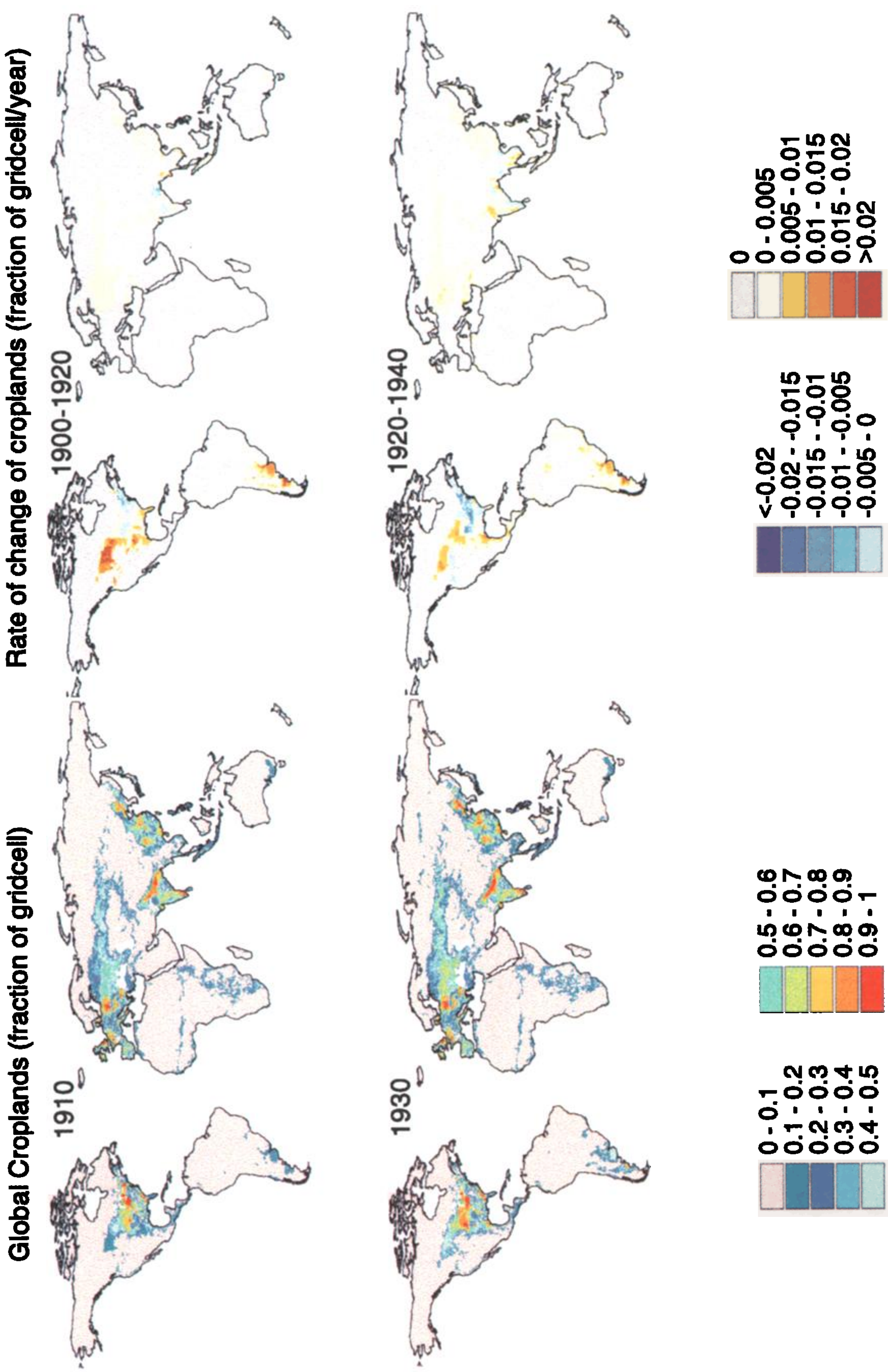


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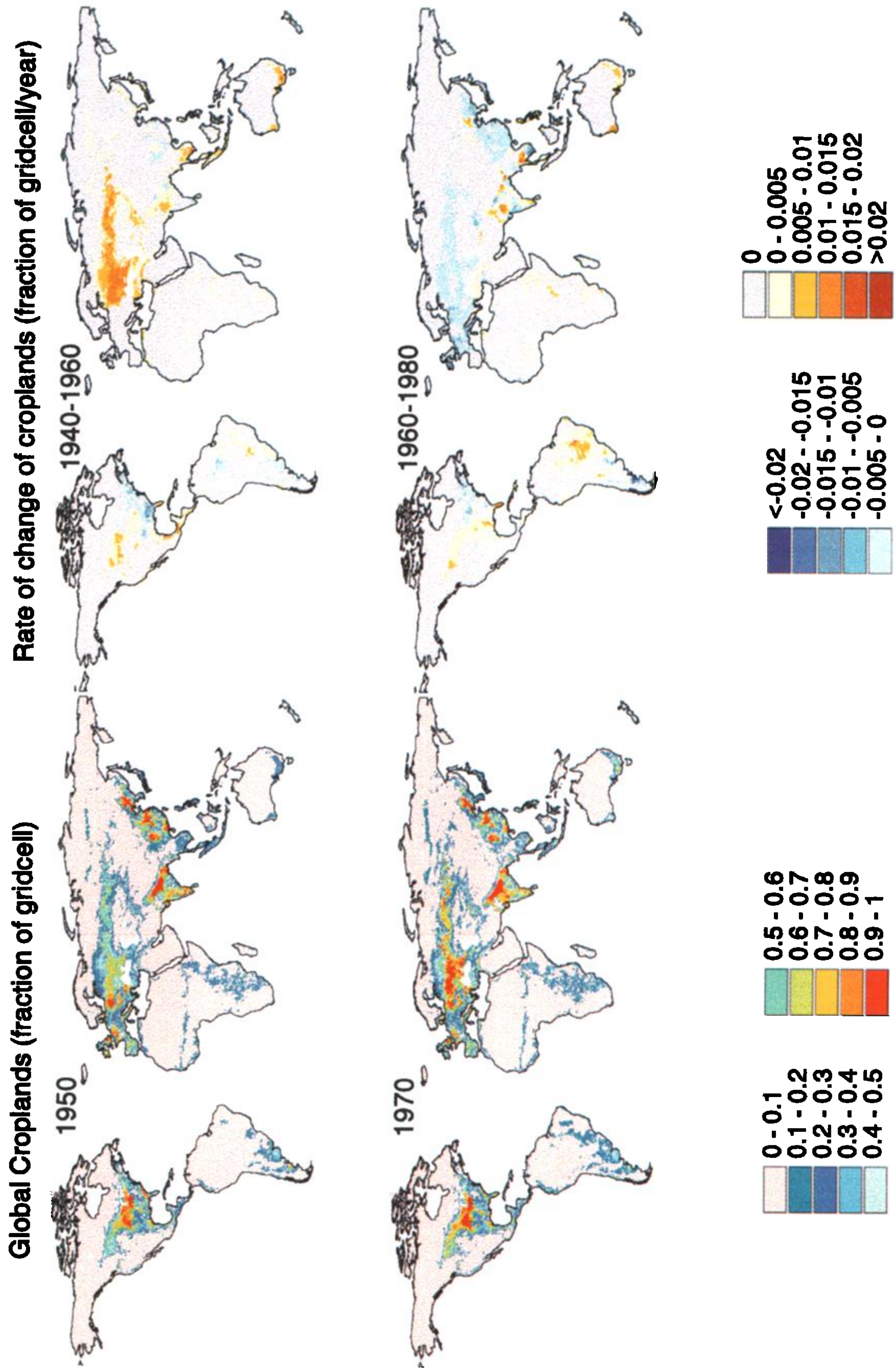


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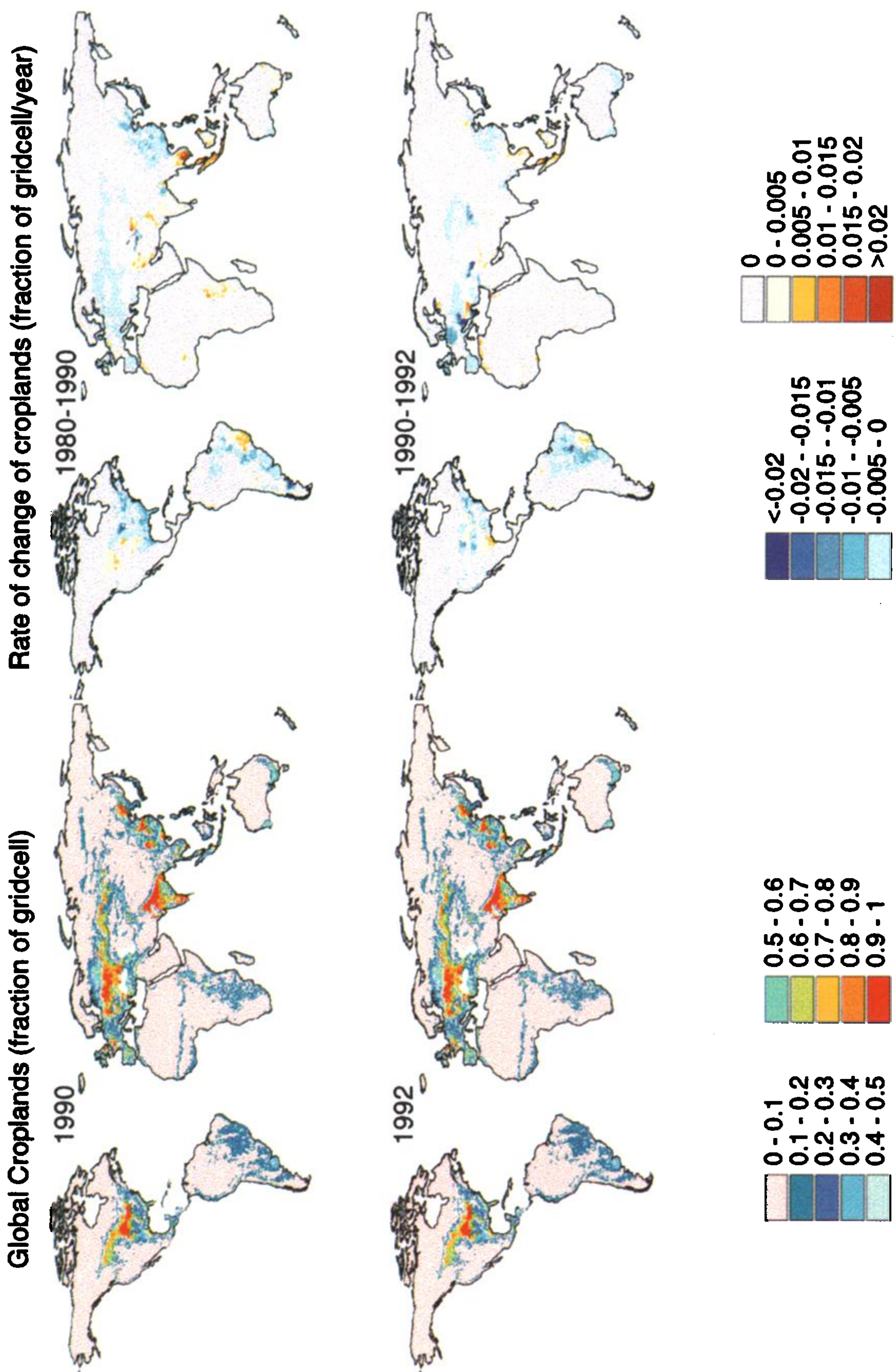


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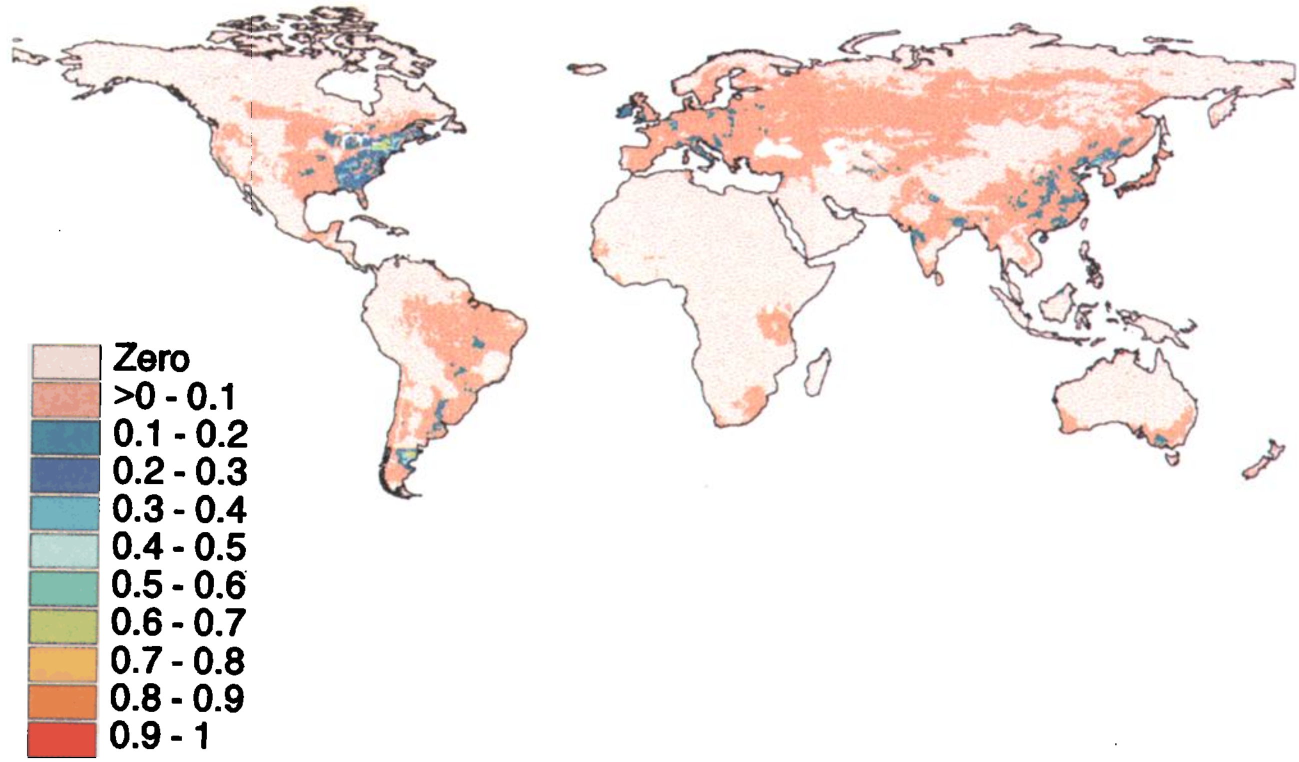


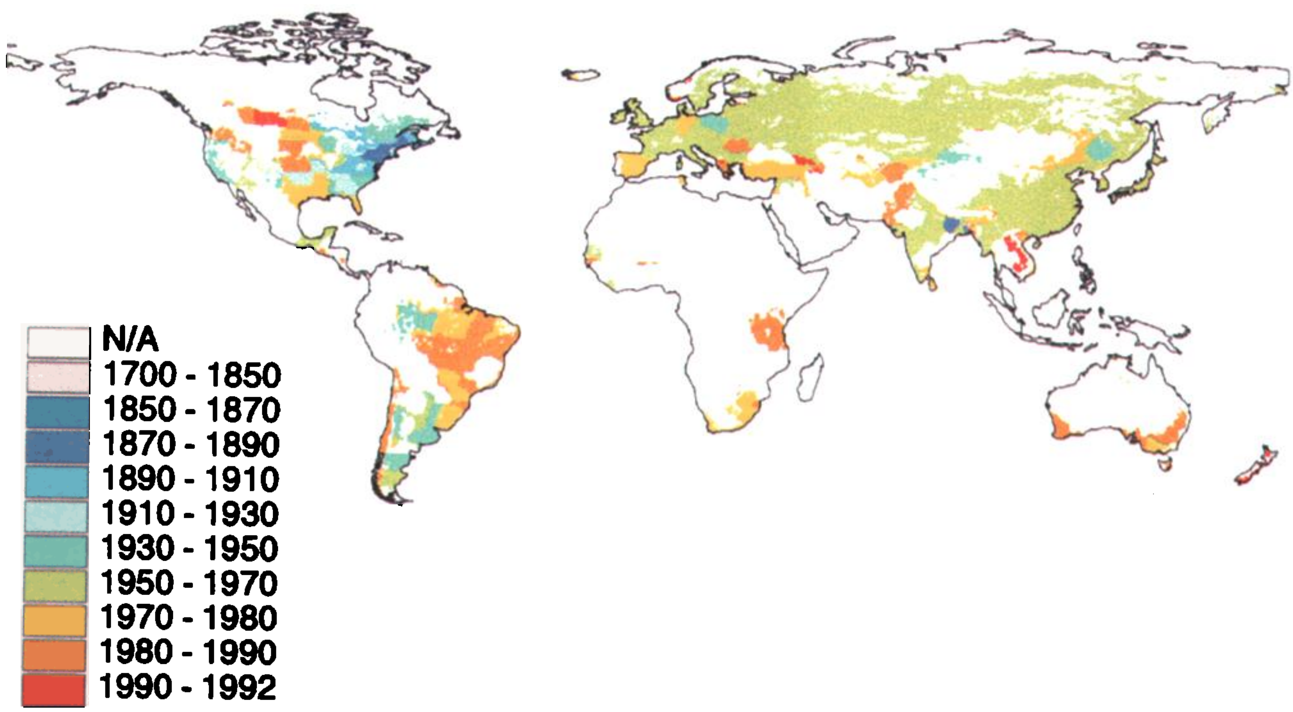


**Plate 3.** (continued)

soil information (e.g., organic content, nitrogen content, pH, and texture), and information on topography. This land suitability map could be used within the land cover change model to guide the allocation of grid cells to cropland. The influence of infrastructure could also be parameterized. However, there is insufficient data at the global scale of historical land use and land cover change to calibrate such a model, much less to validate it. Hence, in our judgment, the simplest possible approach is most appropriate (employing the principle of Occam's razor).

Our basic assumption is that within each political unit, the cropland pattern of 1992 represents the historical spatial patterns. The historical inventory data provides the temporal information needed to describe the differences in cropland area among the political units. Within each political unit, for each year in the past, we adjust the spatial crop cover pattern of 1992 so that the cropland total for that unit matches the historical inventory data (see Figure 2). This assumption will cause problems in large countries with no subnational information, but for several large countries (with the exception of the Russian Federation), we have subnational cropland inventory (see appendix A). The model simulations begin with the initial conditions for 1992 and simulate the crop cover backward in time, annually, until 1700. We have outlined this procedure in more detail in appendix B.

## 5. Expansion of Croplands: 1700-1992

We present our reconstructed historical cropland data in Plate 3 (left), for every 50 years between 1700 and 1850 and for every 20 years thereafter. We also present alongside (Plate 3, right), the rates of change of cropland areas, with the rates calculated as the slope of a linear regression through all the data points within the time interval under consideration. In addition, by superimposing our historical croplands data set over the potential vegetation data set, we have estimated the extent to which different natural vegetation types have been altered since 1700. This result is summarized in Figure 3, where we present the extent to which forests/woodlands and savannas/grasslands/steppes have changed since 1700 in 14 different regions of the world (see Figure 4 to identify the regions). Figure 3 also shows the change in cropland areas, as well as abandoned cropland areas (the latter being expressed separately as the areas abandoned in regions previously occupied by forests/woodlands and in areas previously in savannas/grasslands/steppes). Our estimates are also summarized globally in Table 2, and for the different regions of the world in Tables 3a and 3b. In the regions where croplands have been abandoned, there is a potential for regrowth that will most likely be of the vegetation type that previously occupied that region. However, a caveat to bear in mind is that abandoned cropland areas often have degraded soils that prevent regrowth or are reclaimed for other purposes such as urbanization.

The general pattern of global crop cover change reflects the history of human civilizations as well as the patterns of economic development and European settlement [*Richards*, 1990; *Grigg*, 1974; *Robertson*, 1956]. Europe and south and Southeast Asia (especially India and China) have had a long history of agricultural practice and already have extensive crop cover in 1700. After 1700, the most rapid cropland expansion occurred first in Europe, one of the most economically developed regions of the world at that time, followed by the newly developed regions of North America and the former Soviet Union (FSU). China exhibited a steady rate of expansion throughout the last three centuries. Latin America, Africa, Australia, and south and Southeast Asia experienced very gradual expansion between 1700 and 1850 but have experienced exponential growth rates since then. The one exception was Argentina, where exponential growth of cropland areas occurred between 1850 and 1940 and then cropland areas stabilized. In the last 50 years or so, cropland areas in North America, Europe, and China also stabilized and even decreased in some regions. The FSU experienced a rapid cropland expansion between 1950 and 1960 with the eastward expansion into the "New Lands" area of the southern Siberian lowlands [*Grigg*, 1974; *Brensike et al.*, 1961; *Eckholm*, 1976] followed by decreasing crop cover since 1960.

Table 2 summarizes for the globe the extent to which natural vegetation has been cleared for croplands and the extent of cropland abandonment in regions previously occupied by those natural vegetation types. It is clear that forests/woodlands, savannas, and grasslands have been the most extensively cleared vegetation types. We estimate that there has been a net loss of 11.4 million $km^2$ of forests/woodlands and 6.7 million $km^2$ of savannas/grasslands/steppes. However, there has also been 1.5 million $km^2$ of cropland abandonment in previously forested areas and 0.6 million $km^2$ in areas previously occupied by savanna/grassland/steppe, all of this having occurred since 1850. Accounting for potential regrowth in the abandoned cropland areas, this estimate is similar to the 9.1 million $km^2$ net loss of forests/woodlands and 6.5 million $km^2$ net loss of savannas/grasslands estimated independently by *Matthews* [1983] and the 7.4-8 million $km^2$ net loss of forests/woodlands estimated by *Williams* [1990], since preagricultural times. Our estimate of 2.0 million $km^2$ of shrubland cleared (and 0.15 million $km^2$ cropland abandonment in shrublands), however, is larger than the 0.9 million $km^2$ estimated by *Matthews* [1983].

Since 1850, we estimate that about 6 million $km^2$ of forests/woodlands and 4.7 million $km^2$ of savannas/grasslands/steppes have been cleared. Accounting for potential regrowth in the estimated abandoned cropland areas, these are comparable to the net loss of 4.2 million $km^2$ of forests/woodlands during 1850-1978 and 4.1 million $km^2$ of net savanna/grassland loss during 1860-1978 estimated by *Williams* [1990]. The specific forest types that have been most affected are tropical evergreen and deciduous forests/woodland, temperate needleleaf evergreen forests/woodlands, and evergreen/deciduous mixed forests/woodlands.

In the following sections, we discuss in detail the crop cover changes in different parts of the world over the last three centuries. In our discussion, when we refer to intensity of crop cover, we mean the fraction of a grid cell occupied by crops, while when we refer to extent of crop cover within a region, we are talking about the spatial extent (i.e., number of grid cells within the region which have crop cover). Furthermore, when we refer to significant crop cover, we mean at least 10% crop cover in a grid cell. We should also note that apparent changes in extent seen in Plate 3 when cropland areas drop below 10% is often simply an artifact of the categorical nature of the color scheme.

### 5.1. North America

In North America there were no significant permanent croplands in 1700. To our knowledge, there is no estimate of the extent to which the Native Americans cultivated land. However, prior to 1700, there was no large-scale cultivation of the type practiced today. In 1750 we see some crop cover in the eastern portions of the continent. The cropland change rates show the gradual clearing that occurred there between 1700 and 1825, resulting in extensive croplands in eastern North America by 1850. Almost all of this cropland came at the expense of forests/woodlands (Figure 3). The conversion rates during 1825-1860 show that clearing was starting to move westward. The Midwestern United States experienced high clearing rates during

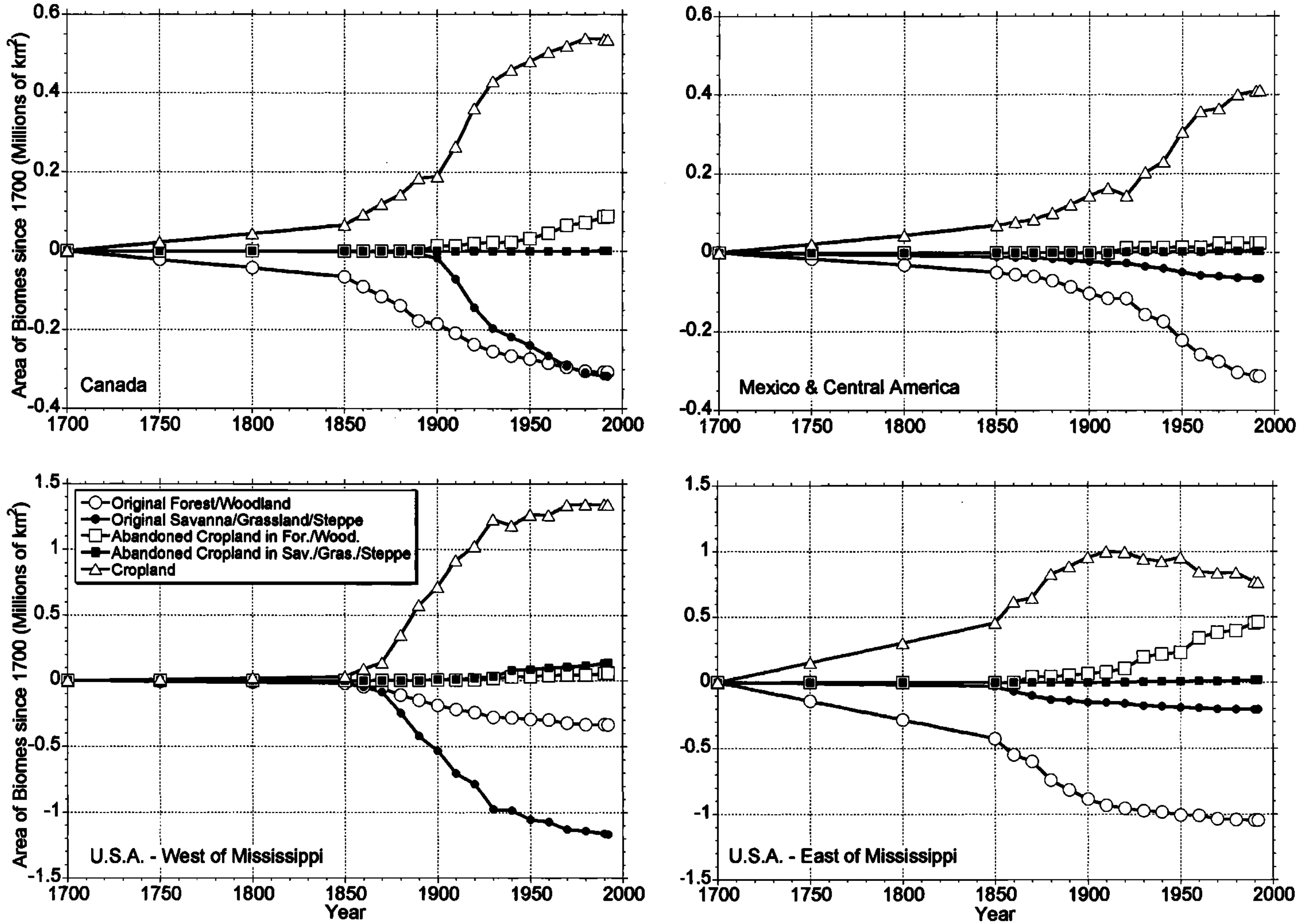


**Figure 3.** Estimated historical changes in natural vegetation extent due to clearing for croplands, in 14 different regions of the world. The chosen regions are depicted here. We present the changes in area of forests/woodlands, savannas/grasslands/steppes, and croplands relative to 1700. The areas of abandoned croplands are expressed separately as the areas previously occupied by forests/woodlands or by savannas/grasslands/steppes. The changes are shown every 50 years between 1700 and 1850 and every decade afterward.

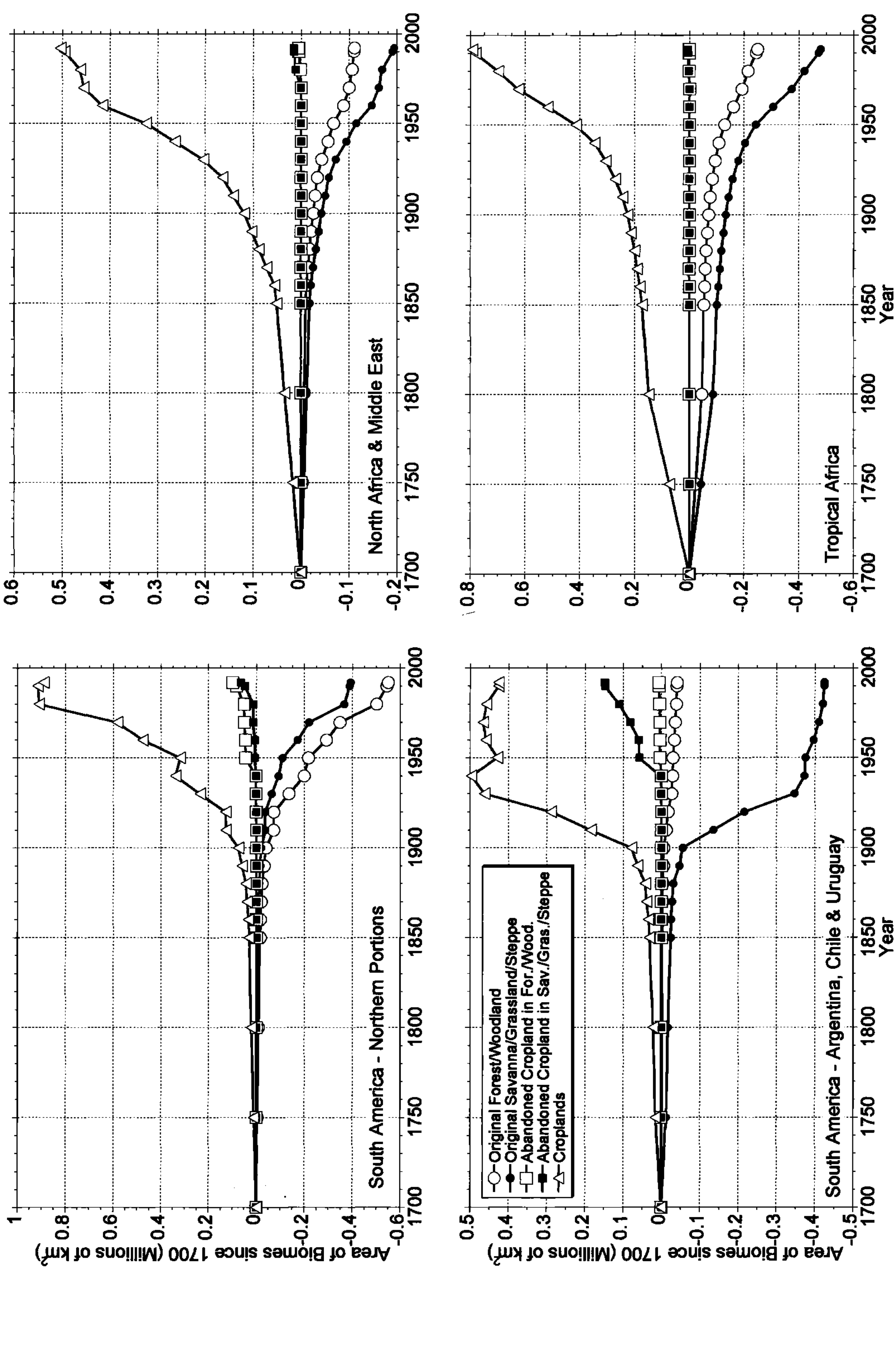


Figure 3. (continued)

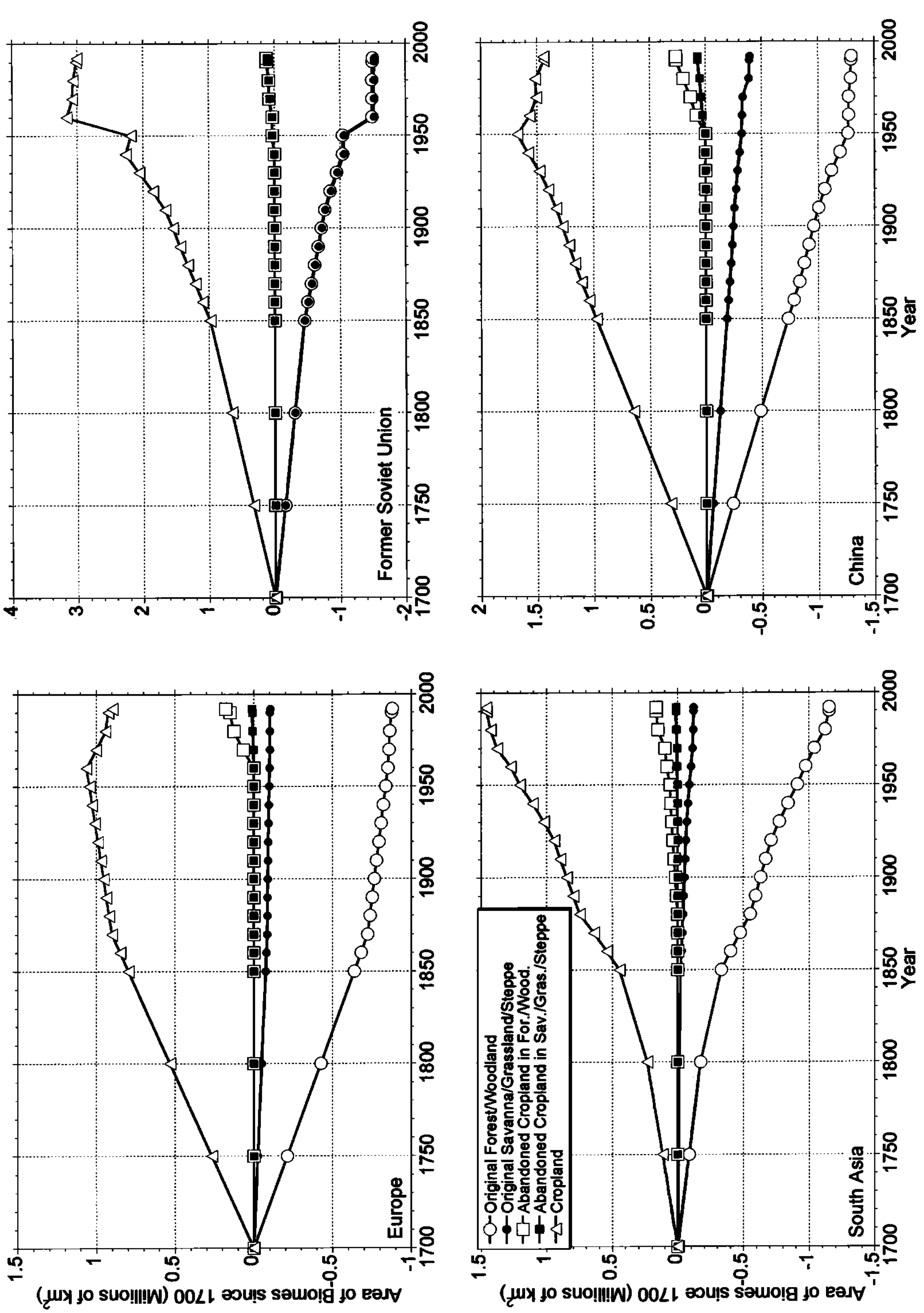


**Figure 3.** (continued)

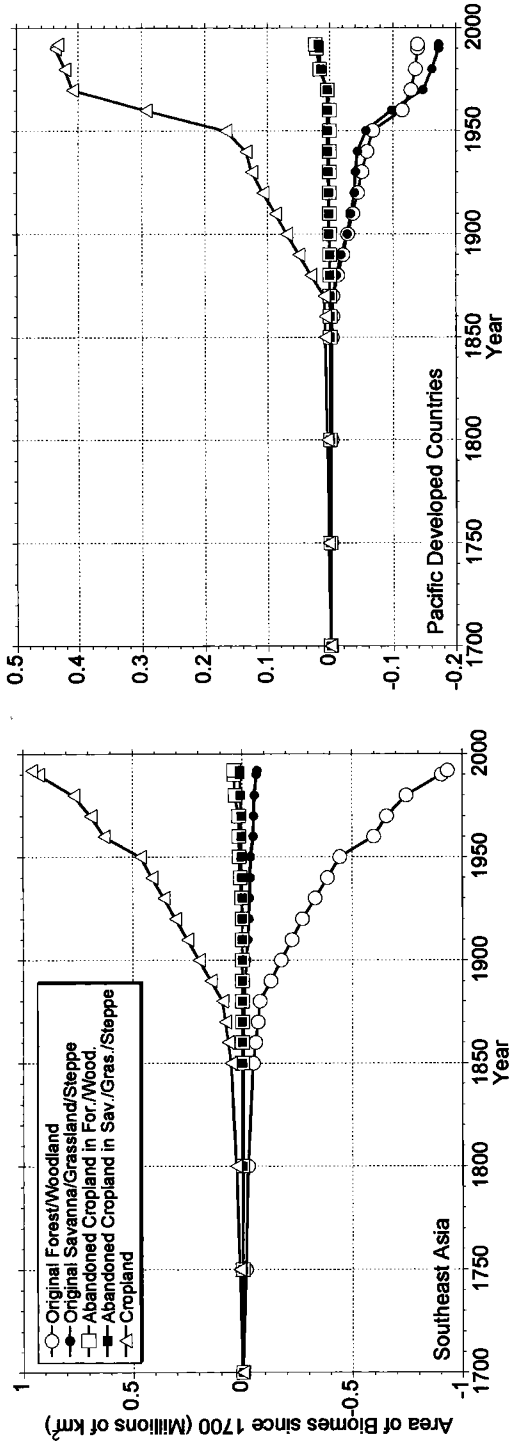


**Figure 3.** (continued)

1860-1880, which extended further west into the Great Plains region during 1880-1900.

A trace of cropland abandonment occurred in the southeastern United States during 1860-1880, followed by higher rates of abandonment in the New England region during 1880-1900. Figure 3 shows both the increased clearing of savannas/grasslands/steppes west of the Mississippi river, and the cropland abandonment after 1900 in previously forested regions of the eastern United States. During 1900-1920, we observe high clearing rates in the prairie provinces of Canada and also more extensive cropland abandonment extending all the way from New England and the mid-Atlantic states to the Midwestern United States. The cropland map of 1910 shows croplands extending into the prairie provinces of Canada and further west into the Great Plains region.

After 1930, cropland areas began to stabilize over North America as a whole, and the lower clearing rates of 1920-1940 suggest this. However, cropland abandonment became more extensive in the eastern parts of North America, extending northward into Canada (in the previously forested regions) and southward into the Virginias and Kentucky (regions previously in savannas/grasslands/steppes). A careful examination of the cropland maps of 1930 and 1950 (Figure 3) reveals the slow down of clearing in the Midwestern United States and prairie provinces of Canada and decreasing crop cover in eastern North America. Between 1950 and 1992, we continue to see the slow down of cropland conversion in the Midwestern United States, in the Great Plains region, and in Canada; during this period, we also see cropland abandonment in eastern North America.

In this section, we omitted any discussion of the patterns of crop cover change in Mexico and Central America. This is because our simulation fails to adequately characterize the changes in crop cover in Mexico, primarily because of the poor characterization of Mexican crop cover in 1992. In Central America, we do not have country-level historical inventory data prior to 1961. Hence, although we might capture the overall trend in cultivation over Central America, we have limited confidence in our simulated spatial patterns.

## 5.2. South America

Until 1850, our results show no significant permanent croplands in South America, except in a small portion of Chile. Again, we are considering only large-scale permanent croplands and not accounting for the cultivation practices of the indigenous peoples. No significant crop cover is seen anywhere else until 1890, when croplands appeared in southern Uruguay and the state of Chubut in Patagonia. However, we believe that the appearance of crop cover in Chubut in 1890 is an artifact of our algorithm. Our map of croplands in 1992 overestimates croplands in Patagonia; because crop cover did not change much in this region (although being very small in reality compared to the neighboring regions), the "hindcast" simulation led to a significant amount of crop cover in 1890 and subsequent periods.

In 1910, we see the appearance of croplands in the Pampa region of Argentina, situated in the province of Buenos Aires, and we also see the corresponding high clearing rates during the 1900-1920 period. During 1920-1940, we see clearing in the western portions of Argentina and continued high clearing rates in the Pampa. By 1930, croplands appeared in the western provinces of Argentina, and there was intensive crop cover in the Pampa. Much of this crop cover expansion came at the expense of savannas/grasslands/steppes (Figure 3). After 1930, crop cover in the Pampa regions stabilized and even decreased, and potentially, savanna/grassland/steppe type of vegetation could have regrown there (Figure 3).

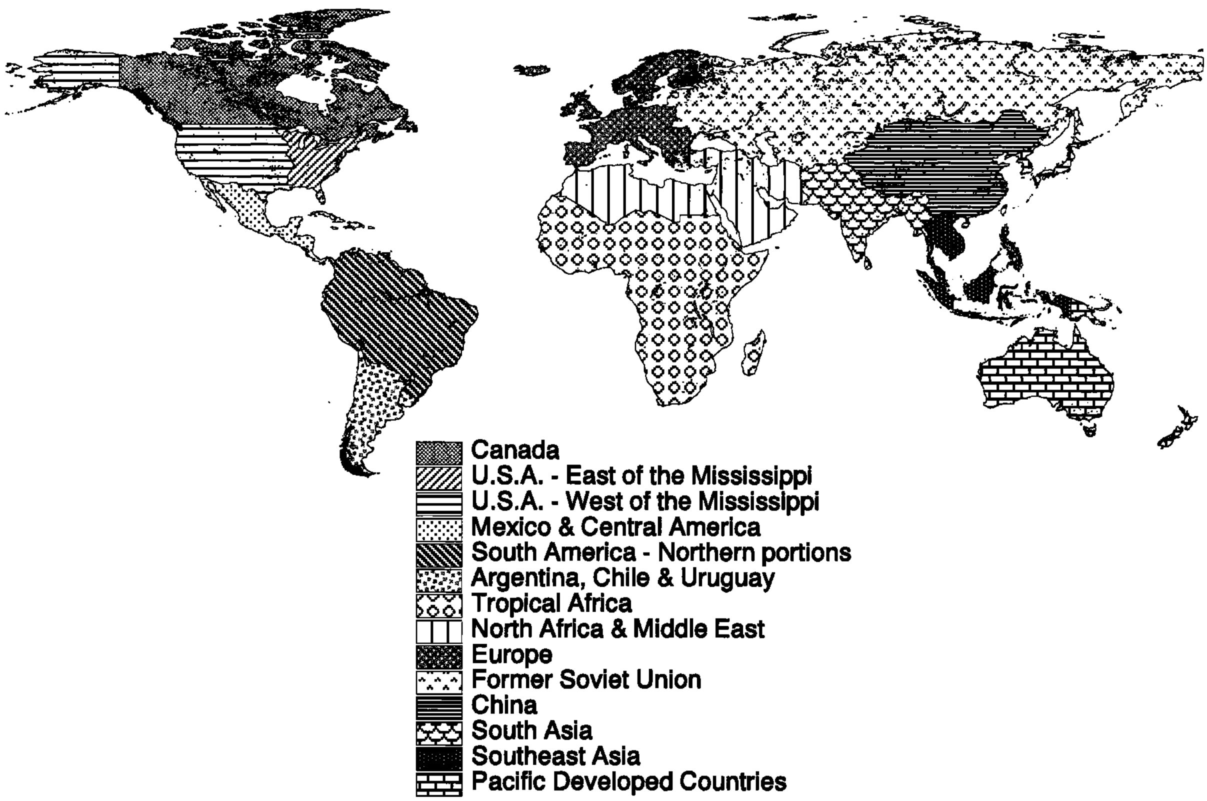


**Figure 4.** Map showing the regions of the world chosen to present the analysis depicted in Figure 3. These regions are based on the 10 regions of *Houghton et al.* [1983], with North America and Latin America split further into 3 separate regions. The assumption is that these regions are typified by homogeneous modes of behavior within each region (or lack subregional cropland inventory data), and different modes of behavior between the regions.

We also see a trace of crop cover in southeast Brazil and in the mountains of Ecuador and Colombia in 1910. Crop cover was also more extensive in Chile by 1910. Crop cover in these regions became more extensive over the period 1910-1950, with about two-thirds of it coming at the expense of forests/woodlands, and one-third coming from savannas/grasslands/steppes (Figure 3). In 1950, we see a trace of crop cover in northeast Brazil, in the state of Piauí. By 1970, crop cover in eastern Brazil extended along the Tocantins and Paranaiba rivers, and by 1990, it spread further east, extending along the São Francisco river. We see the associated high-clearing rates in eastern Brazil during 1960-1980. During 1980-1990 and 1990-1992, there was extensive cropland abandonment everywhere in South America, with the exception of southeast Brazil.

### 5.3. Africa

The evolution of crop cover in Africa between 1700 and 1992 can simply be characterized as increasing intensification of croplands with very little extensification; that is, very few new regions came into cultivation over this time period. So we will briefly summarize the spatial patterns of crop cover in 1992; much of the same pattern holds over the 1700-1992 period. In 1992, the highest intensity of crop cover was found in Uganda north of Lake Victoria, the Nile floodplain, the Mahgreb, eastern Sudan, and Ethiopia east of the Blue Nile. Crop cover also extended east of Lake Victoria in Kenya and southward along Lake Tanganyika in Tanzania and Lake Nyasa in Malawi. It extended farther south into Zambia, Zimbabwe, and northeast South Africa. In addition, crop cover was also found in an east-west strip in the Sahel.

Most of the crop cover in Africa is of very low intensity, which is reflective of the extensive subsistence agriculture practiced in that continent. If we compare the 1700 map of crop cover with that of 1992, we find that crop cover in 1700 was situated in almost the same regions as in 1992 but to a lesser extent in southern Africa, especially in Zambia and Zimbabwe. Figure 3 shows that almost two-thirds of this crop cover came from savannas/grasslands/steppes, while one-third came from forests/woodlands. We also see from Figure 3 that while cropland change was gradual between 1700 and 1850, the growth rates have been exponential since then. One caveat is that our data for Africa is limited to the FAO estimates after 1961 and the estimates of *Houghton and Hackler* [1995] prior to that. Thus our data set could easily be missing shifts in crop cover within Africa.

### 5.4. Europe and the Former Soviet Union

In Eurasia, our data set is limited by the lack of subnational data for the FSU and the lack of good national data for most of the other countries; this caveat needs to be kept in mind while analyzing our results. In Europe and parts of the FSU, there was widespread crop cover in 1700, reflective of the very long history of cultivation. Between 1700 and 1850, our cropland maps and the clearing rates show a gradual intensification of crop cover in Europe and in the western portions of the FSU. In 1850, the most

**Table 2.** Estimated Global Extent of Vegetation Types (in $10^6$ $km^2$) Altered Due to Clearing for Croplands.

| | Potential Vegetation | Actual Vegetation | | | Abandoned Cropland | | |
|---|---|---|---|---|---|---|---|
| | | 1700 | 1850 | 1992 | 1700 | 1850 | 1992 |
| Total Forest/Woodland | 55.27 | 52.77 | 49.92 | 43.92 | 0.00 | 0.00 | 1.54 |
| Tropical Evergreen Forest/Woodland | 16.75 | 16.37 | 16.17 | 14.68 | 0.00 | 0.00 | 0.17 |
| Tropical Deciduous Forest/Woodland | 5.84 | 5.13 | 4.81 | 3.69 | 0.00 | 0.00 | 0.16 |
| Temperate Broadleaf Evergreen Forest/Woodland | 1.13 | 0.98 | 0.78 | 0.57 | 0.00 | 0.00 | 0.05 |
| Temperate Deciduous Forest/Woodland | 3.61 | 3.42 | 3.02 | 2.23 | 0.00 | 0.00 | 0.23 |
| Temperate Needleleaf Evergreen Forest/Woodland | 4.83 | 4.24 | 3.23 | 2.26 | 0.00 | 0.00 | 0.55 |
| Boreal Evergreen Forest/Woodland | 5.97 | 5.93 | 5.87 | 5.72 | 0.00 | 0.00 | 0.02 |
| Boreal Deciduous Forest/Woodland | 2.21 | 2.19 | 2.14 | 2.06 | 0.00 | 0.00 | 0.01 |
| Evergreen/Deciduous Mixed Forest/Woodland | 14.94 | 14.52 | 13.89 | 12.71 | 0.00 | 0.00 | 0.33 |
| Total Savanna/Grassland/Steppe | 33.36 | 32.32 | 31.36 | 26.67 | 0.00 | 0.00 | 0.64 |
| Savanna | 19.12 | 18.40 | 17.90 | 15.66 | 0.00 | 0.00 | 0.27 |
| Grassland/Steppe | 14.24 | 13.92 | 13.46 | 11.01 | 0.00 | 0.00 | 0.37 |
| Total Shrubland | 17.88 | 17.43 | 17.13 | 15.93 | 0.00 | 0.00 | 0.15 |
| Dense Shrubland | 5.97 | 5.70 | 5.51 | 4.77 | 0.00 | 0.00 | 0.09 |
| Open Shrubland | 11.90 | 11.72 | 11.62 | 11.16 | 0.00 | 0.00 | 0.06 |
| Total Tundra/Desert/Polar Desert | 23.57 | 23.52 | 23.47 | 23.31 | 0.00 | 0.00 | 0.03 |
| Tundra | 7.04 | 7.01 | 6.96 | 6.89 | 0.00 | 0.00 | 0.02 |
| Desert | 15.30 | 15.27 | 15.26 | 15.19 | 0.00 | 0.00 | 0.01 |
| Polar Desert/Rock/Ice | 1.24 | 1.24 | 1.24 | 1.24 | 0.00 | 0.00 | 0.00 |
| Global | 130.08 | 126.04 | 121.87 | 109.83 | 0.00 | 0.00 | 2.35 |

**Table 3a.** Estimated Area of Forests/Woodlands, Savannas/Grasslands/Steppes, and Abandoned Croplands From 1700 to 1990.

| Regions | Vegetation Type | 1700 | 1750 | 1800 | 1850 | 1860 | 1870 | 1880 | 1890 | 1900 | 1910 | 1920 | 1930 | 1940 | 1950 | 1960 | 1970 | 1980 | 1990 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Canada | Forest/Woodland | 6.24 | 6.22 | 6.20 | 6.17 | 6.15 | 6.12 | 6.10 | 6.06 | 6.06 | 6.03 | 6.00 | 5.98 | 5.97 | 5.97 | 5.96 | 5.94 | 5.94 | 5.93 |
| | Savanna/Gras./Step. | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.45 | 0.45 | 0.45 | 0.44 | 0.39 | 0.31 | 0.26 | 0.24 | 0.22 | 0.19 | 0.17 | 0.15 | 0.14 |
| | Aband.-For./Wood. | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.02 | 0.02 | 0.02 | 0.03 | 0.05 | 0.07 | 0.07 | 0.09 |
| | Aband.-Sava./Gr./St. | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | Cropland | 0.00 | 0.03 | 0.05 | 0.07 | 0.10 | 0.12 | 0.15 | 0.19 | 0.19 | 0.27 | 0.37 | 0.43 | 0.46 | 0.48 | 0.51 | 0.52 | 0.54 | 0.54 |
| United States East of Mississippi | Forest/Woodland | 1.96 | 1.82 | 1.67 | 1.53 | 1.41 | 1.36 | 1.22 | 1.15 | 1.08 | 1.03 | 1.01 | 0.99 | 0.98 | 0.95 | 0.95 | 0.92 | 0.92 | 0.92 |
| | Savanna/Gras./Step. | 0.24 | 0.23 | 0.22 | 0.21 | 0.17 | 0.14 | 0.11 | 0.10 | 0.09 | 0.09 | 0.08 | 0.06 | 0.06 | 0.05 | 0.05 | 0.04 | 0.04 | 0.04 |
| | Aband.-For./Wood. | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.04 | 0.05 | 0.06 | 0.07 | 0.08 | 0.11 | 0.20 | 0.22 | 0.23 | 0.34 | 0.38 | 0.39 | 0.46 |
| | Aband.-Sava./Gr./St. | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 |
| | Cropland | 0.02 | 0.18 | 0.33 | 0.48 | 0.64 | 0.67 | 0.85 | 0.91 | 0.98 | 1.03 | 1.02 | 0.97 | 0.96 | 0.98 | 0.87 | 0.86 | 0.86 | 0.80 |
| United States West of Mississippi | F Forest/Woodland | 2.51 | 2.51 | 2.50 | 2.49 | 2.47 | 2.46 | 2.40 | 2.36 | 2.33 | 2.29 | 2.27 | 2.23 | 2.23 | 2.22 | 2.21 | 2.19 | 2.18 | 2.18 |
| | Savanna/Gras./Step. | 2.58 | 2.57 | 2.57 | 2.56 | 2.53 | 2.49 | 2.33 | 2.15 | 2.04 | 1.87 | 1.79 | 1.60 | 1.59 | 1.52 | 1.50 | 1.45 | 1.44 | 1.41 |
| | Aband.-For./Wood. | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.02 | 0.03 | 0.03 | 0.04 | 0.04 | 0.05 | 0.06 |
| | Aband.-Sava./Gr./St. | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.02 | 0.04 | 0.08 | 0.09 | 0.10 | 0.11 | 0.12 | 0.13 |
| | Cropland | 0.00 | 0.01 | 0.02 | 0.03 | 0.09 | 0.14 | 0.36 | 0.58 | 0.72 | 0.93 | 1.03 | 1.23 | 1.19 | 1.27 | 1.27 | 1.34 | 1.35 | 1.34 |
| Mexico and Central America | Forest/Woodland | 1.37 | 1.35 | 1.34 | 1.32 | 1.31 | 1.31 | 1.30 | 1.28 | 1.27 | 1.25 | 1.25 | 1.21 | 1.20 | 1.15 | 1.11 | 1.09 | 1.06 | 1.06 |
| | Savanna/Gras./Step. | 0.52 | 0.52 | 0.51 | 0.51 | 0.51 | 0.51 | 0.50 | 0.50 | 0.50 | 0.49 | 0.49 | 0.48 | 0.48 | 0.47 | 0.46 | 0.46 | 0.45 | 0.45 |
| | Aband.-For./Wood. | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.03 |
| | Aband.-Sava./Gr./St. | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 |
| | Cropland | 0.04 | 0.06 | 0.09 | 0.11 | 0.12 | 0.13 | 0.14 | 0.16 | 0.19 | 0.21 | 0.19 | 0.25 | 0.27 | 0.35 | 0.40 | 0.41 | 0.44 | 0.45 |
| South America Northern Portions | Forest/Woodland | 9.10 | 9.10 | 9.09 | 9.08 | 9.08 | 9.08 | 9.08 | 9.07 | 9.06 | 9.03 | 9.03 | 8.96 | 8.90 | 8.88 | 8.81 | 8.75 | 8.60 | 8.56 |
| | Savanna/Gras./Step. | 3.32 | 3.31 | 3.31 | 3.31 | 3.31 | 3.31 | 3.30 | 3.30 | 3.29 | 3.28 | 3.28 | 3.25 | 3.22 | 3.21 | 3.14 | 3.10 | 2.95 | 2.93 |
| | Aband.-For./Wood. | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.05 | 0.05 | 0.05 | 0.05 | 0.08 |
| | Aband.-Sava./Gr./St. | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.05 |
| | Cropland | 0.02 | 0.03 | 0.04 | 0.05 | 0.05 | 0.06 | 0.06 | 0.08 | 0.09 | 0.14 | 0.15 | 0.25 | 0.36 | 0.34 | 0.49 | 0.60 | 0.93 | 0.93 |
| Argentina Uruguay and Chile | Forest/Woodland | 0.53 | 0.53 | 0.53 | 0.53 | 0.53 | 0.53 | 0.53 | 0.53 | 0.53 | 0.52 | 0.52 | 0.51 | 0.50 | 0.50 | 0.50 | 0.50 | 0.49 | 0.49 |
| | Savanna/Gras./Step. | 1.93 | 1.91 | 1.91 | 1.90 | 1.90 | 1.90 | 1.90 | 1.88 | 1.87 | 1.79 | 1.71 | 1.58 | 1.55 | 1.55 | 1.53 | 1.52 | 1.51 | 1.50 |
| | Aband.-For./Wood. | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 |
| | Aband.-Sava./Gr./St. | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.06 | 0.06 | 0.08 | 0.11 | 0.15 |
| | Cropland | 0.02 | 0.03 | 0.04 | 0.05 | 0.05 | 0.05 | 0.06 | 0.08 | 0.09 | 0.20 | 0.30 | 0.48 | 0.51 | 0.44 | 0.47 | 0.48 | 0.47 | 0.44 |
| Tropical Africa | Forest/Woodland | 5.39 | 5.37 | 5.34 | 5.34 | 5.33 | 5.33 | 5.33 | 5.32 | 5.32 | 5.31 | 5.31 | 5.30 | 5.28 | 5.26 | 5.23 | 5.20 | 5.18 | 5.15 |
| | Savanna/Gras./Step. | 10.85 | 10.80 | 10.76 | 10.75 | 10.74 | 10.74 | 10.73 | 10.72 | 10.71 | 10.70 | 10.69 | 10.67 | 10.64 | 10.60 | 10.54 | 10.47 | 10.43 | 10.38 |
| | Aband.-For./Wood. | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | Aband.-Sava./Gr./St. | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 |
| | Cropland | 0.74 | 0.82 | 0.89 | 0.92 | 0.92 | 0.93 | 0.94 | 0.96 | 0.97 | 0.99 | 1.01 | 1.05 | 1.09 | 1.16 | 1.26 | 1.37 | 1.44 | 1.52 |

The abandoned cropland areas in this table are expressed as the areas previously occupied by forest/woodland (Aband.-For./Wood.), and by savanna/grassland/steppe (Aband.-Sava./Gr./St.). They are given in $10^6$ km$^2$.

**Table 3b.** Estimated Area of Forests/Woodlands, Savannas/Grasslands/Steppes, and Abandoned Croplands From 1700 to 1990.

| Regions | Vegetation Type | 1700 | 1750 | 1800 | 1850 | 1860 | 1870 | 1880 | 1890 | 1900 | 1910 | 1920 | 1930 | 1940 | 1950 | 1960 | 1970 | 1980 | 1990 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| North Africa and Middle East | Forest/Woodland | 0.27 | 0.27 | 0.26 | 0.26 | 0.26 | 0.26 | 0.25 | 0.25 | 0.25 | 0.24 | 0.24 | 0.23 | 0.21 | 0.20 | 0.18 | 0.17 | 0.16 | 0.16 |
| | Savanna/Gras./Step. | 0.79 | 0.79 | 0.78 | 0.77 | 0.77 | 0.77 | 0.76 | 0.76 | 0.75 | 0.74 | 0.73 | 0.72 | 0.70 | 0.68 | 0.64 | 0.63 | 0.62 | 0.60 |
| | Aband.-For./Wood. | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 |
| | Aband.-Sava./Gr./St. | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 |
| | Cropland | 0.15 | 0.17 | 0.19 | 0.20 | 0.21 | 0.22 | 0.24 | 0.26 | 0.27 | 0.29 | 0.31 | 0.36 | 0.42 | 0.48 | 0.57 | 0.61 | 0.61 | 0.65 |
| Europe | Forest/Woodland | 3.20 | 2.99 | 2.77 | 2.56 | 2.52 | 2.48 | 2.46 | 2.45 | 2.43 | 2.42 | 2.40 | 2.39 | 2.38 | 2.36 | 2.35 | 2.34 | 2.34 | 2.33 |
| | Savanna/Gras./Step. | 0.29 | 0.26 | 0.24 | 0.21 | 0.21 | 0.20 | 0.20 | 0.20 | 0.20 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 | 0.18 | 0.18 | 0.18 |
| | Aband.-For./Wood. | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.07 | 0.12 | 0.15 |
| | Aband.-Sava./Gr./St. | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 |
| | Cropland | 0.73 | 0.99 | 1.26 | 1.52 | 1.57 | 1.63 | 1.65 | 1.66 | 1.68 | 1.70 | 1.72 | 1.73 | 1.75 | 1.77 | 1.79 | 1.73 | 1.67 | 1.65 |
| Former Soviet Union | Forest/Woodland | 12.28 | 12.13 | 11.98 | 11.82 | 11.77 | 11.72 | 11.67 | 11.62 | 11.57 | 11.51 | 11.43 | 11.33 | 11.24 | 11.24 | 10.79 | 10.79 | 10.79 | 10.79 |
| | Savanna/Gras./Step. | 4.72 | 4.56 | 4.41 | 4.26 | 4.20 | 4.15 | 4.10 | 4.04 | 3.99 | 3.94 | 3.85 | 3.75 | 3.65 | 3.65 | 3.19 | 3.19 | 3.19 | 3.18 |
| | Aband.-For./Wood. | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.03 | 0.03 | 0.08 | 0.09 | 0.12 |
| | Aband.-Sava./Gr./St. | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.03 | 0.03 | 0.07 | 0.08 | 0.10 |
| | Cropland | 0.53 | 0.86 | 1.19 | 1.51 | 1.63 | 1.74 | 1.85 | 1.97 | 2.08 | 2.19 | 2.38 | 2.59 | 2.79 | 2.72 | 3.69 | 3.61 | 3.60 | 3.54 |
| China | Forest/Woodland | 2.96 | 2.72 | 2.48 | 2.23 | 2.18 | 2.13 | 2.08 | 2.04 | 2.00 | 1.96 | 1.90 | 1.84 | 1.77 | 1.69 | 1.69 | 1.69 | 1.67 | 1.67 |
| | Savanna/Gras./Step. | 2.58 | 2.51 | 2.45 | 2.39 | 2.37 | 2.36 | 2.35 | 2.34 | 2.33 | 2.32 | 2.31 | 2.29 | 2.27 | 2.25 | 2.25 | 2.25 | 2.19 | 2.18 |
| | Aband.-For./Wood. | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.08 | 0.13 | 0.20 | 0.26 |
| | Aband.-Sava./Gr./St. | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.02 | 0.04 | 0.05 | 0.07 |
| | Cropland | 0.66 | 0.97 | 1.30 | 1.63 | 1.70 | 1.76 | 1.82 | 1.88 | 1.93 | 1.99 | 2.06 | 2.14 | 2.24 | 2.33 | 2.22 | 2.16 | 2.17 | 2.09 |
| South Asia | Forest/Woodland | 2.32 | 2.24 | 2.15 | 1.99 | 1.92 | 1.85 | 1.77 | 1.73 | 1.69 | 1.65 | 1.61 | 1.55 | 1.48 | 1.41 | 1.35 | 1.28 | 1.20 | 1.17 |
| | Savanna/Gras./Step. | 0.58 | 0.57 | 0.56 | 0.55 | 0.55 | 0.54 | 0.54 | 0.53 | 0.53 | 0.52 | 0.51 | 0.51 | 0.50 | 0.49 | 0.47 | 0.46 | 0.46 | 0.45 |
| | Aband.-For./Wood. | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.02 | 0.03 | 0.04 | 0.05 | 0.06 | 0.06 | 0.08 | 0.10 | 0.15 | 0.16 |
| | Aband.-Sava./Gr./St. | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 |
| | Cropland | 0.96 | 1.07 | 1.19 | 1.40 | 1.50 | 1.59 | 1.70 | 1.75 | 1.80 | 1.85 | 1.90 | 1.98 | 2.06 | 2.16 | 2.23 | 2.33 | 2.38 | 2.41 |
| Southeast Asia | Forest/Woodland | 3.32 | 3.31 | 3.30 | 3.28 | 3.27 | 3.26 | 3.24 | 3.20 | 3.15 | 3.10 | 3.05 | 2.99 | 2.94 | 2.88 | 2.73 | 2.67 | 2.58 | 2.42 |
| | Savanna/Gras./Step. | 0.26 | 0.26 | 0.26 | 0.25 | 0.25 | 0.25 | 0.25 | 0.24 | 0.24 | 0.23 | 0.23 | 0.23 | 0.22 | 0.22 | 0.21 | 0.21 | 0.20 | 0.19 |
| | Aband.-For./Wood. | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.02 | 0.02 | 0.03 | 0.04 |
| | Aband.-Sava./Gr./St. | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| | Cropland | 0.11 | 0.13 | 0.14 | 0.17 | 0.18 | 0.19 | 0.20 | 0.26 | 0.31 | 0.36 | 0.42 | 0.47 | 0.52 | 0.58 | 0.74 | 0.80 | 0.88 | 1.04 |
| Pacific Developed Countries | Forest/Woodland | 1.31 | 1.30 | 1.30 | 1.30 | 1.30 | 1.30 | 1.29 | 1.29 | 1.28 | 1.27 | 1.26 | 1.25 | 1.25 | 1.24 | 1.19 | 1.18 | 1.17 | 1.17 |
| | Savanna/Gras./Step. | 3.23 | 3.23 | 3.23 | 3.23 | 3.23 | 3.23 | 3.22 | 3.22 | 3.21 | 3.20 | 3.20 | 3.19 | 3.19 | 3.18 | 3.14 | 3.09 | 3.07 | 3.06 |
| | Aband.-For./Wood. | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.02 | 0.02 |
| | Aband.-Sava./Gr./St. | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.02 |
| | Cropland | 0.06 | 0.06 | 0.07 | 0.07 | 0.07 | 0.07 | 0.09 | 0.11 | 0.13 | 0.15 | 0.17 | 0.19 | 0.19 | 0.23 | 0.35 | 0.47 | 0.48 | 0.50 |
| Globe | Forest/Woodland | 52.77 | 51.85 | 50.92 | 49.92 | 49.51 | 49.18 | 48.73 | 48.34 | 47.99 | 47.62 | 47.28 | 46.77 | 46.33 | 45.96 | 45.04 | 44.72 | 44.27 | 43.97 |
| | Savanna/Gras./Step. | 32.32 | 31.99 | 31.66 | 31.36 | 31.20 | 31.04 | 30.74 | 30.44 | 30.19 | 29.76 | 29.38 | 28.79 | 28.52 | 28.28 | 27.51 | 27.21 | 26.88 | 26.71 |
| | Aband.-For./Wood. | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.05 | 0.05 | 0.07 | 0.11 | 0.13 | 0.19 | 0.30 | 0.35 | 0.47 | 0.71 | 0.97 | 1.21 | 1.47 |
| | Aband.-Sava./Gr./St. | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.02 | 0.02 | 0.03 | 0.05 | 0.11 | 0.21 | 0.26 | 0.34 | 0.45 | 0.60 |
| | Cropland | 4.05 | 5.41 | 6.78 | 8.21 | 8.82 | 9.31 | 10.11 | 10.83 | 11.44 | 12.29 | 13.01 | 14.10 | 14.81 | 15.28 | 16.88 | 17.30 | 17.83 | 17.92 |

The abandoned cropland areas in this table are expressed as the areas previously occupied by forest/woodland (Aband.-For./Wood.), and by savanna/grassland/steppe (Aband.-Sava./Gr./St.). They are given in $10^6$ km$^2$.

intensive croplands were located in southeast England, in the Flanders region and Paris basin of northern France; the beginnings of a wheat-corn belt can also be seen in Poland, the Morava valley, and the Hungarian plains. Agriculture stretched farther east from the intensely cultivated portions of the wheat-corn belt into the Ukraine and Belorussia, to the central Russian uplands, the Volga uplands, and northern Caucausus and Georgia and extended as an east-west strip along the northern border of Kazakhstan into Siberia. The representation of agriculture so far east in the FSU in 1850 is an artifact of the absence of subnational data for the Russian Federation in our data set, which led to maintenance of the cropland pattern of 1992 back into the past

Between 1850 and 1960, the general pattern is of a gradual intensification of croplands in the agricultural regions mentioned above. However, while the rate of change increased in the FSU, cropland expansion slowed down in Europe (Plate 1 shows a negligible rate of change of croplands in Europe after 1860). Indeed, by 1970, we find an intensely cultivated wheat corn belt in the FSU stretching east and southeast from the Ukraine into the Russian Federation. During 1940-1960, we see high-clearing rates in the FSU, associated with the opening up of the "New Lands." In fact, we can see this as a sharp increase in cropland area between 1950 and 1960 in Figure 3.

During 1960-1980, and thereafter, we see negative rates of change of cropland areas in both Europe and the FSU (also seen as abandoned cropland in Figure 3). In Europe, cropland expanded mostly at the expense of forests/woodlands, while in the FSU, both forests/woodlands and savannas/grasslands/steppes were cleared by an equal amount (Figure 3).

### 5.5. The Middle East

Very little of the land in the Middle East is suitable for cultivation. In 1700, we see a thin strip of low-intensity croplands in the Fertile Crescent region extending from the Mediterranean Sea to the Persian Gulf through the Tigris and Euphrates valley. There was also some low-intensity croplands in northwest Turkey in the Anatolian plateau. The pattern of crop cover change over 1700-1850 was one of gradual intensification over these regions. After 1850, the crop cover change became more rapid. We see a gradual spread of croplands into eastern Turkey and into Georgia, Armenia, and Azerbaijan. We also see the southeastern tip of croplands in the Fertile Crescent region extending farther south into Iran during this period. There was also crop cover intensification over the 1850-1992 time period. Roughly two-thirds of the crop cover came at the expense of savannas/grasslands/steppes, and one-third came from the forests/woodlands (Figure 3).

### 5.6. East Asia

There was widespread crop cover in 1700 in China, reflective of its long history of civilization. China experienced a steady growth of croplands over the last three centuries, mostly at the expense of forests/woodlands (Figure 3). The cropland change rates between 1700 and 1940 show a gradual clearing over most of east China but particularly in the Manchurian plain, the Yangtze delta, Szechwan basin, and Si delta. Indeed, by 1930, we see that these four regions had intense crop cover and were surrounded by less intense cultivation. We see a trace of cropland in Japan in 1910 and no croplands in the Koreas. During 1940-1960, we see some clearing in South Korea and Japan, and the resultant crop cover is seen in the 1950 map. During 1940-1960, we see some negative clearing rates in China, signifying the start of cropland abandonment around 1950 (Figure 3). During 1960-1980, and in the subsequent time periods, cropland abandonment was widespread in China, mainly in previously forested regions (Figure 3). Between 1950 and 1992, the crop cover in the Koreas and Japan became more extensive, covering almost all of Japan and both South and North Korea by 1992. However, the intensity of cropland in the Koreas and Japan was still only 20-30% by 1992.

### 5.7. South Asia and Southeast Asia

The Indian subcontinent is another region with a long history of cultivation, and we can see widespread crop cover in 1700. Between 1700 and 1850, South Asia experienced a very gradual increase in crop cover, while Southeast Asia experienced almost no increase in crop cover (Figure 3). We see some clearing in the Ganges flood plain during 1775-1825 and more widespread clearing all over India during 1825-1860. Our cropland maps from 1700 to 1870 show a gradual intensification of crop cover in the Indian subcontinent. By 1870, the Ganges flood plain, the Ganges-Brahmaputra delta, and the coastal regions of the southeast India were cultivated quite intensely. Lower-intensity croplands are seen all over India, in the Indus flood plain in Pakistan, the Irrawaddy basin in Burma, in Sri Lanka, Vietnam, in southern Sumatra, and in the Philippines. Almost all of this crop cover came at the expense of forests/woodlands (Figure 3).

Between 1850 and 1992, cropland expansion became more rapid in South Asia, while it increased to an exponential rate in Southeast Asia (Figure 3). During 1880-1900 and 1900-1920, we see some cropland abandonment in the states of Maharashtra and West Bengal in India, while clearing became more rapid in the Irrawaddy basin of Burma. Cropland abandonment extended into southeastern India during 1920-1940. After 1940, abandonment continued in various parts of India, while more intense clearing occurred in northwest India and in the Indus flood plain of Pakistan. After 1980, the rates of change of cropland in India became negligible.

In Thailand, Cambodia, peninsular Malaysia, Vietnam, and Sumatra widespread crop cover is seen in 1930, and we also see the associated increased clearing rates in those regions during 1920-1940. The trend in these southeast Asian regions between 1930 and 1992 was one of rapid intensification, and indeed by 1992, we see intense croplands there, and lower intensity cultivation in Borneo, Java, Celebes, and the Philippines. Almost all of the croplands in Southeast Asia came at the expense of forests/woodlands (Figure 3).

### 5.8. Australia

Until 1870, there were no significant permanent croplands in Australia. In 1870, we see the appearance of croplands in South Australia, north of Adelaide. By 1890, crop cover extended eastward into Victoria, and by 1910 crop cover extended into the southern portion of New South Wales. This is also reflected in the patterns of clearing rates. In 1930, we see some crop cover appearing in Western Australia, reflected in the clearing rates of 1900-1920 and 1920-1940. These two regions, in Western Australia and in southeast Australia define the major cultivation zones of Australia. The trend from 1930 to 1990 was a gradual intensification of crop cover in these regions, with also some increases in extent. All the crop conversion came roughly equally at the expense of forests / woodlands and savannas /grasslands/ steppes. There has been very little cropland abandonment in Australia.

## 6. Cropland Abandonment

As discussed in section 5, the developed regions of the world have seen decreasing cropland areas in recent decades. It is difficult to assess the environmental consequences of this cropland abandonment without knowing the fate of the abandoned croplands. In some regions, such as the eastern United States, there is evidence for forest regrowth [*Hart*, 1968; *Williams*, 1989], although urbanization has claimed a large portion of prime farmland as well [*Mather*, 1986]. In China, industrialization, urbanization, and land degradation have been identified as the causes of decreasing cropland areas [*Li and Sun*, 1997], and it is therefore unlikely that forests are growing back. If forests regrow in abandoned cropland areas, there is a potential for sequestering carbon and also for modification of the surface water balance. For instance, *Fan et al.* [1998] have estimated a large sink of carbon in North America, which could be partly due to regrowing forests. However, if abandoned croplands are converted to urban areas, then the consequences might be drastically different. Here we present a global estimate of the total amount of cropland area that has been abandoned until 1992.

From our historical croplands data set, we estimate for each grid cell, the difference between the maximum extent of crop cover ever attained and the crop cover in 1992 (Plate 4 (top)). Plate 4 (bottom) shows the year at which the maximum cropland extent was attained). Clearly, the largest amount of cropland abandonment occurred in eastern North America. This region also experienced the earliest abandonment, beginning in the middle to late 19th century in New England and the mid-Atlantic states; abandonment began in the early 20th century elsewhere. Widespread cropland abandonment is also seen in Eurasia, with most of it occurring during the second half of the 20th century.

In Canada, most of the abandonment has occurred in New Brunswick and in the southern portions of Ontario and Quebec. In the United States, significant cropland abandonment has occurred in New England, in the middle Atlantic States (almost 60-70% of the grid cells in New York), in the Great Lakes states of Michigan and Wisconsin, in the south central states of Kentucky and Tennessee, and in the south Atlantic states. Most of these regions were previously forested (Plate 2), and significant forest regrowth could potentially have been occurring since the turn of the century (Figure 3). Cropland abandonment has also occurred recently, but to a lesser extent, in the prairie provinces of Canada, in the Midwestern United States, and in the Great Plains region.

In South America, the significant abandonment seen in Patagonia is incorrect and is an artifact of our algorithm. Slight amounts of cropland abandonment are also seen over most of Brazil, Uruguay, Argentina, and Chile. The abandonment began around 1930-1950 in Argentina and Uruguay, and more recently elsewhere. In Africa, we see slight amounts of abandonment in Tanzania, portions of South Africa, Senegal, Liberia, Burkina Faso, northern Tunisia, and parts of Kenya. All of this occurred very recently, since 1970. In Eurasia, cropland abandonment is widespread over most of Europe, the FSU, China, South and North Korea, Japan, south Asia, and Southeast Asia. Most of the cropland abandonment in these regions began around 1960 (also see Figure 3). Slight amounts of recent cropland abandonment are also seen in the arable lands of Australia and New Zealand.

## 7. Discussion and Conclusions

We have used a simple algorithm to reconstruct geographically explicit changes in croplands from 1700 to 1992. This was an exercise in pixelizing socioeconomic data, wherein a satellite-derived spatially explicit contemporary croplands data set was used to spatially distribute historical cropland inventory data within various political units. The reconstructed changes in crop cover are in general agreement with common knowledge of the spread of agricultural land in different parts of the world. However, the data set has some obvious deficiencies. For instance, it fails to adequately characterize crop cover change in Mexico, in the Patagonia region of Argentina, and in the Former Soviet Union. These are caused by defects in the 1992 croplands data set and are due to a lack of adequate subnational historical inventory data.

We have limited confidence in our results over the period 1700-1850 and have not discussed them in much detail. For the period after 1850, we made an earnest attempt to compile historical cropland inventory data; however, for the 1700-1850 period, all our data are based on the conversion rates of *Houghton and Hackler* [1995], as described in appendix A, which often has just one value for the whole period. Future efforts should involve a more extensive compilation of historical inventory data, including subnational data for the Russian Federation and other large countries that are still not accounted for and also better data for the earlier time periods. We will continue to revise our historical croplands data set as we collect more and better quality cropland inventory data.

To our knowledge, no independent historical croplands data exist at the global scale. Hence we have no direct means to validate our product. However, good historical land cover data do exist for small regions such as Japan, the Czech Republic, and Costa Rica [T. Himiyama, I. Bicik, personal communication, 1998; *Sader and Joyce*, 1988]. However, comparison of our global-scale data set against such small regions will be an inadequate test. Our data set does not include subnational inventory data for these countries; hence a comparison will be futile. Our 1992 global cropland map can however be evaluated against other contemporary data sets. In *Ramankutty and Foley* [1998], we compared our data set with three other data sets of contemporary croplands. In the United States, our cropland distribution for 1992, as well as our conversion rates over the period 1980-1990, compare reasonably well to the maps produced by the National Resources Conservation Service of the U.S. Department of Agriculture (http://www.nhq.nrcs.usda.gov/land/index/cover_use.html). Furthermore, the DISCover land cover classification data set itself is being validated (http://keystone.geog.ucsb.edu/igbp.html).

In addition to estimating historical crop cover change, we have also derived an estimate of the changes in natural vegetation resulting from clearing for cultivation. This estimate provides a better picture of what kinds of vegetation have been cleared for cultivation and also what types of vegetation are likely to grow back after cropland abandonment (if croplands are not degraded or are not converted to urban areas, pastures, or other human uses). Our estimates show large-scale clearing of forests/woodlands and savannas/grasslands/steppes globally and also a significant abandonment of croplands (and potential regrowth of forests/woodlands) in eastern North America. An adequate representation of this clearing and regrowth process is critical for understanding the global carbon cycle [International Geosphere-Biosphere Programme (IGBP) Terrestrial Carbon Working Group, 1998]. It also has particular significance in the aftermath of the Kyoto protocol, whereby countries have the two following ways of reducing net emissions of carbon to the atmosphere: (1) by limiting fossil fuel consumption or (2) by increasing carbon sequestration in terrestrial sinks [IGBP Terrestrial Carbon Working Group, 1998]. Regrowing natural vegetation in abandoned cropland areas are potentially large sinks of carbon [*Fan et al.*, 1998].

Ultimately, to improve our understanding of human impacts on the global cycles of carbon and water, it is imperative to represent the dynamics of human activities within Earth system models. As a first step, incorporating historical land use data within global climate models will help ascertain the impact of land use on the climate system [e.g., *Bonan*, 1997; R.A. Betts, The impact of land use on the climate of present day, submitted to Research Activities in Atmospheric and Oceanic Modelling, 1998; V. Brovkin, Modelling climate response to historical land cover change, submitted to Global Ecology and Biogeography Letters, 1998]. Furthermore, anthropogenic changes in the carbon stocks of the terrestrial biosphere can be estimated by incorporating historical land use data within dynamic global biosphere models (e.g., IBIS of *Foley et al.* [1996] and HYBRID of *Friendet al.* [1997])

## Appendix A. Compilation of Historical Cropland Inventory Data

The historical cropland inventory data are obtained from a wide variety of sources, such as census data, estimates by historical geographers, etc., and are compiled into one consistent data set. The data are collected at the level of political units, consistent with present-day political boundaries. If political units split (e.g., Czechoslovakia into the Czech Republic and Slovakia), we estimate the areas for each separate unit in the past using proportions of each to the total in the nearest time period with data. We obtain data at the subnational (state, province, etc.) level for some of the largest countries: Canada, the United States of America, Mexico, Brazil, Argentina, India, China, and Australia. With the exception of the Russian Federation, we have subnational information for most of the large countries or countries with extensive croplands. The inventory data is obtained at 5-10 year intervals in the best situation and often at much wider time intervals. We linearly interpolate in between data to obtain annual values. Often the data need adjustments for consistency, and these are described in detail in sections A3-A13. For most regions of the world, the data content is poor prior to World War II. In the absence of any detailed information, we extrapolate data backward using the continental-scale cropland conversion estimates of *Houghton and Hackler* [1995] and *Richards* [1990]. While compiling data from different sources, we often find that the absolute values do not agree over the periods of overlap. To resolve this problem, we apply conversion rates rather than absolute values to match the different sources. The specifics of this process are outlined in detail below.

### A1. The Use of *Houghton and Hackler* [1995] and *Richards* [1990] Data To Extrapolate All National/Subnational Data Backward in Time When Census Data Ends

The sources are as follows: (1) *Houghton and Hackler* [1995] (HH hereafter) for the continental scale cropland conversion rates from 1700 to 1980 (1800-1980 for some regions) at varying frequency and (2) *Richards* [1990] for the continental scale cropland areas for 1700, 1850, 1920, 1950, and 1980; linearly interpolated in between to get annual values. We convert HH conversion rates to actual cropland areas, by choosing the cropland areas from Richards [1990] for 1980 and then calculating annual areas backward by applying HH conversion rates. (For Latin America, we used a cropland area of 180 million ha in 1980 (R. Houghton, personal communication, 1998) instead of the 142 million ha given by *Richards* [1990]). For south & southeast Asia, Latin America, and Tropical Africa, HH data go back to 1800 only. We extend them to 1700 by assuming a constant proportion to the cropland areas of *Richards* [1990]. Also, in the Former Soviet Union (FSU), applying HH conversion rates results in cropland areas becoming negative before 1700. Thus we use the HH conversion rates for the FSU only unto 1850 and estimate areas for 1700-1850 by assuming a constant proportion to the cropland areas of *Richards* [1990].

The above procedure gives us estimates of cropland areas from 1700 to 1980 for Tropical Africa, North Africa/Middle East, North America, Latin America, China, south and Southeast Asia, Europe, FSU, and the Pacific Developed Countries (see HH for the countries that fall within each of these regions). As we compile data back in time, whenever census data becomes unavailable for a nation (or subnational unit), we extend the data back in time by assuming a constant proportion to the continental-scale estimates described in the foregoing paragraph (using, of course, the cropland areas of the region that the nation falls into).

### A2. Special Interpolation Method: When Sub-National Information is Available at Two Different Time Periods and National Totals are Known In-Between

We often have subnational census data for two different census years. If national totals are unknown inbetween the two census years, then a simply linear interpolation of the subnational data can be used. However, if additionally, national totals are available inbetween, then a slightly different method needs to be chosen to incorporate the additional information.

Let $A(\mathbf{x},t_1)$ be the subnational data ($\mathbf{x}$ is the political subunit vector) for a country at time $t_1$, let $A(\mathbf{x},t_2)$ be the subnational data at time $t_2$, and let $\hat{A}(t)$, $t = t_1,\ldots, t_2$ be the national total between time $t_1$ and $t_2$. First the proportions of the subnational data to the national totals are calculated in the census years, i.e., $p_A(\mathbf{x},t_1) = A(\mathbf{x},t_1)/\hat{A}(t_1)$, and $p_A(\mathbf{x},t_2) = A(\mathbf{x},t_2)/\hat{A}(t_2)$. Then the proportions are linearly interpolated inbetween to get subnational proportions; that is, $p_A(\mathbf{x},t)$, $t = t_1,\ldots, t_2$ is calculated. These subnational proportions are then applied to the national totals to obtain the subnational data, i.e., $A(\mathbf{x},t) = p_A(\mathbf{x},t)\, \hat{A}(t)$, $t = t_1,\ldots, t_2$.

### A3. Countries of the World from 1961-1992, Unless Specifically Mentioned In Sections A4-A13

The source for national data for 1961-1992, annually, is *Food and Agriculture Organization* [1995].

### A4. States of the United States (1850-1992)

The sources are as follows: (1) The *U.S. Department of Agriculture* [1992a] for subnational data for 1945-1992, for approximately every 5 years and (2) U.S. Bureau of the Census [1900, 1920, 1940, 1950] for subnational data for 1850-1939, for approximately every 10 years. The following adjustments are made to the U.S. Bureau of the Census data to ensure consistency in definitions:

1. For 1929 and 1939, the U.S. Bureau of the Census [1940] data only list total amount of plowable pastures, and not cropland used for pastures. To estimate the latter, using the *U.S. Department of Agriculture* [1992a] data of 1945 for each state, we calculate the ratio of total cropland (cropland harvested + crop failure + cropland idled/fallow + cropland used for pasture) to (cropland harvested + crop failure + cropland idled/fallow). We then apply this ratio to the U.S. Bureau of the Census [1940] data of cropland harvested + crop failure + cropland idled/fallow for 1929 and 1939 to estimate the total amount of cropland.

2. For 1850-1920, the U.S. Bureau of the Census [1900, 1920] data only list the category "improved land." This is adjusted in

two steps. In step A, U.S. Bureau of the Census [1975] provides area of cropland harvested for the United States as a whole over 1850-1920. Using this, and the U.S. Bureau of the Census [1900, 1920] data on area of "improved land" during 1850-1920, we estimate the ratio of cropland harvested to improved land for the United States as a whole to be 0.58-0.69 over 1850-1920, with the mean being 0.64. We apply the value of 0.64 to the U.S. Bureau of the Census [1900, 1920] data of improved land to estimate cropland harvested area for 1850-1992. In step B, U.S. Bureau of the Census [1950] has data for each state of both harvested land and total cropland for 1944 and 1949. We calculate the ratio for each state, averaged over 1944 and 1949, of total cropland to harvested land. We apply these ratios to the results of step A to estimate total cropland data over 1850-1920.

3. Furthermore, for a few states, there were no census data in the 19th century. For these states, we extrapolate the data backward from those available in later periods or use clearing rates of *Houghton and Hackler* [1995]. In most cases, these extrapolations result 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 adjust some data for changes in political boundaries; we compile data consistent with present-day boundaries and adjust data for states that split using proportions in known time periods.

### A5. Provinces of Canada (1850-1992)

The source is as follows: Custom historical census of agriculture data retrieval (A. Lupien, statistics Canada, personal communication, 1997) for provincial data for 1871-1991, every 10 yrs; the "total improved land" data from the census appears to be consistent with the FAO numbers. The 1992 provincial data is obtained by applying the cropland proportion in each province in 1991 to the FAO 1992 national total. We fill missing data using interpolation/extrapolation or using proportions from closest time period of data availability; we extrapolate national totals from 1871 back to 1850 using a cubic-spline fitting tool.

### A6. Regions of Mexico (1850-1992)

The sources are as follows: (1) *Yates* [1981] for subnational data for 1930-1970, for every decade, (2) *Food and Agriculture Organization* [1995] for national data for 1970-1992, and (3) *Houghton et al.* [1991] for national data for 1850-1920. Yates corrected the official statistics and provided estimates for 1930-1970 over eight regions of Mexico. Between 1970-1992, we use the FAO statistics on country totals, corrected by the ratio of Yates data to FAO data in 1960-1961; for subnational information, we apply the same proportions as Yates data for 1970 over 1970-1992. For 1850, 1875, 1900, 1910, and 1920, we obtain country total data from *Houghton et al.* [1991] (digitized from his Figure 1) and linearly interpolate inbetween. For subnational information during 1850-1930, we apply the same regional proportions as Yates for 1930. Thus our Mexican data is a composite of estimates by *Yates* [1981], *Houghton et al.* [1991] and *Food and Agriculture Organization* [1995].

### A7. Central American Countries (1850-1992)

The source for the national data for 1961-1992, annually, is *Food and Agriculture Organization* [1995]. The 1850 to 1960 estimates are calculated by maintaining a constant ratio to Mexico.

### A.8. States of Brazil (1920-1992)

The source for the subnational data for 1995 is Censo Agropecuário de 1995-1996 (Fundação Instituto Brasileiro de Geografiae e Estatística, http://www.ibge.gov.br/informacoes/censo96/Agro/m-agro.htm) and the source for the subnational data for 1920-1985 is E.J. Reis (Instituto de Pesquisa Econômica Aplicada, personal communication, 1997).

### A.9. Argentina (1900-1992)

**A9.1 National data**. The source is a composite over 1900-1972 created from *Vasquez-Presedo* (1988) and *Rudbeck* (1970).

Data on total agricultural area is obtained from *Vasquez-Presedo* [1988] for every 5 years from 1900-1930. The area of *Forrajeras* (pastures) is available in the same document for every 5 years from 1915-1930. We obtain cropland area during 1915-1930 by subtracting the pasture area from the total area. To obtain cropland area in 1900, 1905, and 1910, we multiply the total agricultural area by 0.65 (ratio of cropland area to total agricultural area in 1915). For the period 1935-1968, we similarly obtain annual cropland area from *Rudbeck* [1970] by subtracting forage area from total area. For 1969-1972, we derive annual cropland areas from *Vasquez-Presedo* [1988], but adjust it by multiplying by a factor of 1.1 (the ratio of *Rudbeck* [1970] area to *Vasquez-Presedo* [1988] area in 1968). We adjust the *Vasquez-Presedo* [1988] areas because both *Rudbeck* [1970] and *Vasquez-Presedo* [1988] have cropland data over the common period 1935-1968. During this period, the ratio of *Rudbeck* [1970] area to *Vasquez-Presedo* [1988] area equals 1.0 during 1935-1954, but increases steadily afterward until it obtains a value of 1.1 in 1968. We think the *Rudbeck* [1970] estimate is more consistent and correct the *Vasquez-Presedo* [1988] estimates accordingly. We thus have a data composite for the period 1900-1972.

**A9.2 Subnational data**. The data for 1998 (Sum of Annual Crops, Perennial Crops, and Annual Forage) is from *Instituto Nacional de Estadistica y Censos* [1995]. The data for 1960 is from *Direccion Nacional de Estadistica y Censos Argentina* [1960].

We assume that the cropland areas over 1989-1992 are the same as of 1988. We linearly interpolate the national totals between 1972 and 1988. Then we use the Special Interpolation Method described in section A2 to obtain subnational data between 1960 and 1988. For 1900 to 1960, we extrapolate the subnational data of 1960 back in time by maintaining a constant ratio to the national totals.

### A.10. Provinces of China (1949-1992)

The sources are as follows: (1) U.S. *Department of Agriculture* [1992b] for annual provincial data for 1978-92, (2) *Chao* [1970] for annual national data for 1949-1957, and (3) *Tang and Stone* [1980] for annual national data for 1952-62.

For the 1978-1992 period, we directly use the *U.S. Department of Agriculture* [1992b] provincial data. We obtain national totals from *Chao* [1970] for 1949-1957 and from *Tang and Stone* [1980] for 1952-1962. These two data sets have different values in the overlap period 1952-1957. The ratios of the two data sets during 1952-1957 follow a straight line, and we use the straight line regression equation to correct the Tang and Stone data because the Chao data seem to have been more carefully derived. We use the corrected Tang and Stone data over the 1958-1962 period. After linearly interpolating the national data between 1962 and 1978, we obtain continuous national data from 1949 to 1977 and subnational data thereafter. We extend the subnational data back from 1977 to 1949 by maintaining a constant proportion to the national totals.

### A11. India (1880-1992)

**A11.1 National data**. The sources are as follows: (1) *Bansil* [1984] for India national data for 1973-1979, (2) *Directorate of Economics and Statistics* [1961] for 1949-1953, (3) *Office of the Agricultural Attache* [1972] for 1956, and (3) *Directorate of Economics and Statistics* [1962] for 1957. (The sum of net sown area, current fallows, other fallows, and land under miscellaneous tree crops and groves etc. is consistent with our definition of croplands.)

*Directorate of Economics and Statistics* [1961] seems to have a steep increase in crop cover between 1949 and 1950 and then a drop again from 1951 to 1952. We ignore their 1950-1951 data. We fill all gaps using the FAO data during 1961-1992 and the rest by linear interpolation. Thus we compile continuous national data from 1949 to 1992.

**A.11.2 Subnational data**. The sources are as follows: (1) *Directorate of Economics and Statistics* [1992] for 1989, (2) *Bansil* [1984] for 1979, and (3) *Richards and Flint* [1994] for 1880, 1920, 1950, and 1970.

For 1990-1992, we extrapolate forward in time from 1989 by maintaining a constant proportion to the FAO national totals for 1990-1992. The subnational data are linearly interpolated between 1979 and 1989 using the Special Interpolation Method described in section A2. The *Richards and Flint* [1994] (RF hereafter) data are not consistent with FAO or other census data during the periods of overlap between 1950 and 1970. We use the RF subnational data for 1970, corrected by a factor to match the 1970 national data, and the subnational data for 1950, corrected to match the 1949 national data. The 1950 correction factor is then applied to the RF data for 1880 and 1920. We then linearly interpolate in between 1880, 1920, 1950, 1970, and 1979 (between 1950 and 1979, we use the Special Interpolation Method described in section A2 because we have national totals during that period).

### A12. Other Countries in South and Southeast Asia (Bangladesh, Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, Philippines, Singapore, Sri Lanka, Thailand, and Vietnam) (1880-1992)

The source of the data for 1880, 1920, 1950 and 1970 is *Richards and Flint* [1994].

We use the FAO data for these regions from 1961 to 1992. In 1970, we find that the RF data are not consistent with FAO. Hence we calculate a correction factor for each country to make the RF data match FAO in 1970 and apply this factor to the entire RF data. We then linearly interpolate between the RF data and FAO data to get a data set from 1880 to 1992. In the DISCover data set, Sarawak and Sabah are part of the Australia-Pacific continent, while the rest of Malaysia is part of the Eurasia continent. Hence we also split the RF data for Malaysia into those two regions using the proportion of croplands found in 1980 (using subnational data provided by RF).

### A13. States and Territories of Australia (1861-1992)

The sources for cropland data, i.e., area used for crops [$A_C$ hereafter] + area under sown pastures and grasses (or area under sown grasses and clovers) [$A_P$ hereafter] are as follows: (1) *Australian Bureau of Statistics* (ABS) [1989, 1990, 1991] for subnational data for 1986-90, (2) *Australian Bureau of Statistics* [1984] for subnational data for 1982-83, (3) *Australian Bureau of Statistics* [1980] for subnational data for 1978-80, (4) *Australian Bureau of Statistics* (1978) for subnational data for 1976, (5) *Commonwealth Bureau of Census and Statistics* [1972] for subnational data for 1968-72, (6) *Food and Agriculture Organization (FAO)* for national data for 1961-67, (7) *Ashton* [1952] for national data for 1950, (8) *Wilson* [1947] for subnational data on $A_C$ from 1861 to 1946, approximately every decade from 1861 to 1939, and annual thereafter, and (9) *Wilson* [1947] for national data on $A_P$ for 1930 and 1946.

For 1991-1992, we extrapolate forward in time from 1990 by maintaining a constant proportion to the FAO national totals for 1991-1992. We linearly interpolate subnational data between 1972-1976, 1976-1978, 1980-1982, and 1983-1986, to get a continuous data set for 1968-1992.

Prior to 1968, we do not have subnational data on $A_P$. Hence we have to interpolate $A_C$ and $A_P$ separately to derive total cropland area. This involves a number of steps:

1. In 1968, we find that the ABS total cropland area does not match the FAO total. Hence we derive national total cropland area during 1961-1967 by correcting the FAO national totals using a correction factor calculated to make FAO data match ABS data in 1968. We interpolate the national cropland areas between 1950 and 1961.
2. In 1950 and 1968, we have national data on $A_C$ and $A_P$. We calculate the proportions occupied by $A_C$ and $A_P$ in these years to the total cropland area. We then interpolate these proportions between 1950 and 1968. We then apply these proportions to the 1950-1968 total cropland areas to derive $A_C$ and $A_P$ between 1950 and 1968.
3. We linearly interpolate national $A_C$ between 1946 and 1950. We have subnational $A_C$ in 1946. We calculate the proportion of $A_C$ to the national total in 1946, and then apply these to the national totals during 1947 to 1950 to derive subnational $A_C$ for 1947 to 1950. Then we derive subnational $A_C$ during 1950 to 1968 using the Special Interpolation Method described in section A2.
4. We interpolate the national $A_P$ data between 1946 and 1950 and between 1930 and 1946. We then calculate the subnational $A_P$ data between 1930 and 1968 by applying the same proportions occupied by subnational $A_P$ to the national total $A_P$ in 1968.
5. Annual subnational $A_C$ data is available between 1939 and 1946. We linearly interpolate the subnational $A_C$ data between 1861 and 1939, using all the available census data in between.
6. For 1861 to 1929, we calculate the national total cropland area by extrapolating back from 1930 using the conversion rates of HH and *Richards* [1990]. We obtain subnational data for this period by first calculating the proportions occupied by each subnational unit in the $A_C$ data during 1861-1929, and then applying the same proportions to the total cropland area data.

## Appendix B. Algorithm for Reconstructing Historical Crop Cover

We first aggregate the fractional crop cover for 1992, $f_{CA}(i,j,1992)$, over each political unit. This estimate, denoted as $A_S(1992,k)$, does not exactly match the cropland inventory data, i.e., $A_S(1992,k) \neq A_I(1992,k)$ [*Ramankutty and Foley*, 1998, Figure 1]. Because our simulations are initialized with $f_{CA}(i,j,1992)$ and because it does not exactly match the inventory data in 1992, we have to necessarily use anomalies of the inventory data from 1992 to calculate target crop areas for the simulation.

However, it is not obvious whether to use differential anomalies or proportional anomalies to calculate target cropland areas. In this study, we use proportional anomalies because we believe that the historical inventory data probably capture the proportional changes in crop area better than the differential changes. However, when there is a large increase in crop area from one year to the next, using proportional anomalies might result in the target crop areas becoming unduly large (in some cases exceeding the total area of the political unit). To avoid this possibility in such circumstances, we switch toward using differential anomalies. Thus the target crop areas are calculated as follows:

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

where $t_1$ is the starting time step, and $t_2$ is the ending time step. In the first simulation, $t_1 = 1992$, $t_2 = 1991$; in the second simulation, $t_1 = 1991$, $t_2 = 1990$, etc. $A_I(t_1,k)$ is the crop area from inventory data for time $t_1$, for political unit $k$; $A_I(t_2,k)$ is the crop area from inventory data for time $t_2$, for political unit $k$; $A_S(t_1,k)$ is the crop area $f_{CA}$ *(i,j,1992)*, aggregated over each political unit for time $t_1$, for political unit $k$; $A_S(t_2,k)$ is the target crop area for the simulation for time $t_2$, for political unit $k$; and

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

Thus, when $A_I(t_2,k)/A(t_1,k) \leq 1.1$, $\alpha(k) = 1$, implying proportional anomalies are used. However, as $A_I(t_2,k)/A(t_1,k)$ becomes large, $\alpha(k) \rightarrow 0$, and we progressively switch toward using relative anomalies.

In addition, we use the following over-riding 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 $(A_S(t_2,k)) = 0$.

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

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

We then spatially distribute the values of $\phi(k)$ to a map at 5 min latitude by longitude resolution, by assigning $\phi(k)$ uniformly to each pixel that lies within the boundaries of each political unit k. Furthermore, we apply a smoothing procedure to $\phi(k)$ to avoid abrupt changes across the boundaries of the political units. In each of 100 iterations, the value of $\phi(k)$ in every grid cell was set to be the average of itself and the surrounding four grid cells. Since this would change the total target crop area of each political unit, we correct the values between each iteration by multiplying them by a factor so that the target crop area is conserved over each political unit. Thus historical croplands are calculated using the following equation:

$$f_{CA}(i,j,t_2) = f_{CA}(i,j,t_1)\ \varphi(k),$$

where $\varphi(k)$ is the spatialized, smoothed version of $\phi(k)$. The first simulation has $t_1 = 1992$, $t_2 = 1991$; in the second simulation, $t_1 = 1991$, $t_2 = 1990$, .....; and in the final simulation, $t_1 = 1701$, $t_2 = 1700$.

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