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China's land cover and land use change from 1700 to 2005: Estimations from high-resolution satellite data and historical archives

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[1] One of the major limitations in assessing the impacts of human activities on global biogeochemical cycles and climate is a shortage of reliable data on historical land cover and land use change (LCLUC). China had extreme discrepancies in estimating contemporary and historical patterns of LCLUC over the last 3 centuries because of its geographical complexity, long history of land use, and limited national surveys. This study aims to characterize the spatial and temporal patterns of China's LCLUC during 1700–2005 by reconstructing historical gridded data sets from high-resolution satellite data and long-term historical survey data. During this 300 year period, the major characteristics of LCLUC in China have been shrinking forest (decreased by 22%) and expanding cropland (increased by 42%) and urban areas (including urban and rural settlements, factories, quarries, mining, and other built-up land). New cropland areas have come almost equally from both forested and nonforested land. This study also revealed that substantial conversion between forest and woodland can be attributed to forest harvest, forest regeneration, and land degradation. During 1980–2005, LCLUC was characterized by shrinking cropland, expanding urban and forest areas, and large decadal variations on a national level. LCLUC in China showed significant spatial variations during different time periods, which were caused by spatial heterogeneity in vegetation, soils, and climate and regional imbalance in economy development. During 1700–2005, forests shrunk rapidly while croplands expanded in the northeast and southwest of China. During 1980–2005, we found a serious loss of cropland and urban sprawl in the eastern plain, north, and southeast regions of China and a large increase in forested area in the southeast and southwest regions. The reconstructed LCLUC data sets from this study could be used to assess the impacts of land use change on biogeochemical cycles, the water cycle, and the regional climate in China. To further eliminate uncertainties in this data set and make reliable projections of LCLUC for the future, we need to improve our understanding of the drivers of LCLUC and work toward developing an advanced, spatially explicit land use model.

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1. Introduction

[2] During the past several centuries, humans have altered the Earth's environment with unprecedented intensity and speed through land use change [*Turner and Meyer*, 1994; *Foley et al.*, 2005]. China, which is the third largest country in the world and home to more than 1.3 billion people (20.2% of the world population) (United Nations Population Division, 2008, http://esa.un.org/unpp/index.asp?panel=1; accessed 13 February 2008), has a long history of land cultivation associated with intensive land cover and land use change (LCLUC) [*Houghton and Hackler*, 2003; *Lin and Ho*, 2003; *Ge et al.*, 2004; *Liu et al.*, 2005a, 2005b]. A growing demand for food due to an increasing population has caused substantial expansion of cropland, accompanied by shrinking primary forest and grassland areas during the past 3 centuries [*Houghton and Hackler*, 2003; *Ge et al.*, 2004; *He et al.*, 2007]. However, the dramatic growth and globalization of China's economy and market since economy

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reforms in 1978 have brought about a massive loss of croplands, most of which were converted to urban areas and transportation routes during 1978–1995 [*Lin and Ho*, 2003; *Liu et al.*, 2005a; *Deng et al.*, 2006; *Chen*, 2007]. In recent decades, increasing concern for the environment and sustainability has compelled the Chinese government to continuously adjust its land use policies to balance multiple uses of land resources. These policies have caused changes in cropland and its spatial distribution, as well as an increase in forest plantations [*Yang and Li*, 2000; *Zhang et al.*, 2000; *Hyde et al.*, 2003; *Wang et al.*, 2004; *Liu et al.*, 2005a; *Yan et al.*, 2009; *Wang et al.*, 2007].

[3] China's LCLUC is an important driving force that governs changes in atmospheric CO_2 concentrations, food production, climate, and water resources; its influence is seen not only at the national level, but also on the global scale [*Brown*, 1995; *Fang et al.*, 2001; *Houghton and Hackler*, 2003; *Zhou et al.*, 2004; *Liu et al.*, 2008; *Tian et al.*, 2003]. The magnitudes and patterns of China's LCLUC over long-term historical periods, however, are considered one of the largest uncertainties in global change studies [*Wu and Guo*, 1994; *Heilig*, 1997; *Frolking et al.*, 1999; *Fu*, 2003; *Houghton and Hackler*, 2003; *Lin and Ho*, 2003; *Tian et al.*, 2003, 2008; *Xiao et al.*, 2003; *Foley et al.*, 2005; *Liu et al.*, 2005b; *Richter et al.*, 2005; *Huang et al.*, 2006]. Several national and global spatial data sets reveal long-term or contemporary changes in China's major land use types such as cropland and forest (Table 1). Some of these data sets were based on remotely sensed information [e.g., *DeFries et al.*, 2000; *Loveland et al.*, 2000; *Friedl et al.*, 2002; *Wu et al.*, 2004; *Liu et al.*, 2005a], some were based on land surveys (e.g., Forest Inventory Data [*Ministry of Land and Resources of China* (*MLR*), 2003]), and others were derived from historical archives over a century-long period [e.g., *Ramankutty and Foley*, 1999; *Houghton and Hackler*, 2003; *Ge et al.*, 2004; *He et al.*, 2007]. Several papers have shown that there are large discrepancies in estimations of cropland area in China [e.g., *Heilig*, 1997; *Frolking et al.*, 1999; *Tian et al.*, 2003; *Xiao et al.*, 2003; *Liu et al.*, 2005b]. For example, *Liu et al.* [2006] discussed the issue of forested areas using estimates from MODIS and Landsat TM/ETM imagery. *Giri et al.* [2005] reported that land cover product from SPOT VEGETATION, i.e., Global Land Cover 2000, is apparently different from MODIS. However, until now, no national level comparison has been done on remotely sensed data and survey data from contemporary land cover and land use (LCLU) and its changes over time.

[4] The current global data sets cannot adequately reflect the detailed spatially explicit LCLU conversions that occur in China because of their coarse resolution and limited input data (Table 1) [*Ramankutty and Foley*, 1999; *Klein Goldewijk*, 2001; *Houghton and Hackler*, 2003; *Hurtt et al.*, 2006]. Even national data sets and reports on China's LCLUC show great inconsistencies concerning magnitude and spatial distributions [*Shi*, 1991; *Frolking et al.*, 1999; *Heilig*, 1997; *Wu and Guo*, 1994; *Ma*, 2000; *Zhang and Song*, 2006; *Lin and Ho*, 2003; *Liu et al.*, 2005b]. Limitations on spatial resolution and/or short-term coverage are common problems for all of these data sets. For instance, the long-term historical data sets of cropland [*Ge et al.*, 2004] and forest [*He et al.* 2007] reconstructed from historical archives cannot provide detailed spatial information beyond the provincial level. Even national inventories and survey data on forested land and cropland from the *State Forestry Administration of China* (*SFAC*) [2005] and the *MLR* [2000–2006], respectively, are unable to provide spatially explicit information on changes in forest and cropland areas. Recently, high-resolution satellite observations have been used to detect LCLUC over the past several decades, such as Landsat TM/ETM based National Land Cover Data Sets (NLCD) of China generated by *Liu et al.* [2005a, 2005b] which reveal many spatial details of land use change and conversions over a short time period. However, it is impossible to produce land use history on a national scale earlier than the mid-1970s. Therefore, it is imperative that these two kinds of information are integrated to produce more reliable and useful data sets which cover longer time periods and have higher spatial resolutions than any single data set.

[5] This study has characterized the spatial and temporal patterns of LCLUC that occurred in China during 1700–2005 by combining high-resolution satellite data and long-term historical land survey data. Three major LCLU categories, i.e., cropland, forest, and urban, are specifically emphasized in this research. We used the same definitions of land cover types in NLCD [*Liu et al.*, 2005b]. Cropland is defined as land cultivated for crops and includes mature cultivated land; newly cultivated land; fallow land; shifting cultivated lands; intercropping land, such as crop-fruit trees, crop-mulberries, and crop-forest land in which one crop is dominant; and bottomland or beaches that can be cultivated for at least 3 years. Urban is defined as land used for urban and rural settlements, factories, quarries, and mining, as well as built-up land used for special purposes, such as airports. Forest is natural or planted forest (tea garden, orchards, groves, and nursery forest are also included) where tree canopy cover (the proportion of the forest floor covered by a vertical projection of the tree crowns [*Jennings et al.*, 1999]) is more than 30%. The net changes and conversions between these three major types have been widely accepted as key forces influencing the biogeochemical cycles in terrestrial ecosystems and water resources in China [*Houghton and Hackler*, 2003; *Tian et al.*, 2003, 2008; *Sun et al.*, 2006; *Liu et al.*, 2008]. We also analyze transitions between human-dominated land use and other natural land covers by developing a potential vegetation map from multiple data sources.

[6] We organize this paper into three different sections: a description of our input data, our methodologies, and an analysis of the magnitude and spatial distributions of LCLUC during the last 300 years and over the course of the last several decades. We also discuss the uncertainties involved in current land use data sets and make recommendations for cautiously using these data sets for scientific research and policy making. The core products we generated were a number of 10 × 10 km gridded annual maps which show China's cropland, forest, and urban areas and also how these areas have transitioned between different land covers during 1700–2005. It is our hope that the results and data pro-

Table 1. Major Land Cover and Land Use Data Sets of China

Data Set Name	Methodology	Spatial and Temporal Coverage	Spatial Resolution	LCLU Types	Notes	References
ChinaNLCD[a]	Landsat TM/ETM	China, 1990, 2000	30 m	25 categories of LCLU	We used it as baseline of reconstructing historical data. Forests: natural or planted forests with tree canopy cover greater than 30%	*J. Liu et al.* [2005a, 2005b]
FRIC[a]	Inventory	China mainland, 1973–2003 per 5 years	Provincial data (publicly available)	Forest	The sixth inventory data is used to calibrate *He et al.*'s [2007] data sets; Canopy coverage > 0.3 before 1994; >0.2 starting in 1994	*Chinese Ministry of Forestry* (*CMF*) [1982, 1989, 1994, 1999] and *State Forestry Administration of China* (*SFAC*) [2005]
Ge2004[a]	Historical archives	China's 18 regions, for period 1661, 1685, 1724, 1784, 1820, 1973, 1887, 1893, 1913, and 1933	Provincial	Cropland	This data set covers most of contemporary provinces of China	*Ge et al.* [2004]
GLC2000[a]	SPOT/VEGETATION	Global, 2000	1 km	All LCLU	We used the China part as comparison	*Wu et al.* [2004] and *Bartholomé and Belward* [2005]
GLM data	Land use model; inventory; remote sensing	Global, 1700–2000	1°	Agricultural, primary and secondary forest, land transition		*Hurtt et al.* [2006]
He[a]	Historical archives	China mainland	Provincial	Forest	Tree canopy coverage greater than or equal to 0.2	*He et al.* [2007]
Heilig	SSB after correction	China mainland, 1985, 1995	Provincial	Cropland	Corrected SSB data sets	*Heilig* [1997]
Houghton and Hackler	Literature based	China, 1700–2000	Regional	Cropland, forest, pasture		*Houghton and Hackler* [2003]
HYDE3	Model; inventory	Global, 1700–1990	5′	Cropland, pasture, urban area	New data sets have been updated to 2005	*Klein Goldewijk and Ramankutty* [2004]
Land use map of China	Landsat MSS; field surveys; Aero	China, around 1980	1: 1 million map	All LCLU		*Wu* [1990] and *Wu and Guo* [1994]
LRM	Landsat MSS; cartography map; inventory; land use assessment model	China mainland, around 1980	1:1 million	All LCLU	Mainly used as land use assessment	*Shi* [1991] and *CISNR* [1993]
MLR	Satellite data; aerial photos; survey	China mainland, 1996–2008	Provincial (publicly available)	Cropland, forest, grassland, residential and construction area		*Ma* [2000] and *State Statistical Bureau* (*SSB*) [2000–2009]
MODIS[a]	MODIS-derived land cover map	Global, 2001	1 km	All LCLU	Pure cropland type was used as comparison	*Friedl et al.* [2002]
Ramankutty2008	MODIS land cover; VEGETATION-derived land cover (GLC2000); inventory data; model	Global, 2000	5′	Cropland		*Ramankutty et al.* [2008]

Table 1. (continued)

Data Set Name	Methodology	Spatial and Temporal Coverage	Spatial Resolution	LCLU Types	Notes	References
RF[a]	AVHRR-based land cover; inventory data; model	Global, 1700–1990	5′ × 5′	All LCLU	The forest area is estimated from the historical cropland and potential vegetation map	*Ramankutty and Foley* [1999]
SAGE	AVHRR-based land cover; inventory data; model	Global, 1700–1990	5′	Cropland	Fractional data	*Ramankutty and Foley* [1999]
SSB[a]	Survey	China mainland	Provincial, 1949, 1952, 1962, 1978–1996	Cropland	Underestimated cropland area before 1996. From 2000, MLR data are used.	*State Statistical Bureau of China (SSB)* [2000]
Tree Cover	AVHRR; model	Global, 1992/1993	30 s	Forest		*DeFries et al.* [2000]
Xu1983[a]	Historical archives	China's 29 provinces, 1873, 1893, 1913, 1914, 1932, 1934, 1946, and 1949	Provincial	Cropland		*Xu* [1983]

[a]The data sets are used to reconstruct the historical LCLU of China in this study. FRIC, Forest Resource Inventory of China; GLM, Global Land use Modeling; LRM, China's Land Resources Map; MLR, China's Ministry of Land and Resources; SSB, State Statistical Bureau of China.

duced by this study can be used not only in spatially explicit models of biogeochemical cycles and regional climate, but also in policy-making processes related to land use and land management.

2. Reconstructing Historical LCLU Data Sets: Methodology and Data Sources

[7] We generated three data sets to characterize historical LCLUC in China. The first one is a potential land cover map, which represents primary land cover without human disturbance. The other two are a fractional gridded data set and a Boolean gridded data set, which represent the distributions of cropland, forest, and urban area in each 10 × 10 km grid cell. The fractional data set is composed of percentages of different LCLU types in each grid cell. The Boolean data set represents only one LCLU type for each grid cell and is used to estimate transitions from this LCLU to other types of land cover. The following sections describe our methodologies and the data sources used in this study.

2.1. Potential Land Cover Map

[8] This potential land cover map was generated to track land conversions between natural land cover and human-dominated land cover and land use. Historical land cover transitions between forest and woodland were also identified by comparing this map with reconstructed forest distribution. To derive this potential land cover map, we had to make two assumptions. First, we assume that contemporary natural land cover (i.e., forest, shrubland, grassland, and desert) accurately represents its potential condition without human disturbance over the past 3 centuries. This assumption was also made by *Ramankutty and Foley* [1999] in developing their global natural vegetation map. Second, we assume that the spatial distribution of potential forest should be greater than its real historical distribution. This means that we need to update the potential land cover map with the reconstructed historical forest map (see section 2.2.4 and Figure 1); that is, once a grid cell is identified as forest during any period, its potential land cover is classified as forest.

[9] We classified potential land cover into the following types: Tundra, Boreal Broadleaf Deciduous Forest/Woodland (BBDF), Boreal Needleleaf Evergreen Forest/Woodland (BNEF), Temperate Broadleaf Deciduous Forest/Woodland (TBDF), Temperate Broadleaf Evergreen Forest/Woodland (TBEF), Temperate Needleleaf Evergreen Forest/Woodland (TNEF), Temperate Needleleaf Deciduous Forest/Woodland (TNDF), Tropical Broadleaf Deciduous Forest/Woodland (TrBDF), Tropical Broadleaf Evergreen Forest/Woodland (TrBEF), Deciduous Shrub (Dshrub), Evergreen Shrub (Eshrub), C_3 grass, C_4 grass, Wetland, and Desert. This classification system has been widely used in global land cover mapping and biogeochemical models [*Loveland et al.*, 1999, 2000; *Tian et al.*, 2003]. We produced this potential land cover map by integrating multiple sources of data and information, including the China National Land Cover Data Set (NLCD) for the year 2000 (thereafter, NLCD2000) [*Liu et al.*, 2005a, 2005b] and the global potential vegetation map developed by *Ramankutty and Foley* [1999]. Figure 1

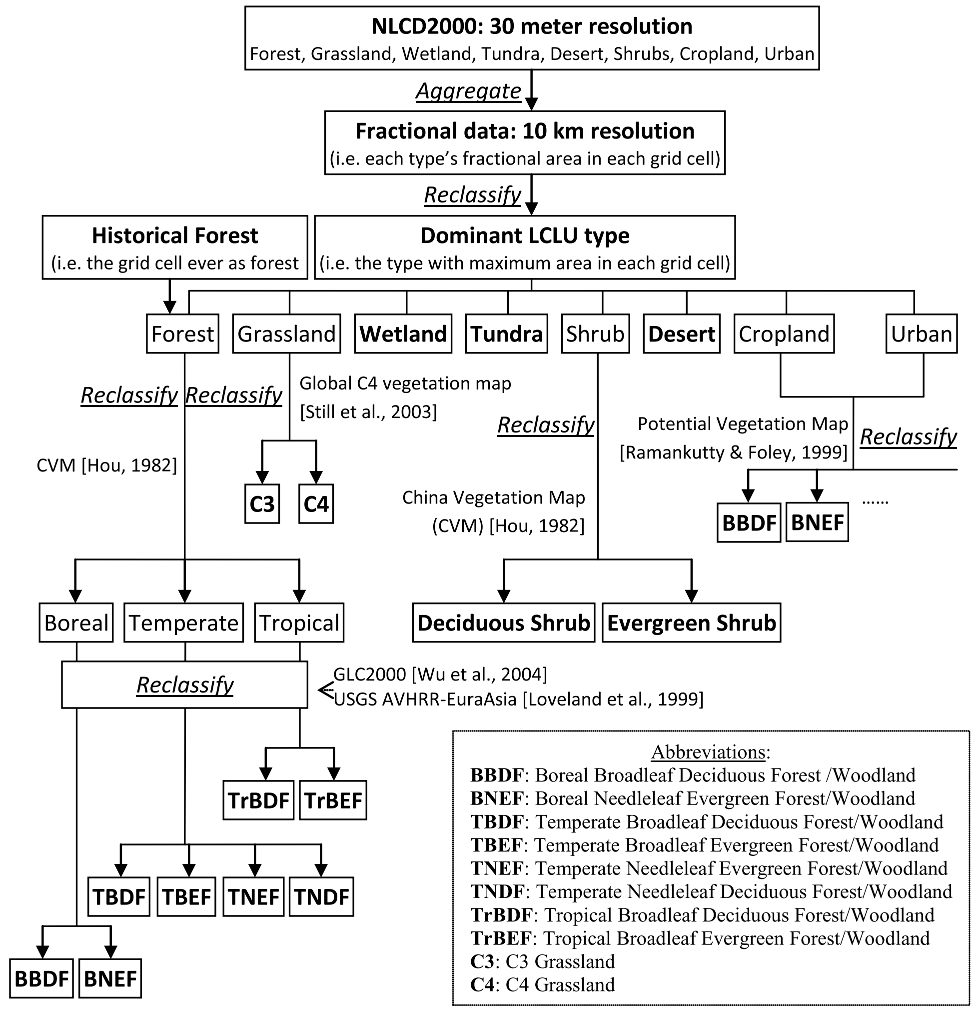

Figure 1. Workflow for generating the potential land cover map of China.

provides the workflow for generating the potential land cover map of China. For additional details, see Text S1.[1]

2.2. Historical Cropland, Forest, and Urban Distributions

2.2.1. Data Sources

2.2.1.1. Baseline Cropland, Forest, and Urban Distributions

[10] We used NLCD fractional data sets of cropland, forest, and urban regions as the baseline for reconstructing their historical distributions. These NLCD data sets reflect the status of and changes in LCLUC during 1990–2000 [*Liu et al.*, 2005a, 2005b].

2.2.1.2. Historical Records of Cropland Area

[11] Several recent studies have tried to use historical records found in archives and other documents to reconstruct the historical distributions of cropland and forest over the past 300 years; this is done by linking these historical records with land cover maps derived from low-resolution satellite images such as AVHRR (Table 1) [e.g., *Ramankutty and Foley*, 1999; *Klein Goldewijk*, 2001; *Klein Goldewijk and Ramankutty*, 2004; *Leff et al.*, 2004; *Hurtt et al.*, 2006]. For our study, we collected more reliable, higher-resolution historical data for reconstructing China's historical land use.

[12] 1. Ge2004: *Ge et al.* [2004] reconstructed historical cropland area in 18 regions of China during particular years (Table 1). These data cover most of the contemporary provinces of China.

[13] 2. Xu1983: *Xu* [1983] collected historical cropland area in 29 provinces of China (Table 1). The average cropland area in 1932 and 1934 is used to estimate cropland area in 1933, which provides the necessary overlap with the analysis of Ge2004.

[14] 3. State Statistical Bureau (SSB): SSB has published the longest records of cropland area at the provincial level over the last 5 decades. These records are thought to be the most reliable sources for tracking cropland variations during

[1] Auxiliary materials are available with the HTML. doi:10.1029/2009GB003687.

1950–1990; however, many scientists have argued that in the past, SSB substantially underestimated total cropland area [*Heilig*, 1997; *Frolking et al.*, 1999; *Smil*, 1999; *Yang and Li*, 2000; *Xiao et al.*, 2003; *Liu et al.*, 2005b]. The provincial cropland areas for 1952, 1962, and 1978 are derived from records of cropping areas and cropping indices given by *SSB* [2000]. The cropland areas for 1949, 1982, and 1989 are from SSB yearbooks [*SSB*, 1983, 1990]. The cropland area for 1949 from SSB is consistent with Xu1983.

[15] 4. China's Ministry of Land and Resources (MLR): In order to accurately estimate national land resources, particularly croplands, a large-scale national survey was conducted by China's State Land Administrative Bureau (now MLR) during 1984–1996 using aerial photos, Landsat images, and maps [*Ma*, 2000; *Lin and Ho*, 2003]. Since 2000, SSB has started to use this national land survey data [*SSB*, 2000]. In this study, we used their provincial survey data for the period 2000–2005, even though there are still some uncertainties about their data because of their sample size and human involvement in their survey [*Lin and Ho*, 2003; *Liu et al.*, 2005b].

2.2.1.3. Historical Records of Forest Area

[16] Reports on China's forest area before 1949 are rare and are under suspicion because of limited data sources [*Houghton and Hackler*, 2003]. Here, we applied data products from *He et al.* [2007] (HE2007) as input to reconstruct the historical distribution of forest before 1949. In HE2007, provincial forest area (tree canopy coverage greater than or equal to 20%) in China from 1700 to 1949 was reconstructed using historical archives and documents. We believe this estimate to be the most reliable at provincial level before 1949 because of its rigorous calibration and validation with multiple sources of local historical archives and contemporary surveys [*He et al.*, 2007].

[17] Data on provincial forest area during 1949–1990 was obtained from national inventories; these inventories are part of a database of six time periods of forest inventory (1973–1976, 1977–1981, 1984–1988, 1989–1993, 1994–1998, and 1999–2003), which was developed by the State Forestry Administration of China [*Chinese Ministry of Forestry* (*CMF*), 1999; *Zhang and Song*, 2006]. The definition of forest, however, varies slightly during these periods because of varying considerations of tree canopy cover. Prior to 1994, areas with tree canopy cover greater than or equal to 30% were considered forest; later, this amount decreased to 20% [*CMF*, 1999].

2.2.1.4. Historical Records of Urban Area

[18] Urban sprawl and a growing demand for road construction and industry are critical forces which have the potential to produce serious environmental problems in China [*Liu and Diamond*, 2005]. In addition, increasing pressure on agricultural land resources due to rapid urbanization has caused great concern within the international community and China's government [*Heilig*, 1997; *Bloom et al.*, 2008; *Grimm et al.*, 2008; *Liu et al.*, 2008]. However, there is little reliable data on urban development during the past several centuries. In this study, we use population to estimate the expansion of urban areas by assuming that urban areas have expanded at the same rate as population during 1700–1990 [*Commission for Integrated Survey of Natural Resources of the Chinese Academy of Sciences*, 1993]. This assumption is based on research indicating a strong relationship between population and urban area in China [*Lo and Welch*, 1977]. While a slight change in urban area per capita during a historical period may introduce some uncertainties in our estimates of urban area growth [*Verburg et al.*, 1999], because of the limitations of robust data sets on historical urban areas, we considered this assumption most appropriate for this study. For 2001–2005, we used the trend of residential and contractual land use area as a reference for urban area.

2.2.2. Reconstructing Provincial Level of Cropland, Forest, and Urban Areas Over the Past 300 Years

[19] To reconstruct this long-term history of LCLU, we combined multiple data sources covering different time periods (Figure 2). We integrated these different data sets into one time series of historical LCLU by calibrating them against the NLCD data. The objective of our calibrations was to estimate historical cropland, forest, and urban areas in each province by comparing the baseline of NLCD with other historical data sets. For instance, cropland areas in the years 1949, 1952, 1962, 1978, 1982, 1983, and 1989 from SSB were calibrated with their relative changes compared to *SSB* [1990] and their value in NLCD1990. Assuming a time series of i and j, i and j have an originally estimated or recorded area of A and B, respectively. If the calibrated area in time i (such as NLCD1990 in the year 1990 and NLCD2000 in the year 2000) is known as A', the calibrated area in time j (B') can be estimated as $(B/A) \times A'$. The ratio of A' and A, or the ratio of B' and B, is called the calibration coefficient.

[20] The calibration coefficients for Ge2004 range from 0.26 in Gansu to 2.10 in Zhejiang for the year 1933. They range from 1.09 in Qinghai to 2.11 in Guizhou and Tibet for the SSB's 1982 data [see *SSB*, 1983] (for major coefficients of each province, see Table S1). Next, the calibrated model constructed continuous historical cropland areas over the 300 year period. For regions without historical records, we assumed that no change occurred (for major coefficients for each province or other regions, see Table 1). For regions where historical records covered multiple contemporary provincial boundaries, we used their records for all covered provinces. For instance, relative changes in cropland in Hainan and Chongqing before 1990 were in Guangdong and Sichuan, respectively.

[21] To reconstruct historical forest distribution, we first combined HE2007 and NLCD2000 with the sixth forest inventory (1999–2003) from SFAC. HE2007 and the sixth forest inventory data are directly comparable in forest area for the year 1700 and the period 1999–2003 because they have the same definition of forest as far as tree canopy cover (i.e., greater than or equal to 0.2). Thus, we reconstructed forest area during 1700–1949 by calibrating the sixth forest inventory data against NLCD2000, which covers almost the same time period (see Table S1 for coefficients of forest area for each province). Because of limited available data, we assumed no change in forest occurred after 2000. Because of the unreliability of forest inventory data before 1981

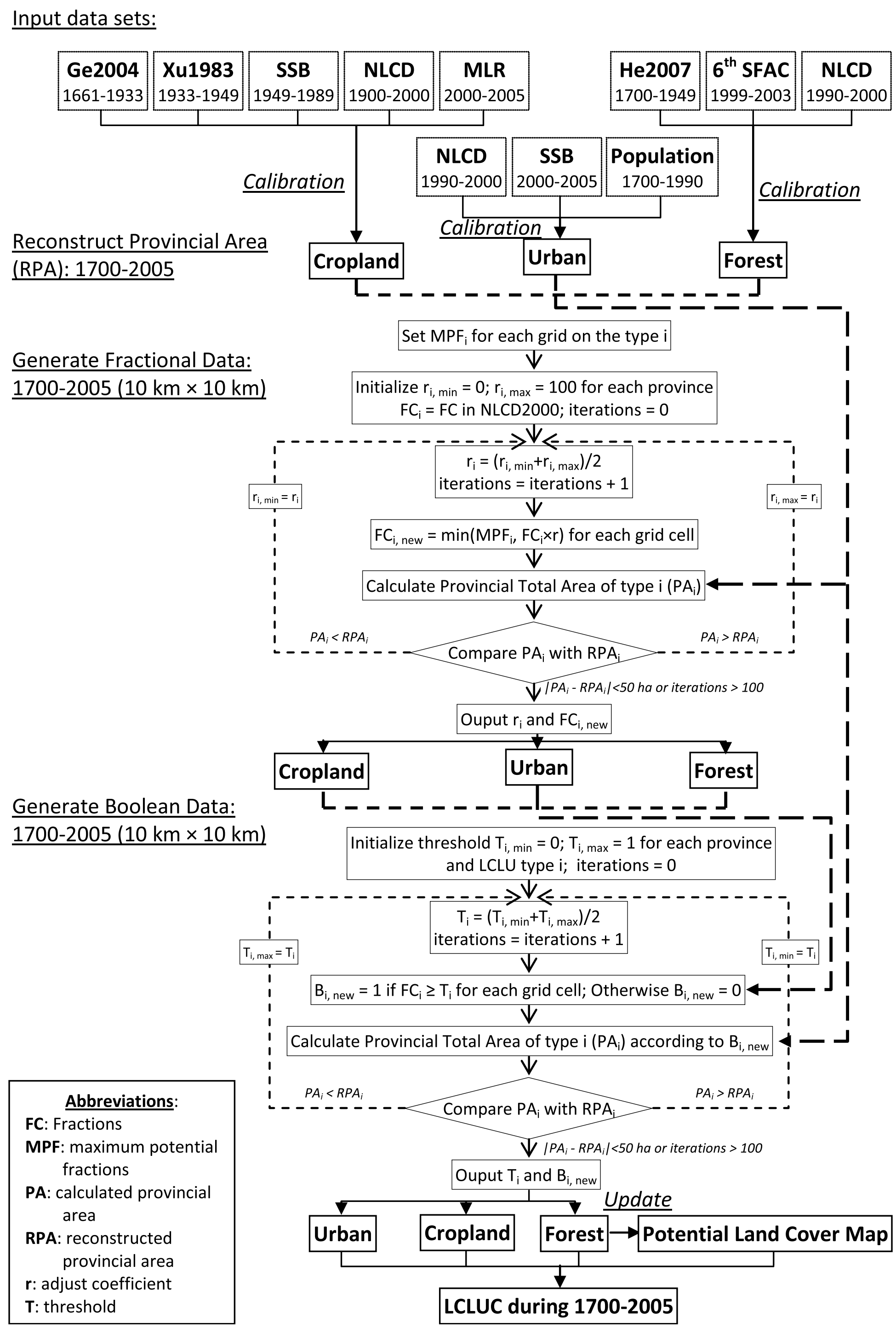

Figure 2. Workflow for reconstructing historical land cover and land use change of China.

[*Zhang*, 1988; *Houghton and Hackler*, 2003], we used only the sixth forest inventory data to calibrate HE2007. The calibrated HE2007 and NLCD1990 were linearly interpolated to generate forest area during 1949–1990. To obtain an annual cropland, forest, and urban area for each province, the calibrated data for specified time periods were linearly interpolated.

2.2.3. Generating the Fractional Grid Data of Cropland, Forest, and Urban Areas

[22] In order to generate the fractional grid data and the Boolean grid data, we applied the principle that the provincial area (PA) of each LCLU should stay consistent with the original reconstructed provincial area (RPA). The major procedures we used to generate these fractional grid data are

depicted by Figure 2 and described in Text S2. Figure 3 shows some of the results of these fractional data for different time periods.

2.2.4. Generating the Boolean Data of Cropland, Forest, and Urban Areas

[23] In these Boolean data sets, one unique LCLU category was assigned to each grid cell at an annual time step. These data sets were generated to retrieve historical LCLU transitions on a grid level.

[24] A similar method of calculation was used to estimate the threshold (*T*) for each province and each LCLU category in order to generate the Boolean data from the fractional grid data (Figure 2). Detailed descriptions can be found in Text S3.

[25] By overlaying the annual Boolean gridded data of cropland, forest, and urban areas on the natural land cover map, we obtained historical LCLU conversions between human-dominated land use and natural land cover. Conversions between forest and woodland were also reconstructed by comparing forest distributions in the Boolean gridded data sets with the potential land cover map which represents the distributions of both forest and woodland.

3. Results

3.1. LCLUC in China From Prehistory to 1700

[26] According to the reconstructed LCLU data sets, before 1700, the Chinese people had cultivated about 95 million ha of cropland, which accounts for 10.1% of the total land area; they had also built up 1.6 million ha of land for settlement or other construction purposes. Primary forest and woodland were major sources of cropland and urban during this period (Table 2). Of the total cropland, 70.4 million ha was converted from forest/woodland, and the other 24.5 million ha was from nonforest land. A total of 22.2 million ha of grassland was converted to cropland before 1700. These earlier land use activities were unevenly distributed across China. For instance, 76% of the total land conversions from forest/woodland to cropland occurred in the Eastern Plain and southeast China. Conversions from nonforest natural land cover (including grassland, shrubs, wetland, and desert) to cropland mostly occurred in the north (9.9 million ha) and northwest (8.6 million ha).

3.2. LCLUC During 1700–2005

[27] The main characteristics of LCLUC from 1700 to 2005 are the expansion of cropland and urban areas and the shrinking of natural land cover. A total of 38.4 million ha of forest (i.e., 21.8%) was lost during this period while cropland and urban increased by 39.7 million ha (41.8%) and 17.1 million ha, respectively. Grassland area decreased by 15.0 million ha (i.e., 5.3%), and shrub area decreased slightly by a total of 3.6 million ha (Table 2). However, the temporal and spatial patterns of these LCLUC are more complex than depicted by the net change in numbers.

3.2.1. Temporal Patterns of LCLUC During 1700–2005

[28] Figure 4 shows the changes in cropland, forest, woodland, and urban areas in China from 1700 to 2005. During 1700–1900, the forest area decreased slowly by 2.7 million ha per decade. Then it decreased rapidly by 7.4 million ha per decade in the following 50 years. However, starting in the 1950s, forested area began to recover, and a total of 51.8 million ha of new forest was developed. The expansion of forested areas is mainly due to an increase in plantations and is affected slightly by the regeneration of natural forest [*Fang et al.*, 2001; *Houghton and Hackler*, 2003; *Zhang and Song*, 2006].

[29] The trends in area covered by woodlands and forests were opposite, with woodlands slowly increasing in spatial cover from 1700 until a maximum of 169 million ha by the middle of the 1930s. Since then, woodland has declined to 107 million ha in the year 2000.

[30] The area covered by grasslands and other nonforested land did not change significantly from 1700 to the 1930s. However, from the 1930s to the 1960s, their combined loss was a substantial 16.0 million ha. In the last 5 years, their area has increased by 2.7 million ha.

[31] Changes in China's cropland area have been complex throughout the historical period under study. Cropland had a relatively slow increase of 22 million ha from 1700 to the middle of the 1930s. Then, cropland increased substantially to its historical maximum of 152 million ha in the mid-1950s, followed by a steady decrease of 13.6 million ha through 1990. The substantial increase in cropland and decrease in forest area from the 1930s to the 1950s was driven by many factors: the large-scale exploitation of natural resources in the northeast during the Sino-Japanese War, the land reform campaign in other areas that took place in 1946–1952, and the low productivity of land which needed more cultivation to support increasing populations [*Xu*, 1983; *Ge et al.*, 2004; *Feng et al.*, 2005]. In the 1990s, however, cropland area recovered by about 3.0 million ha, as described in detail by *Liu et al.* [2005b]. In the most recent 5 year period, cropland lost 6.8 million ha.

[32] There were two periods of quick expansion in urban area over the past 300 years. The first period was from 1700 to the middle of the 1810s with an expansion of 4.0 million ha. The second period was from 1950 to 2005 with an increased rate of 2.0 million ha per decade.

3.2.2. LCLU Conversions During 1700–2005

[33] Information on land use conversions, rather than just net changes in area for each major land use type, can provide a better understanding of the path and fate of LCLUC and its consequences. During 1700–2005, a total of 53.1 million ha of forest was converted to other LCLU. Of these conversions, 77.0% were degraded into woodland, and 21.2% were reclaimed as cropland. Meanwhile, 7.2 million ha of primary cropland were urbanized, and 4.8 million ha were abandoned or degraded into natural land cover. Nonforested land as a whole had almost the same amount of conversions as forest. A total of 40.9 million ha of nonforested land (including woodland, grassland, shrub, wetland, tundra, and desert) was cultivated. Overall, the new croplands were converted almost equally from forested and nonforested lands. Although total forest area decreased in this period, 14.1 million ha of new forests appeared in some regions; these new forests were converted from woodland through either forest regrowth or plantation.

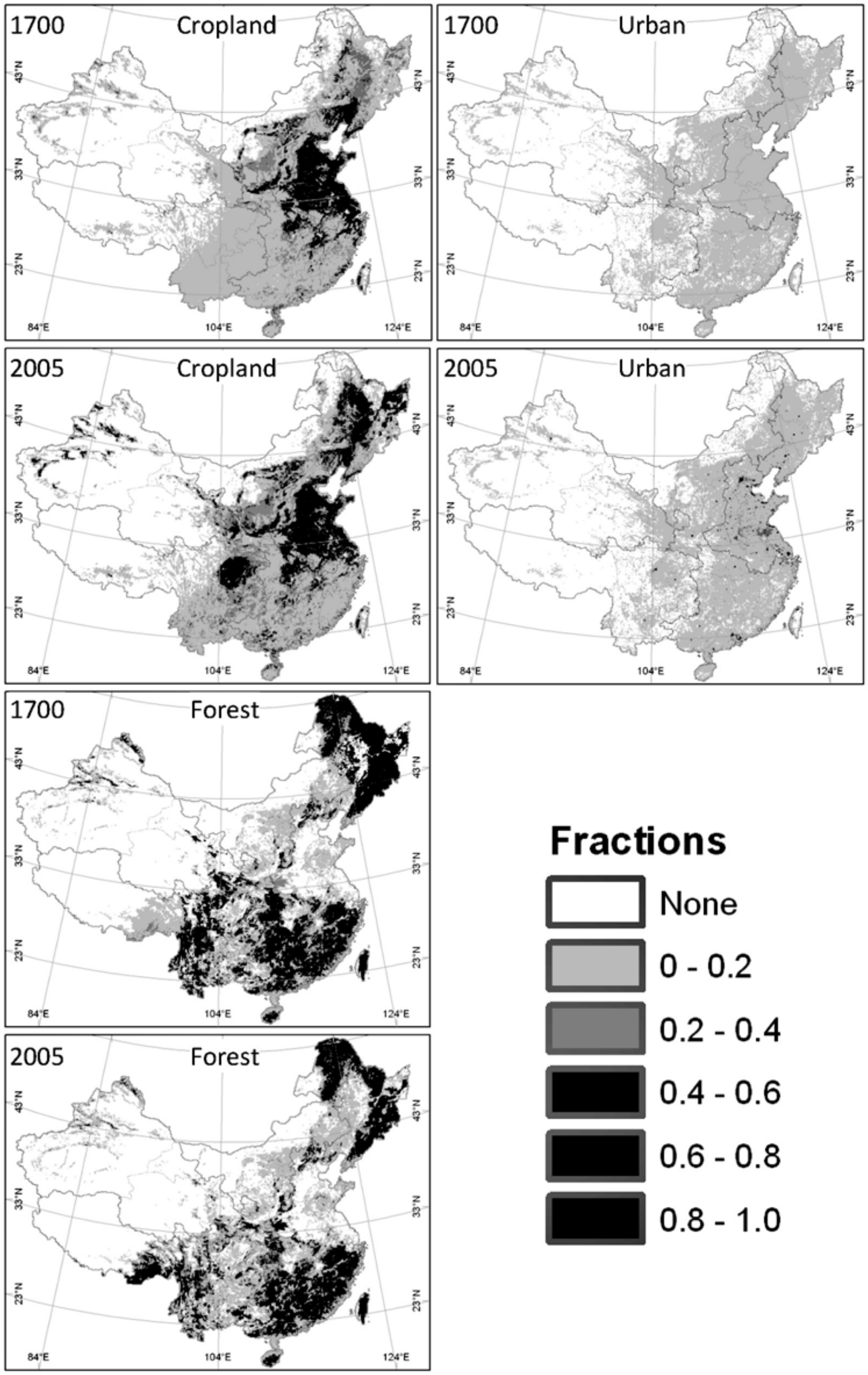

Figure 3. Historical distributions of cropland, forests, and urban during 1700–2005 (fraction of grid cell).

Table 2. Prehistory and Recent Land Cover and Land Use Change in China[a]

LULC	Prehistory[b]	1700[c]	Prehistory to 1700 Changes	2005[c]	1700–2005[c] Changes	Percent
Tundra	68.0	67.9	−0.1	67.9	0	0.0
BBDF	0.8	0.3	-	0.4	0.1	33.3
BNDF	15.2	12.4	-	12.0	−0.4	−3.2
TBDF	117.4	57.7	-	36.1	−21.6	−37.4
TBEF	36.4	26.1	-	21.0	−5.1	−19.5
TNEF	156.3	62.4	-	52.4	−10	−16.0
TNDF	10.9	8.6	-	6.4	−2.2	−25.6
TrBDF	0.6	0.2	-	0.0	−0.2	−100.0
TrBEF	18.7	8.3	-	9.2	0.9	10.8
Woodland[b,c]	-	109.5	-	110.3	0.8	0.7
Dshrub	12.4	10.1	−2.3	8.6	−1.5	−14.9
Eshrub	23.9	23.3	−0.6	21.2	−2.1	−9.0
Grassland	306.5	284.3	−22.2	269.3	−15	−5.3
Wetland	2.6	2.6	0	2.5	−0.1	−3.8
Desert	168.9	168.5	−0.4	168.0	−0.5	−0.3
Crop	0.0	94.9	94.9	134.6	39.7	41.8
Built-up	0.0	1.6	1.6	18.7	17.1	1068.8

[a]Area unit: million ha. BBDF, Boreal Broadleaf Deciduous Forest/Woodland; BNEF, Boreal Needleleaf Evergreen Forest/Woodland; TBDF, Temperate Broadleaf Deciduous Forest/Woodland, TBEF, Temperate Broadleaf Evergreen Forest/Woodland; TNEF, Temperate Needleleaf Evergreen Forest/Woodland; TNDF, Temperate Needleleaf Deciduous Forest/Woodland; TrBDF, Tropical Broadleaf Deciduous Forest/Woodland; TrBEF, Tropical Broadleaf Evergreen Forest/Woodland; Dshrub, Deciduous Shrub; Eshrub, Evergreen Shrub.
[b]In potential land cover map, forests and woodlands are combined together;
[c]In contemporary LCLU, forests and woodlands are separated; that is, forest type only represents forests, not woodlands.

3.2.3. Spatial Patterns of LCLUC During 1700–2005

[34] Because of China's substantial heterogeneity in climate, soil, and vegetation type, as well as their unevenly developed socioeconomics across different regions, its LCLUC showed significant spatial variations during 1700–2005. For example, in forested land, the largest loss occurred in the northeast (e.g., Liaoning, Jilin, and Heilongjiang) with 22.8 million ha, followed by the southwest (e.g., Sichuan, Chongqing, Guizhou, Yunnan, and Tibet) with 8.7 million ha (Table 3 and Figure 3). Conversely, in the north (e.g., Inner Mongolia, Shannxi, Shanxi, and Ningxia) and the Eastern Plain (e.g., Hebei, Beijing, Tianjin, Shandong, Henan, Jiangsu, Shanghai, and Anhui), the forested land increased slightly during this period (Table 3 and Figure 3).

[35] Changes in nonforest natural land cover occurred mostly in the Eastern Plain which lost 12.3 million ha; the northeast had the largest expansion of 9.6 million ha (Table 3 and Figure 5a). Cropland expansion was widely distributed across China but had different rates in each region (Figure 3). The southwest and the northeast had the largest cropland expansion, with increases of 14.8 million ha and 11.0 million ha, respectively. All other regions experienced an increase in cropland area totaling 13.9 million ha. The sources of these new croplands were different in each region (Figure 5a). In the northeast, for instance, the primary source of cropland was the conversion of 9.6 million ha of forest. In the southwest and the northwest (e.g., Xinjiang, Qinghai, and Gansu), however, the conversion of nonforest natural land cover was the major source of new cropland, which accounted for 14.0 million ha and 7.1 million ha, respectively (Table 3 and Figure 5a).

[36] Urbanization was widespread in China during the last 300 years. The Eastern Plain and the southeast had the largest expansion, with urban areas increasing by 8.2 million ha and 3.3 million ha, respectively (Figures 3 and 5a).

3.2.4. LCLUC During 1980–2005

[37] In recent decades, China has experienced enormous economic growth and urbanization. Simultaneously, many policy reforms and forestry and agricultural economy laws have been promulgated and implemented [*Hyde et al.*, 2003; *Wang et al.*, 2004, 2007]. According to our new data sets, LCLUC during 1980–2005 was characterized by shrinking cropland and expanding urban and forest areas, although there were significant annual variations at the national level (Table 4 and Figure 5b). Cropland area decreased by a total of 8.4 million ha (−5.8%) while urban and forested land increased by 4.9 million ha (+35.7%) and 12.6 million ha

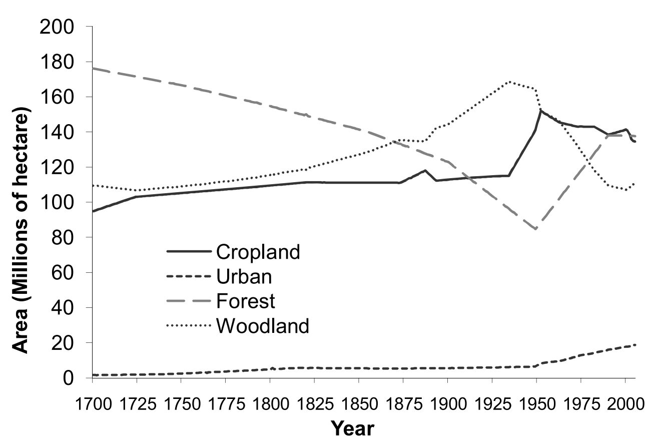

Figure 4. Changes in the area of forest, cropland, urban, and woodland during 1700–2005 (unit: million ha).

Table 3. Land Cover and Land Use Change During 1700–2005 in Each Region of China[a]

Region	Forest			Other Natural Land Cover[b]			Crop			Urban		
	1700	2005	Change	1700	2005	Change	1700	2005	Change	1700	2005	Change
Northwest (NW)	8.6	3.8	−4.8	261.8	258.7	−3.1	3.3	10.2	+6.9	0.1	1.0	+0.9
Northeast (NE)	52.4	29.6	−22.8	10.5	20.1	+9.6	14.9	25.9	+11.0	0.2	2.5	+2.3
Eastern Plain (E)	6.5	7.6	+1.1	38.2	25.9	−12.3	31.7	34.9	+3.2	0.7	8.9	+8.2
North (N)	13.5	16.0	+2.5	124.4	117.1	−7.3	16.5	19.4	+2.9	0.2	2.1	+1.9
Southeast (SE)	58.1	52.4	−5.7	44.1	45.4	+1.3	23.4	24.4	+1.0	0.3	3.6	+3.3
Southwest (SW)	37.0	28.3	−8.7	187.2	180.5	−6.7	5.1	19.9	+14.8	0.1	0.7	+0.6
Total	176.1	137.7	−38.4	666.1	647.7	−18.4	94.9	134.7	+39.8	1.6	18.8	+17.2

[a]Area unit: million ha.
[b]Includes grassland, tundra, desert, wetland, shrub, and woodland.

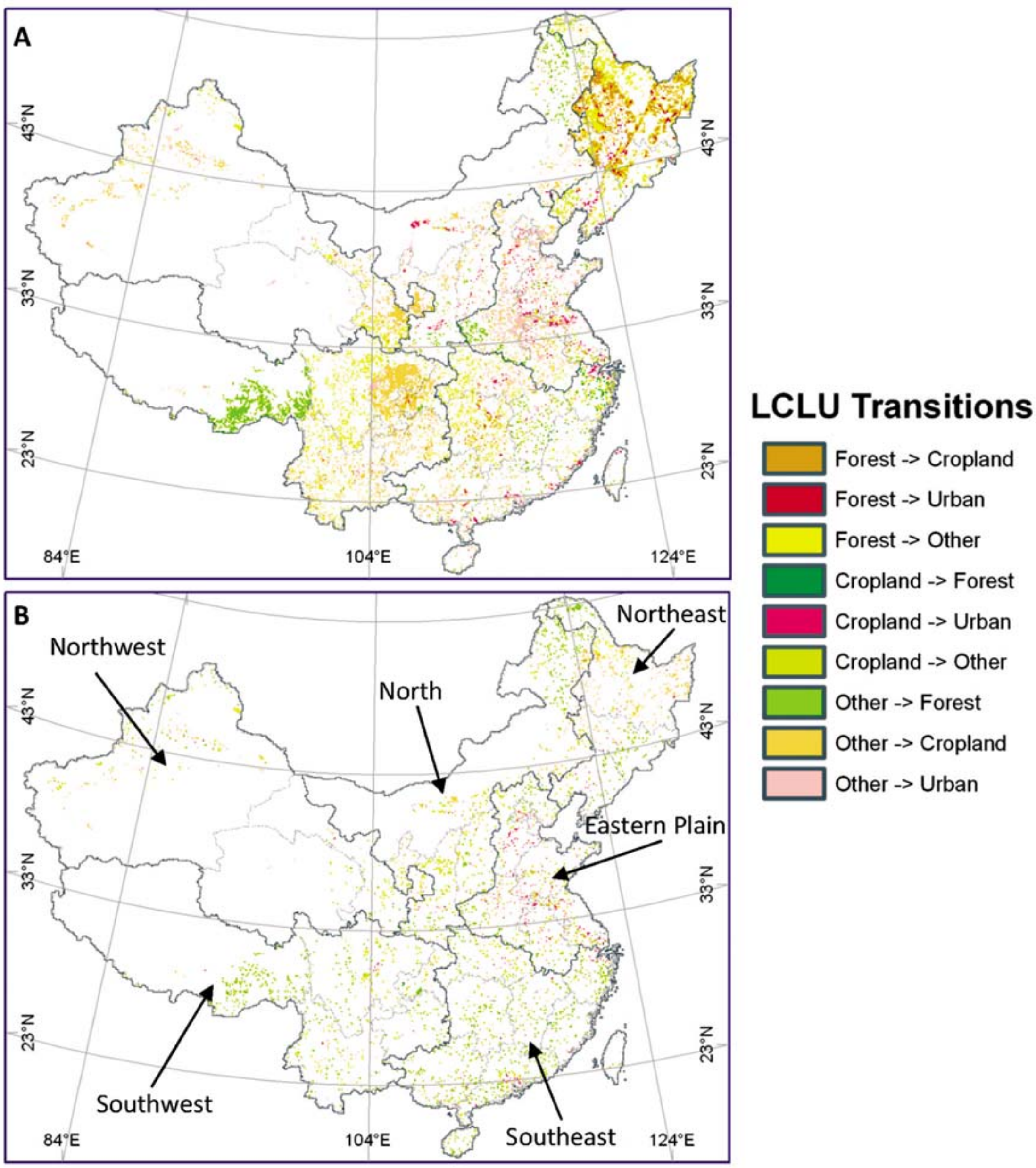

Figure 5. Land cover and land use transitions between (a) 1700 and 2005 and between (b) 1980 and 2005.

Table 4. Land Cover and Land Use Change During 1980–2005 in Each Region of China[a]

	Forest		Other Natural Land Cover[b]		Cropland		Urban	
	Change	Percent	Change	Percent	Change	Percent	Change	Percent
Northwest	+0.4	+12.3	−0.2	−0.1	−0.5	−4.4	+0.3	+36.7
Northeast	+0.1	+0.5	−2.7	−11.9	+2.1	+8.9	+0.4	+21.8
Eastern Plain	+1.3	+21.0	+0.1	+0.3	−3.9	−9.9	+2.5	+38.4
North	+2.2	+16.3	−0.6	−0.5	−2.1	−9.6	+0.4	+26.5
Southeast	+5.3	+11.2	−3.6	−7.3	−2.8	−10.2	+1.1	+42.7
Southwest	+3.2	+12.8	−2.1	−1.2	−1.3	−6.3	+0.2	+54.0
Total	+12.6	+10.1	−9.2	−1.4	−8.4	−5.8	+4.9	+35.7

[a]Area unit: million ha.
[b]Includes grassland, tundra, wetland, shrub, woodland, and desert.

(+10.1%), respectively (Table 4). Cropland area decreased by 4.6 million ha during 1980–1990 and increased by 3.0 million ha during 1990–2000. In the last 5 years, cropland has declined again, by 6.8 million ha (Figure 5b). Forest area increased by 13 million ha during the 1980s but declined slightly in the 1990s.

[38] Figure 5b shows the spatial distributions of LCLUC during this period. The Eastern Plain, the north, and the southeast had lost more than 10% of their cropland (Table 4 and Figure 5b). The northeast, on the contrary, showed a cropland expansion of over 10%. All regions had more than a 20% expansion in urban area during 1980–2005, and the Eastern Plain had the largest increase in urban area (2.5 million ha). The southeast and the southwest had the largest increases in forested land, with increases of 5.3 million ha and 3.2 million ha, respectively.

[39] The major LCLU conversions in this period were not between forest and cropland; even though these two land cover types had almost the same amount of change, the change was in opposite directions. Among the converted cropland, about 71% was converted into nonforest land, and 27% was urbanized. *Chen* [2007] reported a similar trend in shrinking cropland in China during 1977–2003 and attributed it to urbanization. Of the new forest, 98% came from woodland and a small fraction from cropland. These results indicate that transitions among natural land covers, forest plantations over woodland, and the abandonment of croplands are major features of contemporary LCLUC and that this trend may extend into the near future along with current socioeconomic developments and policies [*Zhang*, 2000].

4. Discussion

4.1. Comparisons With Other LCLU Data Sets of China

[40] In order to investigate discrepancies among different data sets in their estimations of historical cropland and forest and evaluate our new data sets, we set up a comparison of forest, cropland, and urban areas. If spatial data sets were available, we used a consistent boundary map and land-water mask map to derive the amount of forest, cropland, and urban area in each region from these spatial data. Otherwise, we directly used regional data that had our same administrative boundaries.

4.1.1. Cropland Area

[41] Large discrepancies among different estimations of China's cropland area, even for contemporary periods, have been widely reported [*Heilig*, 1997; *Frolking et al.*, 1999; *Liu et al.*, 2005b]. These estimations range from a minimum of 96 million ha by SSB to a maximum of 293 million ha by Global Land Cover 2000 (GLC2000) (Table 5). However, a generally accepted estimate is that China had about 120–140 million ha of croplands around the 1990s [*Wu and Guo*, 1994; *Alexandratos*, 1996; *Heilig*, 1997; *Verburg et al.*, 1999; *Lin and Ho*, 2003; *Feng et al.*, 2005; *Liu et al.*, 2005b]. Our historical LCLU data sets were very close to the national land survey data by MLR on contemporary cropland area. The total national cropland area from our estimations was also close to the following data sources: *Ramankutty et al.*'s [2008] updated cropland data sets, HYDE3.0 [*Klein Goldewijk*, 2001], *Houghton and Hackler*'s [2003] China land use data, and China's Land Resources Map with a scale of 1:1,000,000 (LRM) [*Shi*, 1991] (Tables 1 and 5). Generally, remote-sensing-based estimations from low-resolution sensors (e.g., MODIS and SPOT VEGETATION) overestimate cropland area (Table 5) [*Frolking et al.*, 1999; *Smil*, 1999]. Differences in spatial resolution in these data sets can also produce discrepancies in the results. For instance, Global Land use Modeling (GLM) with 1 degree latitude-longitude resolution has much higher estimations of cropland area than other data sets. Our data show that the southwest and the Eastern Plain of China have the largest discrepancies among different data sets, particularly MODIS, GLC, and GLM (Table 5).

[42] Estimations of change in cropland area also range widely among different data sources, such as +120 million ha (hereafter, a plus sign indicates an increase, and a minus sign indicates a decrease) from GLM, +42 million ha from *Houghton and Hackler* [2003], +26 million ha from HYDE3, and +15 million ha from *Ge et al.* [2004] for the period from 1700 to 1900 (Table 4). Our study estimated that during this period, the change in cropland was +22 million ha, which was slightly higher than estimations based on historical archives from the Qing Dynasty [*Ge et al.*, 2004].

[43] For the period 1980–2000, there were even greater discrepancies. For instance, HYDE3 [*Houghton and Hackler*, 2003] and GLM indicated an increase in cropland area ranging from 3 to 33 million ha. The SSB, however, estimated

Table 5. Comparisons of Estimations on Cropland Area Among Different Studies[a]

Data Sources	Period	NW	NE	E	N	SE	SW	Total	Reference
This study	1700	3	15	32	16	23	5	95	
	1900	4	15	35	17	25	17	113	
	1980	11	24	39	21	27	21	143	
	2000	11	26	36	22	25	21	141	
	2005	10	26	35	19	24	20	135	
GLM[b]	1700	3	11	12	7	18	12	63	*Hurtt et al.* [2006]
	1900	10	31	36	22	50	35	184	“”
	1980	11	33	40	26	54	38	201	“”
	1999	11	31	39	29	41	54	204	“”
HYDE3	1700	4	5	12	9	9	10	50	*Klein Goldewijk* [2001] and *Klein Goldewijk and Ramankutty* [2004]
	1900	8	8	17	15	14	15	76	“”
	1980	7	16	27	14	18	17	100	“”
	2000	10	22	36	19	24	22	133	“”
Houghton and Hackler	1700							47	*Houghton and Hackler* [2003]
	1980							128	“”
	2000							140	“”
SSB[c]	1952	5	16	39	15	20	10	106	*SSB* [1991]
	1990	7	16	30	13	18	11	96	“”
MLR[c]	1996	10	22	35	19	24	21	130	*MLR* [2000–2006]
	2005	9	21	33	16	23	19	122	“”
Ge[b]	1685			30		16		59[e]	*Ge et al.* [2004]
	1724			33		19		72[e]	“”
	1893			34		19		79[e]	“”
LRM[c]	around 1980	11	23	38	20	26	21	139	*Shi* [1991]
Heilig[c]	1985	10.8	21.2	38.7	20.4	26.3	22.2	139.7	*Heilig* [1997]
	1995	11.0	21.0	37.4	20.7	25.1	22.0	137.1	“”
ChinaNLCD	1990	10.4	23.6	37.0	20.2	25.8	21.2	138.2	*Liu et al.* [2005a]
	2000	10.9	26.1	36.2	21.5	25.4	21.1	141.1	“”
FAO[d]	1961							105	*FAOSTAT* [2001]
	1980							100	“”
	2005							156	“’
SAGE	1700							66	*Ramankutty and Foley* [1999]
	1900							193	’’’
	1980							217	’’’
	1990							209	’’’
GLC2000[e]	2000	23	10	64	17	76	103	293	*Wu et al.* [2004]
MODIS[f]	2001	7	43	56	23	28	24	181	*Friedl et al.* [2002]
Ramankutty	2000	11	26	36	22	25	21	140	*Ramankutty et al.* [2008]

[a]Area unit: million ha.
[b]Global Land use Modeling data. The value is recalculated from the original data.
[c]Area does not include Taiwan. According to our new data sets, Taiwan has 0.7 million ha of cropland in 2005.
[d]Arable land and permanent crops.
[e]Type is pure cropland (The original types of cropland, rice paddy, and wheat).
[f]Type is pure cropland.

a significant decline in cropland area during 1980–1995, which was comparable to the amount of urban expansion estimated from satellite data [*Ji et al.*, 2001; *Houghton and Hackler*, 2003]. The reported large increase (about 23 million ha) in cropland area during 1981–1985 [*Food and Agriculture Organization* (*FAO*), 2001] was used by *Houghton and Hackler* [2003] in estimating the effect of LCLUC on China’s terrestrial carbon budget. This study estimated a 1.9 million ha decrease in cropland area during 1980–2000, which was less than the 4.3 million ha decrease reported by the SSB for the period 1980–1995. We attribute the difference between these numbers primarily to our use of the data source derived from Landsat TM/ETM images [*Liu et al.*, 2005b; *Deng et al.*, 2006; *Yan et al.*, 2009], which had been intensively validated with ground truths, and which indicated an expansion of cropland during 1990–2000.

[44] Our new data sets developed by this study not only make estimates of the amount and spatial distributions of cropland, but also reflect long-term trends recorded by national surveys and high-resolution satellite data. Our study further suggests that using high-resolution satellite data as a baseline or initial map is essential for accurately reconstructing historical LCLUC.

4.1.2. Forest Area

[45] As with croplands, there are significant discrepancies among various studies' estimations of the contemporary status of forest area and its changes over time (Table 6). In its sixth survey, the Forest Resource Inventory of China (FRIC) reported that China had 175 million ha of forest (with tree canopy cover > 20%) during 1999–2003, including all national forest cover and additional forest (i.e., economic plantations and bamboo forest). MODIS, GLC, and MLR had estimations that were close to the FRIC survey. AVHRR-based tree cover data sets had the lowest estimations of total forest area (Table 6). Differences in the definition of forest land and spatial resolution may have caused these discrepancies, which were also indicated by *Zhang and Song* [2006] (Table 6). In our new data sets, forest is defined as land with tree canopy cover greater than or equal to 30%, which is consistent with forest inventories before 1994, but higher than the current FRIC definition, which has changed since the fourth inventory [*CMF*, 1999]. Our estimations of forest area in 1990 (i.e., 136 million ha) are similar to the results of the third forest inventory for the period 1989–1993 (i.e., 132 million ha) in mainland China.

[46] Various available data sets differ significantly in their estimations of change in forest area during 1700–1900 (Table 6). *He et al.* [2007] estimated that China's forest decreased by 88 million ha, and *Houghton and Hackler* [2003] estimated the forest loss at 127 million ha. Using He et al.'s historical data set that was calibrated against satellite data, we estimated that the forest area decreased by 53.3 million ha during 1700–1900.

[47] Many variations exist in estimations of forest area and its changes over the last 2 decades. FRIC reported that total forest area increased by 52 million ha (42%) during 1984–2003. The change in the definition of forest after 1994, however, may have led to some biases [*CMF*, 1999; *Houghton and Hackler*, 2003; *Zhang and Song*, 2006]. *Houghton and Hackler* [2003] estimated that forest area increased by 21 million ha during 1980–2000. They also mentioned some disagreement concerning contemporary forest area even within the same official data sets. For instance, *Fang et al.* [2001] reported that forest area increased only by 10.2 million ha during the period 1977–1998, which is close to our estimation of a 12.6 million increase in forest area during 1980–2000.

[48] Plantations have made substantial contributions to forest expansion in China during recent decades. According to the sixth forest inventory, plantation forest reached 53.6 million ha (about 31% of total forest area). *Houghton and Hackler* [2003] mentioned that the increase in forest area after 1980 was the result of new plantations. Since economic reforms, which started in 1978, Chinese forestry policy has shifted from its focus on timber production to multiobjective forestry, which includes protecting the environment and increasing household income [*Wang et al.*, 2004]. Six major forest projects have been started since 1989, concentrating on ecologically sensitive areas [*Zhang et al.*, 2000; *Zhang and Song*, 2006]. Our data set reflects the historical expansion of plantation forest. However, detailed information on plantation forest, such as their survival rate and rotations, is needed for accurately reconstructing the dynamics of plantation forest over past decades.

4.1.3. Urban Area

[49] To the best of our knowledge, there is no spatial data set for LCLU change in China over this long historical period that includes urbanization. In our newly reconstructed historical LCLU data sets, urban includes urban and rural settlements, factories, quarries, mining, and other built-up land for special uses such as airports, but does not include roads and railways which could not be mapped directly from Landsat TM/ETM with a scale of 1:100,000 [*Liu et al.*, 2005b]. Our estimation of total urban area in 1996 is 17 million ha, which is less than the survey (urban and rural settlements and industrial and mining sites) from MLR, which estimated 24 million ha. However, our estimation of its changes in recent decades is consistent with analyses from *Chen* [2007] and remotely sensed data [*Liu et al.*, 2005a].

[50] Urbanization in developing countries is considered a local disturbance on the land surface with minor impact on the environment. However, urban sprawl in developing countries has received more attention in recent decades because of recent discoveries concerning its long-term effects on water and air quality, natural resources, and social sustainability [e.g., *Chen*, 2007; *Grimm et al.*, 2008; *Bloom et al.*, 2008; *Liu et al.*, 2008]. Our data sets reveal that significant urbanization across China has formed an important component of land transitions during recent decades. Therefore, because we included urban areas in our study, our data sets demonstrate significant improvements over those produced by *Hurtt et al.* [2006] and other global and national data sets for China.

4.2. Implications to China's LCLU in the Future

[51] This study indicates that human activities in China have led to significant changes in land surfaces through land use, particularly cultivation and construction, which have affected 16% of the total land area. Urbanization has exceeded cropland expansion as the major use of converted natural land cover. The large area of land that has transitioned from woodland to forest over the last several decades indicates that it is possible for large areas of deforested land to recover and return to forest in China. Even though Chinese government agencies have promoted many conservation policies to restrict cropland conversions, especially on highly productive cropland, the loss of cropland in many regions is becoming a serious concern [*Lichtenberg and Ding*, 2008]. China faces increasing demands on limited land resources, including the competing demands of food production,

Table 6. Comparisons of Forest Area Among Different Data Sources[a]

	Time Period	NW	NE	E	N	SE	SW	All China	References
This study[b]	1700	8.6	52.4	6.5	13.5	58.1	37.0	176.1	
	1800	6.7	50.9	4.9	11.4	50.0	30.6	154.6	
	1900	3.6	45.8	3.0	8.5	39.6	22.3	122.8	
	1980	3.4	29.4	6.3	13.7	47.1	25.1	125.0	
	2000	3.8	29.6	7.6	16.0	52.5	28.3	137.7	
	2005	3.8	29.6	7.6	16.0	52.5	28.3	137.7	
Houghton and Hackler	1700							322	*Houghton and Hackler* [2003]
	1850							234	”’
	1950							157	””
	1980							121	“”
	2000							142	“”
MLR[c]	1996	5	32	10	24	50	41	162	*MLR* [2000]
RF[d]	1700							296	*Ramankutty and Foley* [1999]
	1900							200	“”
	1980							167	“”
	1990							167	“”
He[c]	1700	23	58	10	25	62	70	248	*He et al.* [2007]
	1900	10	46	5	16	42	42	160	“”
	1949	5	27	3	12	35	26	109	“”
LRM[c]	1978–1985	7	31	10	24	51	47	170	*Shi* [1991]
GLC	2000	18	49	8	39	42	29	185	*Wu et al.* [2004]
MODIS	2001	4	24	7	15	50	50	150	*Friedl et al.* [2002]
Tree Cover	1992/1993	7	23	6	19	23	38	116	*DeFries et al.* [2000]
ChinaNLCD[e]	1990	3.8	30.4	7.6	16.1	52.0	28.4	138.3	*Liu et al.* [2005a]
	2000	3.8	29.5	7.6	15.9	52.5	28.3	137.6	“”
FAO[f]	1990							157	*FAOSTAT* [2001]
	2005							197	“”
Fang[c]	1977–1981							95.6	*Fang et al.* [2001]
	1984–1988							102.1	“”
	1989–1993							108.6	“”
	1994–1998							105.8	“”
FRIC[c,g,h]	1984–1988	4	26	8	20	37	29	123	*CMF* [1982, 1989, 1994, 1999] and *SFAC* [2005]
	1989–1993	4	26	9	20	42	31	132	“”
	1994–1998	4	29	11	23	52	37	157	“”
	1999–2003	11	30	13	30	56	50	175	“”

[a]Area unit: million ha.
[b]Forests (natural or planted forest (tea garden, orchards, groves, and nursery forest are also included) where tree canopy cover is more than 30%).
[c]Area does not include Taiwan. According to our new data sets, Taiwan has 2.45 million ha of forests in 2005.
[d]Includes forests and woodlands.
[e]Forests (natural or planted forests with tree canopy cover greater than 30%) [*Liu et al.*, 2005b].
[f]Land under natural or planted stands of trees, whether productive or not. This category includes land from which forests have been cleared but that will be reforested in the foreseeable future, but it excludes woodland or forest used only for recreation purposes. The question of shrub land, savannah etc. raises the same problem as in the category “permanent pastures.” From 1995 and onward there are no data for this category. Data relating to forest area can be obtained from the FAO Forest Resources Division.
[g]Type is forest cover and additional forests.
[h]Canopy coverage > 30% before 1994; >20% starting in 1994.

bioenergy, housing, environmental protection, industry, and other construction infrastructures. Consequently, China’s land cover and land use trends will most likely continue across the nation, though these trends may have different speeds and directions in different periods, similar to the decadal variations during 1980–2005. Changes in climate and atmospheric chemical compositions can also affect LCLUC [*Liu et al.*, 2005]. As a result, China’s land cover and land use will not stabilize, but will continuously fluctuate with even broader spatial extension than that of earlier stages. The direction of LCLUC, however, is becoming more focused on environment protection through the restoration of natural forest and the mandatory conversion of marginal cropland to forest or grassland [*Zhang et al.*, 2000; *Wang et al.*, 2004; *Zhang and Song*, 2006]. Certainly, LCLUC will greatly impact regional climate, water resources, and biogeochemical cycles in China [*Fu*, 2003; *Tian et al.*, 2003; *Liu et al.*, 2008; *Tian et al.*, 2008].

4.3. Uncertainties and Needs for Future Studies

[52] This study focused on the consequences of agricultural activities and urbanization processes in China over the last 300 years based on historical archives and contemporary satellite data. These historical archives, however, only documented net changes in total cropland and forest area, rather than transitions between these and other land covers. Hence, shifting cultivation, which was described as "the largest contributor to gross land use transitions through the 1700–2000 period" by *Hurtt et al.* [2006, p. 19], could not be directly revealed by these reconstructed LCLU data sets.

[53] Because of data limitations and the emphasis on long-term trends, our current results may not have caught significant fluctuations in land use during specific, short time periods, such as the massive increase in cropland between 1949–1957 in Xinjiang and Heilongjiang that was reported by *Lin and Ho* [2003]; rather, our study attempted to capture significant changes over longer periods of time.

[54] Land degradation in China is widely distributed and substantially decreases land productivity [*Fang and Xie*, 1994; *Yan et al.*, 2009]. This study's comparison of forest and cropland area with other data sources indicated that large areas of lost forest did not convert to cropland, but degraded into other land covers during the last 300 years. This study did not consider vegetation dynamics, except for conversions between forest and woodland. Therefore, it could not provide a direct and detailed history of land degradation caused by environmental change and human activities. Further studies need to be conducted in order to investigate land degradation and long-term natural vegetation dynamics driven by human disturbances and environmental changes.

[55] This study documents historical LCLUC in China over the last 3 centuries. In order to improve current understanding of the patterns of LCLUC and their driving forces, much work still needs to be done. First, more data sources, especially remotely sensed data that cover a wider range of spatial and temporal dimensions, land survey data on forest plantations and settlements, historical archives on different themes, detailed surveys of land management, and information on woody harvest and products are needed to generate more detailed, multiple thematic historical LCLU data sets. Second, although the new data sets from this study have the most reliable estimations of historical land use, they are still based on the assumption that the current patterns of cropland and forest mimic their historical distributions, which may be problematic, as suggested by *Houghton and Hackler* [2003]. Therefore, in order to improve future research, it is essential that long-term historical data sets be reconstructed using validated, spatially explicit land use models. These spatially explicit land use models could be used to reconstruct historical LCLU and project future LCLU with high spatial resolutions by coupling land survey data, socioeconomic factors, and biophysical and biogeochemical processes as described by *Verburg et al.* [1999]. Consequently, driving force analyses of these historical LCLUC as conducted by *Liu et al.* [2005] for contemporary LCLUC in China would be very helpful in calibrating a land use model. Thirdly, more specific investigations should be made to study the impact of extreme events, such as political anomalies, extreme climate events, and policy shifts on the land use dynamics. These investigations could be made on a national scale or by focusing on small-scale case studies. Finally, continuous land cover characteristics, such as tree canopy coverage and productivity, which can indicate the quality of land resources and land cover, should be considered in the next generation of LCLUC data sets. As *Zhang* [2000, p. 61] pointed out, the total net conversion of natural land cover to competing land uses, especially between two totally different categories, will "never again be [as] radical and rapid [as the] changes in major land uses such as [those which have] occurred during history". Quantifying the changes in characteristics of LCLU is essential for assessing its progressive impacts and its interactions with regional climate, biogeochemical cycles, and hydrological processes.

5. Conclusions

[56] Relying on state-of-the-art high-resolution, remotely sensed data and highly reliable historical archives, we reconstructed historical LCLU data sets for the period 1700–2005. Our results suggest that China has experienced substantial LCLUC due to human activities and environmental changes over the past 300 years. These LCLUC had significant spatial and temporal variations, which were driven by complex social and economic development in different regions throughout our study period. The main features of LCLUC in China during the past 3 centuries were the expansion of cropland and urban areas and the shrinkage of natural land covers. The largest shrinkage in forest and expansion of cropland area occurred in the northeast and southwest of China. This study reveals that increases in cropland area came almost equally from the conversion of both forested and nonforested land and that a large amount of this conversion between forest and woodland occurred during 1700–2005.

[57] The substantial fluctuations and high spatial variations of LCLUC during 1980–2005 indicate that competition for different land uses (food, environmental conservation, infrastructures, and industry) is becoming increasingly intense and that the direction of land use change is becoming more sensitive to government policies and social-economical development. Our study indicates that rapid urbanization across China has been an important component of land transitions during recent decades. Most of the vanished cropland, however, was converted into nonforest land, of which urbanized land was less than 30%. These results indicate that transitions among natural land covers, forest plantations on woodland, and the abandonment of croplands are major features of contemporary LCLUC.

[58] The data sets produced from this study show the major LCLUC in China over a long historical period and can be used by ecosystem, hydrological, and climate models for assessing the impacts of LCLUC on regional climate,

water resources, and biogeochemical cycles in terrestrial ecosystems. To further eliminate the uncertainties of LCLUC data and make a reliable projection of LCLUC for the future, we need to advance our understanding of its driving forces and develop an advanced, spatially explicit land use model by coupling remotely sensed data, Geographical Information Systems (GIS), vegetation dynamics, and socioeconomic information.

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