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History of land use in India during 1880–2010: Large-scale land transformations reconstructed from satellite data and historical archives

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ABSTRACT

In India, human population has increased six-fold from 200 million to 1200 million that coupled with economic growth has resulted in significant land use and land cover (LULC) changes during 1880–2010. However, large discrepancies in the existing LULC datasets have hindered our efforts to better understand interactions among human activities, climate systems, and ecosystem in India. In this study, we incorporated high-resolution remote sensing datasets from Resourcesat-1 and historical archives at district (N = 590) and state (N = 30) levels to generate LULC datasets at 5 arc minute resolution during 1880–2010 in India. Results have shown that a significant loss of forests (from 89 million ha to 63 million ha) has occurred during the study period. Interestingly, the deforestation rate was relatively greater under the British rule (1880–1950s) and early decades after independence, and then decreased after the 1980s due to government policies to protect the forests. In contrast to forests, cropland area has increased from 92 million ha to 140.1 million ha during 1880–2010. Greater cropland expansion has occurred during the 1950–1980s that coincided with the period of farm mechanization, electrification, and introduction of high yielding crop varieties as a result of government policies to achieve self-sufficiency in food production. The rate of urbanization was slower during 1880–1940 but significantly increased after the 1950s probably due to rapid increase in population and economic growth in India. Our study provides the most reliable estimations of historical LULC at regional scale in India. This is the first attempt to incorporate newly developed high-resolution remote sensing datasets and inventory archives to reconstruct the time series of LULC records for such a long period in India. The spatial and temporal information on LULC derived from this study could be used by ecosystem, hydrological, and climate modeling as well as by policy makers for assessing the impacts of LULC on regional climate, water resources, and biogeochemical cycles in terrestrial ecosystems.

1. Introduction

Human activities have altered the Earth's environment by changing the land use and land cover (LULC) in the past several centuries (Liu et al., 2005a, 2005b; Hurtt et al., 2006; Liu and Tian, 2010). LULC changes are major driving forces for biogeochemical cycles, climate change, and food production from regional to global scales (Houghton and Hackler, 2003; Feddema et al., 2005; Jain and Yang, 2005; Tian et al., 2012a; Tao et al., 2013). Since 1850, LULC change alone has contributed to approximately 35% of anthropogenic carbon dioxide (CO_2) emissions across the globe (Houghton et al., 2012). However, these environmental changes occur at multiple spatial and temporal scales that may highly differ among regions. In the 20th century, India has experienced a 6-fold increase in population (200 million to 1200 million) coupled with economic growth (especially after the 1950s) that has resulted in LULC transformations (Richards and Flint, 1994; DES, 2010). For example, Richards and Flint (1994) have reported that total forest area decreased from 100 million ha to 81 million ha while cropland area increased from 100 million ha to 120 ha during 1880–1950. The temporal pattern of deforestation during 1880–2000 has a major control over temporal pattern of carbon emissions due to land use change (Chhabra and Dadhwal, 2004). Therefore, accurate LULC estimation is key for understanding interactions among human activities, climate systems, and ecosystem as well as for the formulation of policies at national level (Houghton and Hackler, 2003; Tian et al., 2003; Arora and Boer, 2010).

In India, detailed LULC dataset collected from village level survey and aggregated at district level (N = 590) is available only for the period of 1950–2010 from the Department of Economics and Statistics (DES), Government of India (DES, 2010). In addition, Richards and Flint (1994) have compiled the historical LULC archives including croplands,

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forests, grasslands/shrublands, and built-up areas at state level (N = 30) during 1880–1980. However, there are certain limitations of the inventory LULC datasets. For example, LULC datasets in the tabular forms are inadequate for the use in climate, hydrological and biogeochemical models that require LULC in the gridded format (Feddema et al., 2005; Liu et al., 2008; Tian et al., 2010). On the other hand, the remote sensing techniques make it possible to monitor contemporary LULC pattern at high spatial resolution but only cover a relatively shorter time period. In India, several coarse resolution LULC dataset products such as moderate resolution imaging spectroradiometer (MODIS; Loveland and Belward, 1997; Hansen and Reed, 2000), GlobCover developed from Envisat's Medium Resolution Imaging Spectrometer (MERIS; Arino et al., 2008), and GLC2000 based on SPOT4 satellite (Bartholome and Belward, 2005) are available for the recent years. In addition, a regional LULC dataset based on the Advanced Wide Field Sensor of Resourcesat-1 has been developed at a spatial resolution of 56-m by the National Remote Sensing Agency, India during 2004–2010 (NRSA, 2007). Linking remote sensing data (short time series but high spatial resolution) and inventory data (long time series but coarse spatial resolution in tabular format) is also a big challenge (Verburg et al., 2011).

Recently, Banger et al. (2013) reported that contemporary total cropland and forest area estimated at state level from inventory DES was better represented by LULC datasets developed from Resourcesat-1 than global scale remote sensing datasets. It is difficult to generate the historical LULC datasets using coarse resolution global remote sensing datasets that have large discrepancies with the inventory datasets in India. Therefore, it is imperative to integrate contemporary remote sensing datasets from Resourcesat-1 with the historical tabular archives to generate more reliable and useful LULC datasets, which cover longer time periods in India. Previously, several global scale LULC datasets have been developed by combining remote sensing and inventory land use records at state level in India (Ramankutty and Foley, 1999; Klein Goldewijk et al., 2011). In this study, we made the first attempt to integrate the high-resolution satellite (Resourcesat-1 at 56-m resolution) and existing inventory datasets at district and state levels to generate the LULC datasets at 5 arc minute resolution for the period of 1880–2010 in India. We focused on five major LULC types including cropland, forest, grasslands/shrublands, wastelands, and built up or settlement areas. We believe that our newly developed LULC dataset would provide more detailed and accurate information on the spatial and temporal pattern of LULC changes in India. Previous studies have shown that land conversions among these LULC types as well as associated management practices have significant effects on the terrestrial biogeochemical cycles at regional and global scales (Banger et al., 2012; Tao et al., 2013). Therefore, our LULC datasets would be greatly helpful to enhance our understanding on the impacts of LULC on regional climate, water resources, and terrestrial biogeochemical cycles.

This paper is organized into three different sections: a description of the input data sources, methodologies for constructing the gridded LULC datasets at 5′ arc resolution, and an analysis of the magnitude as well as major drivers for land conversions during 1880–2010. In addition, we also discussed the uncertainties in our newly developed LULC datasets and made recommendations to cautiously use these LULC datasets for scientific research and formulation of policies.

2. Data and methods

India is located between 8–38° N latitudes and 66–100° E longitudes, covering a geographical area of approximately 328 million ha. There are four distinct seasons in India including: winter (December–February), summer (March–June), south-west monsoon season (June–September), and post-monsoon season (October–November) (Prasad et al., 2007). A four month period of south-west monsoon season accounts for approximately 80% annual rainfall in the country. However, there is a large spatial variability in the south-west monsoon rainfall that gives rise to different kinds of vegetation across India. Natural vegetation ranges from tropical evergreen in the south to the alpine meadows in the north, and from the deserts in the west to the evergreen forests in the north-east of India (Joshi et al., 2006).

2.1. Land use and land cover databases

In this study, we focused on the five dominant LULC types including cropland, forest, grasslands/shrublands, wastelands, and built-up or settlement areas. Cropland category is defined as the land cultivated for crops including single season, double or triple crops, shifting cultivation, horticultural plantations, and orchards. The Food and Agricultural Organization of the United Nations (FAO) has also included temporary fallow lands into the Agricultural Area category (FAO, 2013). However, we did not include fallow lands in cropland category since fallow lands have a significantly different influence on the biogeochemical and hydrological cycles (Tian et al., 2003). Forest category includes the area evergreen and deciduous trees with >10% canopy cover as well as degraded forest types that has <10% of the canopy cover. This definition is similar to the forest cover definition used by the National Remote Sensing Center, India (NRSA, 2007). The built-up or settlement area is defined as the land occupied by buildings, roads and railways. In the historical archives, it is difficult to differentiate the grasslands, grazing areas, and shrublands. Therefore, we classified the term grasslands/shrublands as the areas occupied by grasslands and permanent pastures, meadows, and shrublands. Wastelands include the area that cannot be brought under cultivation such as area covered by mountains, deserts, and ice caps.

In this study, we used inventory LULC datasets available at district (N = 590) and state level (N = 30) from different sources along with the LULC datasets developed from remote sensing datasets available from the Advanced Wide-Field Sensor (AWiFS) of Resourcesat-1 to construct LULC at 5 arc minute resolution during 1880–2010 (Richards and Flint, 1994; DES, 2010; Table 1). The LULC generated in this study are represented in fractional forms which consists percentages of five LULC types (cropland, forest, grasslands/shrublands, wastelands, and built-up) in each grid cell.

2.2. Contemporary land cover and land use datasets from Resourcesat-1

We used contemporary LULC datasets (for the year 2005 and 2009) generated from imagery of the satellite Resourcesat-1 (NRSA, 2007). Resourcesat-1 was launched in 2003 with a near-polar sun synchronous orbit at a mean altitude of 817 km. Two main imaging sensors of the satellite include Linear Imaging Self-Scanner (LISS-III) and AWiFS. The AWiFS sensor operates in four spectral bands with three in the visible and near-infrared bands and one in the short-wavelength infrared region. The swatch size of AWiFS is 740 km with temporal resolution of 5-days and spatial resolution of 56-m at nadir. Based on the imagery of the AWiFS sensor, National Remote Sensing Agency, India (NRSA) has generated yearly 19-LULC classes at 56-m grid resolution in India during 2005–2009 (NRSA, 2007). In brief, NRSA (2007) has used 680 multi-temporal quadrant data that covered different crop growing seasons and were used to generate the LULC datasets. Stratified random points generated through ERDAS imagine software was used to assess the accuracy of the LULC classes generated by the Resourcesat-1. A minimum of 20 sample points were considered for each class to estimate the accuracy of the classified output. Ground truth data, legacy maps, and multi-temporal FCC have formed the basis for assessment and generation of Kappa co-efficient (NRSA, 2007). In this study, we used the following LULC classes from the Resourcesat-1 datasets: urban (built-up), cropland (kharif crop, rabi crop, shifting cultivation, plantation/orchards, and zaid crop only), forest (evergreen forest, deciduous forest, scrub, and degraded forest), grasslands/shrublands (grasslands and scrubland), and wastelands (snow covered, gullied, rann, and other wastelands). However, we did not use the waterbodies, littoral swamps, and current fallow LULC categories available in the Resourcesat-1 datasets.

Table 1
Land cover and land use datasets used in this study.

Dataset	Methodology	Spatial resolution	Time period	LCLU[a] types
Department of Economics and Statistics	Inventory	District level	2000–2010	9-fold LCLU classes
Indiastat	Inventory	District level	1950–2000	9-fold LCLU classes
Richards and Flint (1994)	Inventory	State level	1880–1920	Agriculture, forests, wastelands, grasslands, built-up
Resourcesat-1	Remote sensing	56 m	2005–2009	19-fold LCLU classes

[a] LCLU: Land cover and land use.

2.3. District level datasets during 1950–2010

In India, district level (N = 590) yearly LULC datasets are available from the Directorate of Economics and Statistics (DES), India during 1998–2010 (DES, 2010, http://eands.dacnet.nic.in/ accessed in September, 2012). Of the total geographical area of 328 million ha, LULC datasets are available for only 305 m ha. The land use survey is conducted annually and is based on a 9-fold classification including (1) forests; (2) area under non-agricultural uses; (3) barren and uncultivable land; (4) pastures and other grazing lands; (5) land under miscellaneous tree crops; (6) culturable waste land; (7) fallow land other than current fallows; (8) current fallows; and (9) net area sown area. The LULC data is collected at village level and is later aggregated to higher hierarchical units such as districts and states in India.

District level LULC datasets were not available for the years earlier than 1998 (DES, 2010). Therefore, we collected the district level LULC datasets from Indiastat datasets during 1950–2000 (http://www.indiastat.com/aboutus.aspx, accessed September 2012). Indiastat is a private organization that collects, collates, and compiles the socio-economic information about India. LULC classes archived by the Indiastat were similar to the 9-fold LULC classification system developed by DES. Their district level LULC datasets were collected at a decadal time scale during 1950–2000.

2.4. State level datasets during 1880–1950

Richards and Flint (1994) have compiled the historical LULC archives at state level for five time periods including 1880, 1920, 1950, and 1980 in India. They collected the LULC datasets from official agricultural and economic statistics; historical and demographic texts, reports, and articles; and from any other available datasets for the region. In brief, LULC categories in their datasets included temporary and permanent crops, settled and built up areas, forests, grasslands and shrubland, wetlands, and surface waters (Richards and Flint, 1994). For this study, we collected the state level LULC datasets for three time periods including 1880, 1920, and 1950. In order to make the LULC classification from Richards and Flint (1994) similar to other LULC datasets, temporary and permanent crops were aggregated and classified as cropland, grasses and shrubland were aggregated as grasslands/shrublands category, while built-up and forests were used as such from Richards and Flint (1994).

2.5. Algorithm for the reconstruction of LULC during 1880–2010

Several studies have combined the contemporary remote sensing datasets with historical LULC archives to construct the distributions of cropland and forest cover over several centuries (Ramankutty and Foley, 1999; Klein Goldewijk, 2001; Leff et al., 2004; Ramankutty et al., 2008; Fuchs et al., 2013). For India, global scale studies have used the LULC records at state level (N = 30) to reconstruct the historic LULC datasets which may produce significant discrepancies (Ramankutty and Foley, 1999; Leff et al., 2004; Banger et al., 2013). In this study, we used finer scale district level (N = 590) datasets during 1950–2010 and state level (N = 30) LULC records during 1880–1950 combined with remote sensing datasets from Resourcesat-1 to reconstruct LULC at 5 arc minute resolution during 1880–2010 in India. During the study period, several bifurcations as well as exchange of boundaries have occurred in different states and districts in India. Therefore, our first task was to construct the uniform boundaries throughout the study period for district and state units in India. In this study, the inventory LULC datasets from two or more states that are bifurcated or exchanged boundaries in recent years were aggregated to make state boundary similar to the ones used by Richards and Flint (1994). For example, we aggregated LULC datasets and Uttar Pradesh and Uttarakhand; Madhya Pradesh and Chhattisgarh; Bihar and Jharkhand, where bifurcations occurred during the study period. A similar exercise of aggregating the LULC records was performed for several districts in order to make uniform district boundaries in India. In 2010, approximately 590 districts existed and we aggregated LULC datasets from two or more districts that exchanged boundaries that made a total of 290 district units throughout the study period.

In this study, LULC records from inventory datasets were calibrated with Resourcesat-1 datasets to construct LULC at 5 arc minute resolution during 1880–2010. Flow chart of the procedure followed for generating historical LULC using remote sensing and inventory datasets is provided in Fig. 1. In brief, the objective of our calibrations was to estimate total as well as spatial distribution of historical built-up, cropland, forest, grassland/shrublands, and wastelands areas in each district or state by comparing the baseline of Resourcesat-1 datasets. 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 Resourcesat-1 2005) 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. In order to generate the fractional grid datasets, we applied the principle that the district or state area (UA) of each LULC category should stay consistent within the original constructed unit area (RUA).

During the calibration process, built-up areas are generated first followed by croplands, forests, grasslands/shrublands, and wastelands in turn. In the DES datasets, urban or settlement areas were not separately reported, while another category "non-agricultural area" was available that included the land occupied by buildings, roads and railways or under water, e.g. rivers and canals, and other lands put to use other than cropland (DES, Department of Economics and Statistics, Government of India, 2010). We generated the historical built-up area from non-agricultural area category available in the DES datasets. Firstly, we assumed that area under water-bodies has not changed during 1950–2010 and therefore calculated area under water-bodies using Resourcesat-1 and subtracted it from non-agricultural area to generate the inventory settlement area in the DES datasets. Then, we used the ratio of contemporary built-up area in Resourcesat-1 to contemporary settlement area in the inventory datasets and used this factor to generate historical built-up areas in each district or state in India. There are several procedures to allocate the built-up areas in pixels within a district or state (Fuchs et al., Lu et al., 2008). In this study, the location of the changes in the built-up areas in pixels within a district or state was determined by the population density based on the assumption that urban sprawl tends to occur in the region with higher population density (Fuchs et al., 2013). The 5 arc min resolution population layers were generated by combining global 1 km population maps (CIESIN, 2011) and state level population data in India.

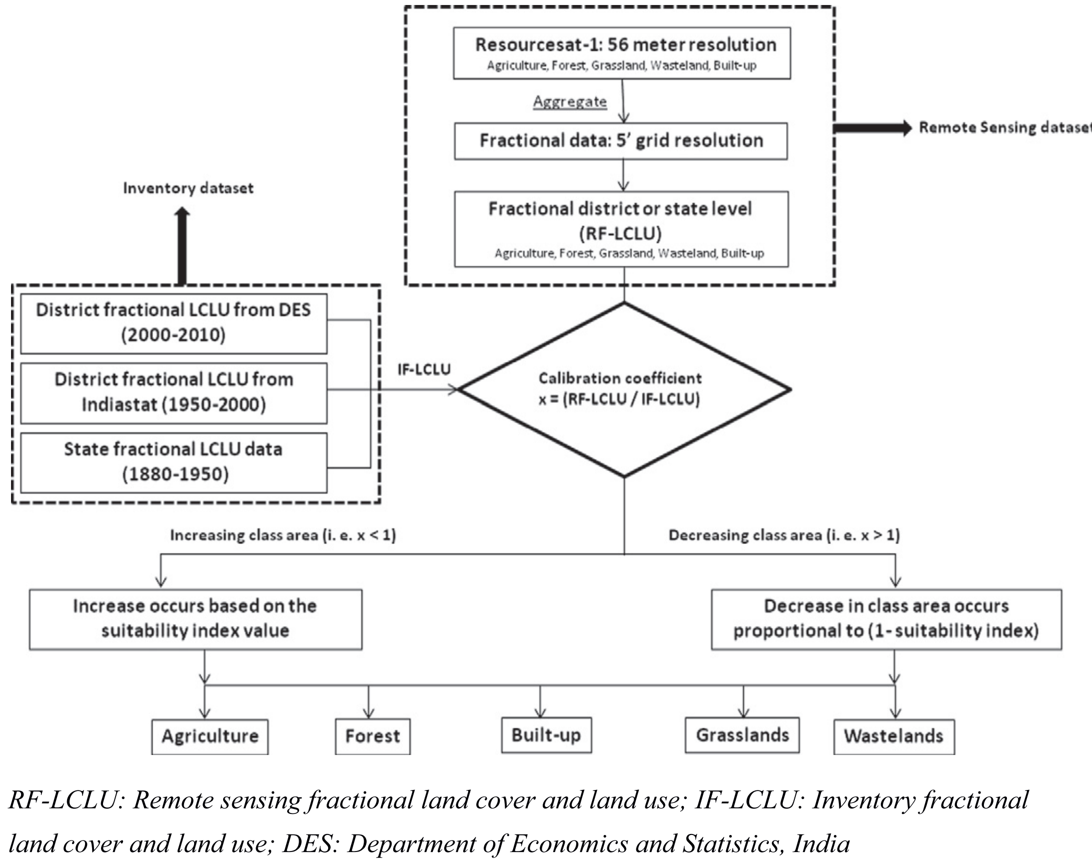

Fig. 1. Procedure for generating the historic land cover and land use dataset using remote sensing and inventory datasets during 1880–2010. RF-LCLU: Remote sensing fractional land cover and land use; IF-LCLU: Inventory fractional land cover and land use; DES: Department of Economics and Statistics, India.

In the calibration process, the allocation of the cropland within a state or district was determined by the crop suitability index, a similar approach used by Fuchs et al. (2013). The crop specific suitability index was available at 5 arc minute resolution by FAO (2013). The crop suitability index of FAO is based on the multiple factors affecting crop production such as long term average climate data (during 1960–1990), soils, land cover, and elevation (http://www.fao.org/nr/gaez/faqs/en/#sthash.sS02NC2r.dpuf). The allocation of cropland within a state or district was a two-step process. Firstly, we generated the distribution of different crop types using DES datasets at state level in India. We assumed that distribution of major croplands has not changed during the study period. After developing the crop distribution maps, we extracted the cropland suitability maps for the relevant crop types generated at 5 arc minute resolution by FAO (2013). Finally, the suitability index of different crops was added together to develop one overall crop suitability map over the country. During the calibration process, if total cropland area has to be decreased in a state or district, the pixels with the lowest cropland suitability probability were reduced at a greater rate than pixels with higher suitability index within a district or state. On the contrary, if the cropland area has to be increased during the calibration process, the pixels with higher cropland suitability index were increased at a higher rate than pixels with lower cropland suitability index.

In contrast to built-up and cropland, uniform suitability or probability of changes is assigned to all locations within a state or district for the forests and grasslands/shrublands. In this study, we assumed that each grid cell is initially covered by undisturbed potential vegetation and other land cover types (i.e. bare land, glacier, river, lake, and ocean); the surface areas of lakes, streams, oceans, glaciers, and bare ground in each grid do not change over the study period. When a land conversion occurs, such as cropland expansion from forest, a new cohort is formed and cropland within the grid cell is then subtracted from the undisturbed potential vegetation proportionally. We acknowledge that our assumptions may bring uncertainties, but this is the best way to quantify land conversions given detailed land use/cover information is not available at grid cell level. In this way, changes in natural vegetation types (deforestation, conversion of grasslands/shrublands to cropland, built-up etc.) partially determined the allocation of natural vegetation in pixels within a district or state level. Other land uses which are not classified into any of the category primarily include fallow lands.

3. Results

3.1. Overall changes in land cover and land use during 1880–2010

India has experienced significant loss of grasslands/shrublands and forests followed by the expansion of cropland as well as built-up areas during 1880–2010 (Table 2; Fig. 2a and b). A total of 26 million ha forest areas (from 89 million ha in 1880 to 63 million ha in 2010) and 20 million ha of grasslands/shrublands (from 45 million ha to 25 million ha) has decreased in India. In contrast, total cropland area has increased by 48 million ha (from 92 million ha in 1880 to 140 million ha in 2010). The built-up area was one order of magnitude lower than forest, cropland, and grasslands/shrublands but has increased by 5-fold from 0.46 million ha to 2.04 million ha during 1880–2010.

Table 2
Comparison of land cover and land use estimated (in million ha) by different sources in India.

Dataset	Year	Cropland	Forest	Built-up	References
This study	1880	92.6	89.7	0.46	
	1950	110.1	71.1	0.74	
	1970	120.4	64.7	1.02	
	2005	135.0	65.1	1.7	
	2010	140.1	63.4	2.04	
DES, India	2005	143.26	70.9	–	DES, India
ISLSCP II	1950	132.6	36.4	–	Klein Goldewijk (2007)
ISLSCP II	1970	153.2	33.8	–	Klein Goldewijk (2007)
ISLSCP II	1990	158.5	35.1	–	Klein Goldewijk (2007)
HYDE 3.1	1880	–	–	0.27	Klein Goldewijk et al. (2011)
HYDE 3.1	1950	–	–	0.36	Klein Goldewijk et al. (2011)
HYDE 3.1	1970	–	–	0.58	Klein Goldewijk et al. (2011)
HYDE 3.1	2005	–	–	1.48	Klein Goldewijk et al. (2011)
MODIS-UMD	2001	163.7	29.1	3.9	Hansen and Reed (2000)
MODIS-IGBP	2001	159	28.9	8.04	Loveland et al. (2000)
GlobCover	2005	150.0	24.12	2.64	Bicheron et al. (2008)
GLC2000	2000	135.2	60.3	1.4	Bartholome and Belward (2005)
FAO datasets	2000	179.85	67.71	–	FAO (2013)

FAO datasets also include fallow lands in croplands; therefore, total area may be more than croplands.

3.2. Land conversions during 1880–2010

In this study, we determined the land conversions between different LULC types during 1880–2010 (Fig. 3). Our results have shown that majority of the cropland expansion has been resulted from conversion of forest (16.9 million ha), grasslands/shrublands (14.8 million ha) as well as other LULC types that primarily include fallow lands. Our results have shown that majority of the urbanization has primarily occurred in the cropland areas (0.7 million ha) while only 0.12 million ha of the forest areas were cleared for urban development during 1880–2010 (Fig. 3).

3.3. Spatial and temporal variations of LULC changes during 1880–2010

The landscape of India is diverse with substantial heterogeneity in the climate and soil, as well as has different socio-economic factors that may influence the LULC changes (Mishra, 2002; Joshi et al., 2006). Therefore, there were significant variations in spatial and temporal distribution of LULC changes in India during 1880–2010 (Fig. 2a and b). For example, deforestation has occurred in the central east and west coastal areas while cropland expansion has occurred widely across the entire country during 1880–2010. However, cropland expansion in the central east and southern parts was primarily from the forest clearing while in the Indo-Gangetic Plains it was from grasslands/shrublands and other land uses that primarily include fallow lands. Urbanization has occurred in small patches all over India; however urbanization was more conspicuous in the Indo-Gangetic Plains during 1880–2010.

Results of our study have shown that three time periods (1880–1950, 1950–1980, and 1980–2010) have distinctive LULC conversions in India (Figs. 3 and 4). For example, deforestation has occurred by approximately 2 million ha per decade during 1880–1960 while forest area remained similar (62–64 million ha) in the late half of the 20th century. The time period from 1980 to 2010 was unique that had significant reforestation through the forest regeneration programs in India (Bhat et al., 2001). Therefore, net changes in the total cropland and forest area were negligible during 1980–2010. In contrast, total cropland area showed a significant increasing trend during 1880–2010 (Fig. 4). However, majority of cropland expansion has occurred over a period of two decades (8 million ha increase per decade) from 1950 to 1970. Interestingly, total grassland area roughly remained constant during 1880–1980 that showed decreasing trends after the 1950s (Fig. 4).

Total built-up or settlement areas increased from 0.43 million ha to 2.02 million ha during 1880–2010 and the rate of urbanization was relatively slower (0.03 million ha per decade) during 1880–1950 and then built-up areas increased by 0.26 million ha per decade from 1950 to 2010.

4. Discussion

In this study, we have tried to understand the major drivers that caused LULC changes in India during 1880–2010. For this purpose, we divided the time period from 1880 to 2010 into different sub-groups when the land conversions were significantly greater than other years. In addition, we compared the newly developed LULC datasets with existing datasets for several time periods.

4.1. Major land conversions in India during 1880–2010

Results of our study have shown that majority of the deforestation has occurred during the British government as well as early years after independence that include the time period of 1880–1960 (Figs. 3 and 4). The British government policies that were focused on increasing revenue from timber export as well as infrastructure development may have resulted in the large deforestation in India. For example, in the Forest Policy of India (1894) of the British government, significant emphasis was given to generate maximum revenue through timber cultivation as well as permanent agricultural crops rather than forest sustainability in India (Negi, 1986; Gadgil and Guha, 1995). The rate of deforestation decreased during 1960–1980 while afforestation has occurred in several patches in India during 1980–2010 (Fig. 3). After independence (1947) afforestation and protection of the forests have started in the late half of the 20th century following the government policies to protect forests in India (Bhat et al., 2001; Forest Conservation Act, 1980; The National Forest Policy, 1952). For example, The National Forest Policy of India (1952) stipulated to maintain one-third of its total land area under forest for securing ecological stability (FSI, 1999). After the passage of the National Forest Policy of India (1952), another act Forest Conservation Act (1980) banned forest clearing in India. Under the provisions of this act, approval by the Central Government is necessary for the states to divert forest for cropland and other infrastructural facilities. Under the same act, individual states were directed to raise the compensatory forest equivalent to the forest area being diverted into other land uses. Similarly, the National Forest Policy of 1988 also set the target of 33% forest cover in plains and 66% in forest cover in hilly and mountainous areas in order to prevent erosion and ecosystem degradation (Joshi et al., 2011). Therefore, the government's forest protection policies may have decreased the deforestation rate in the late half of the 20th century in India.

Our results have shown that rate of cropland expansion was significantly greater (8 million ha increase per decade) during 1950–1970 than other time periods (Fig. 3). This might be the result of the special programs such as Grow More Food Campaign (1940s) that was undertaken to improve food and cash crops supply in India. In addition, mechanization, electrification, and the use of high yielding crop varieties and chemical fertilizers made cropland a profitable business resulting in rapid expansion of cropland during 1950–1970. This time period also coincides with the green revolution (in the 1960s) when food production became sufficient to feed the population of India.

The rate of urbanization was relatively slower in 1880–1950 (0.03 million ha per decade); this increased after the 1950s in India. Another interesting observation was a population growth after the 1950s due to food security as well as improvements in the health facilities. Greater increase in human population coupled with economic growth may have resulted in rapid growth of built-up areas during 1950–1980 and 1980–2010 in India (Fig. 5).

4.2. Comparison of cropland, forest, and built-up areas with other datasets

In order to investigate discrepancies among LULC datasets, we compared total forest, cropland, grassland, wasteland, and urban areas from different regional and global LULC data sources. For this effort, we used consistent boundary area for India which is slightly lower than the land boundary used by the NRSA (2007).

4.3. Cropland area

Previously, large discrepancies in the total cropland areas have been reported by various remote sensing LULC datasets (Table 2; Hansen and Reed, 2000; Klein Goldewijk, 2001; Bartholome and Belward, 2005). Contemporary cropland area estimated by our newly developed datasets was 135–140.1 million ha during 2005–2010 which is lower than estimates from the Food and Agricultural Organization (FAO) of United Nations, MODIS-IGBP, MODIS-UMD, and GlobCover (Table 2).

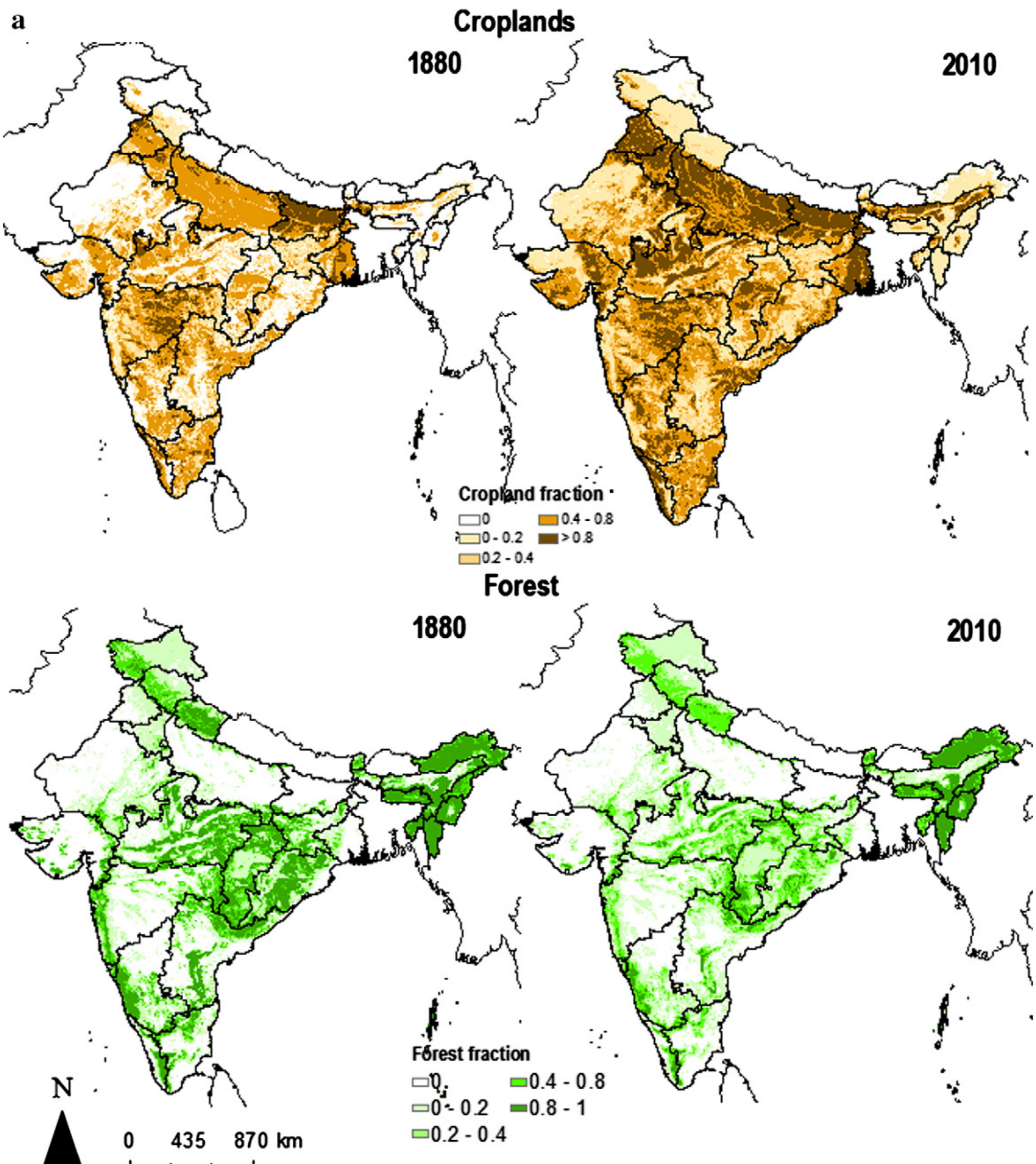

Fig. 2. a. Spatial pattern of croplands and forests in India during 1880–2010. b. Spatial pattern of grasslands/shrublands and urban areas in India during 1880–2010.

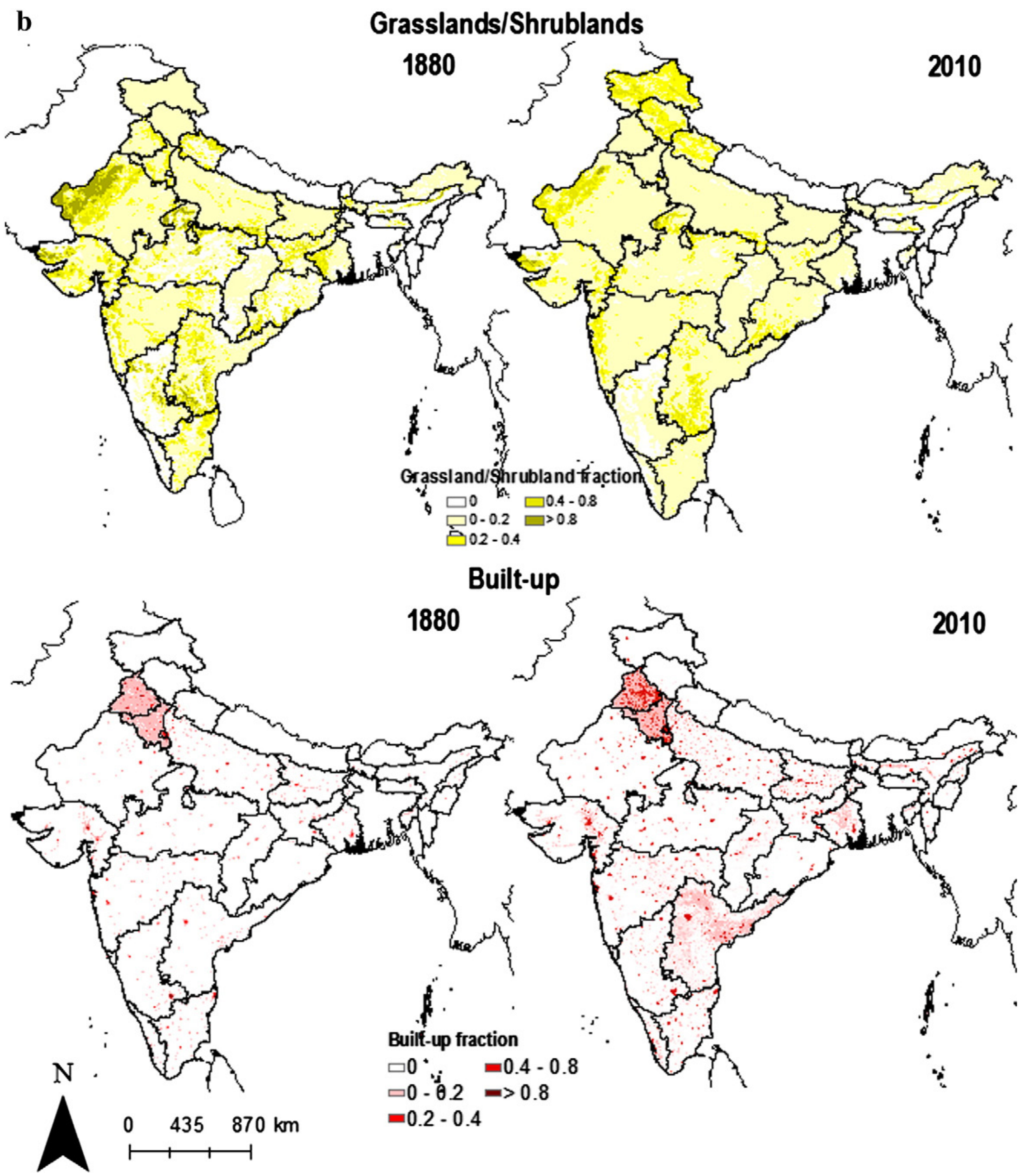

Fig. 2 (*continued*).

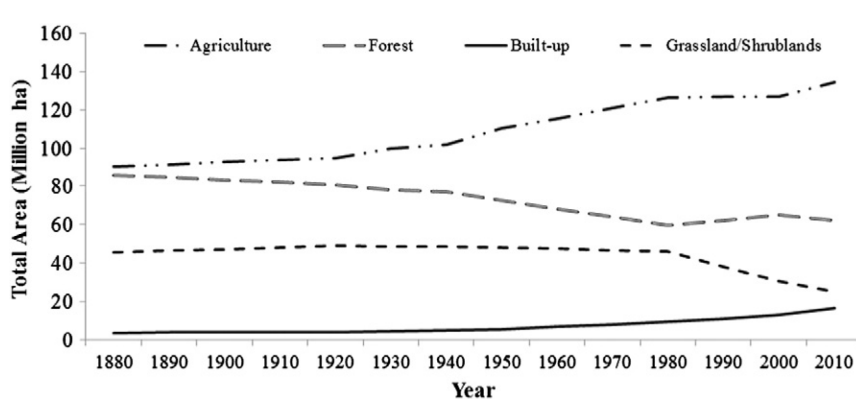

Fig. 3. Temporal pattern of land cover and land use change during 1880–2010.

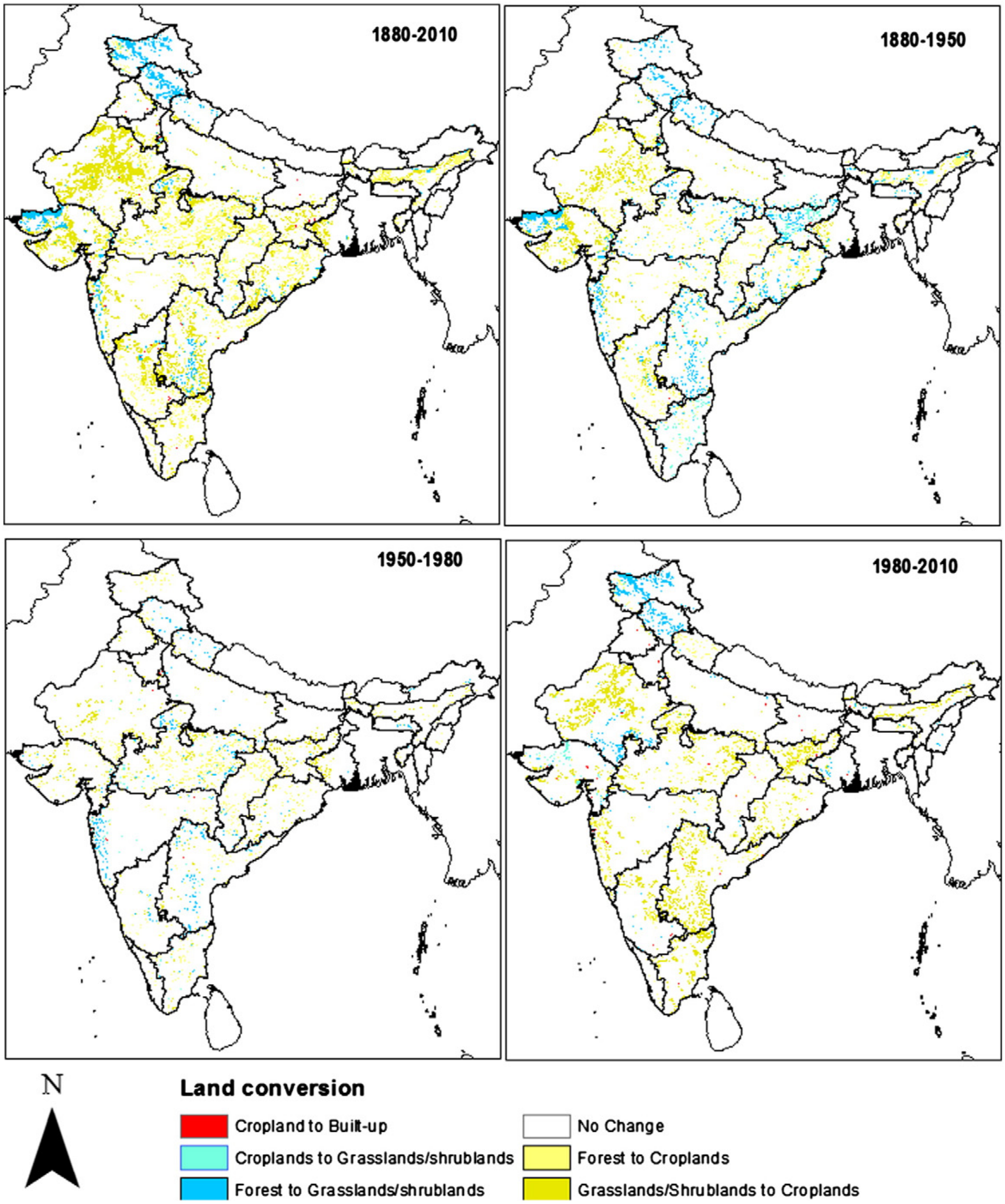

Fig. 4. Land conversions in India during 1880–2010.

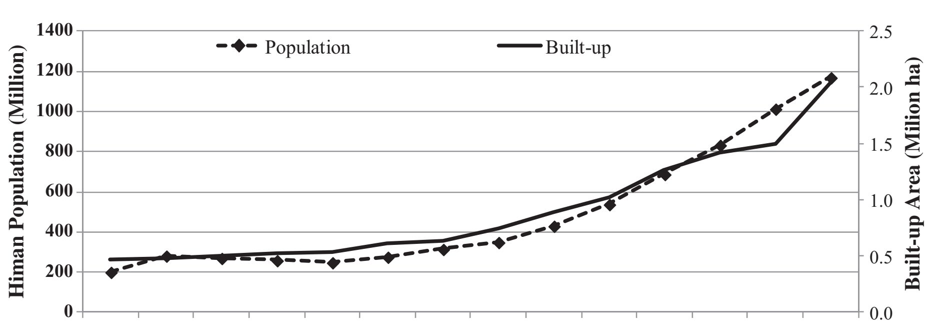

Fig. 5. Changes in the human population and built-up area in India during 1880–2010.

Among all the global datasets, total agricultural area is highest in the FAO datasets (179 million ha in 2005) which also include fallow lands and pastures in the cropland land category (FAO, 2013).

In this study, we have compared the temporal trends in the total cropland area with the International Satellite Land-Surface Climatology Project (ISLSCP II) which are available at 0.5 grid resolution (Klein Goldenwijk, 2007). Our study has shown that agriculture area has increased from 92 million ha in to 140 million ha during 1880–2010 which is similar to ISLSCP II; however the magnitude of increase was different (Table 2). Another long-term study by Dadhwal and Chhabra (2002) also reported an increase in cropland area and production in the Indo-Gangetic Plain region during the period 1901–1990. The increased agricultural production resulted in six-eight fold increase in primary production indicating an intensification of carbon cycling in this agriculturally dominant 'food basket' region of the country. Therefore, cropland datasets developed by our study reflects the long term trends recorded by the national surveys and high-resolution datasets in addition to providing the extent and spatial distribution of such LULC changes.

4.4. Forest cover

In this study, we have compared our historical forest cover estimates with 0.5 degree grid resolution datasets available from ISLSCP II (Klein Goldenwijk, 2007). In 1950 and 1970, forest cover in ISLSCP II ranged from 33 to 36 million ha which is significantly lower than inventory based forest cover estimates from Richards and Flint (1994) and DES (2010). In this way, inclusion of inventory datasets in this study represents an improvement in the forest cover estimations in India.

Except for few global scale datasets, only few coarse historical forest cover estimations exist for India. Therefore, we are restricting our discussion to contemporary estimates of forest cover from different remote sensing datasets (Table 2). Various remote sensing and inventory LULC datasets showed significant discrepancies in the contemporary forest area estimations in India (Banger et al., 2013; Table 2). Our datasets showed that forest area was 63 million ha which is comparable to the 66–69 million ha forest area estimated by the Forest Survey of India in 2010 (FSI, 2012). In contrast to our estimation, the global remote sensing datasets including MODIS-IGBP, MODIS-UMD, and GlobCover have estimated significantly lower forest area (24–40 million ha) in 2005. Greater discrepancy in the forest area estimation may be attributed to the differences in the definition of forest cover in various remote sensing datasets (Banger et al., 2013). For example, MODIS-UMD and MODIS-IGBP which consider an area with >60% canopy cover as forest area showed approximately 30 million ha lower forest area than our dataset in which forest area is covered by >10% canopy cover. We used the forest definition similar to that of the NRSA (2007) where forests include evergreen, deciduous (>10% canopy cover) and degraded forest (<10% canopy cover) in India. When MODIS derived Vegetation Continuous Field (VCF) is segmented with tree fraction similar to definitions adopted by the Forest Survey of India and NRSA, the MODIS estimated forest cover as well as its spatial correspondence with FSI and NRSA estimates is much higher (Jeganathan et al., 2009).

4.5. Built-up areas

To the best of our knowledge, none of the national level LULC datasets showed the changes in the built-up areas over such a long time period in India. However, urbanization has received more attention due to harmful effects on water and air quality, natural resources, and social sustainability (Foley et al., 2005; Lu et al., 2010). Contemporary built-up areas estimated by our LULC datasets were similar to HYDE 3.1 datasets in 2005. Among the global remote sensing datasets, only MODIS-IGBP datasets showed built-up areas of approximately 8 million ha in 2005 (Banger et al., 2013). In MODIS-IGBP, built-up areas were land areas covered by buildings and other man-made structures were overlaid from the populated places layer from the EDC Global Land Cover Characterization project (GLCC, http://edcdaac.usgs.gov/glcc/glcc.html). In another study on the comparison of urban areas by six methods, Potere and Schneider (2007) have reported that urban area has a wide range from 0.81 to 20.4 million ha in India. We believe that further efforts are needed to adequately map the built-up areas in India. In this study, we have made the first attempt to reconstruct the historical built-up areas by combining Resourcesat-1 and national inventory datasets during 1880–2010.

4.6. Concerns for environment and food security

Our results have shown that those human activities have caused significant alterations in the LULC including deforestation, cropland expansion, and built-up growth during 1880–2010. In the recent three decades (1980–2010), built-up areas were increasing to accommodate more and more people (Fig. 3). It is projected that that population will keep on increasing for the coming two decades in India. One of the biggest concerns is how to increase the food production to feed increasing population? One way of increasing food production by cropland expansion is by conversion of forests and other natural vegetation that occurred during the 1880–1980s. Currently, forest cover is lower than 33% in plains and 66% in hilly and mountainous areas, a minimum standard set by National Forest Policy of 1988 in order to prevent erosion and ecosystem degradation (Joshi et al., 2011). Further, deforestation may result in ecosystem degradation from soil erosion and carbon flux to the atmosphere. Another way of increasing food production is following intensive agricultural management practices (e.g. more application of fertilizers, improved irrigation facilities, and increasing cropping intensity) on existing croplands. Previously, Mishra (2002) reported that population growth has significant effects on each indicator of agricultural intensification. However, greater fertilizer inputs may result in nutrient transport from croplands to water-bodies; thereby causing eutrophication. Further, agricultural intensification may substantially alter regional climate, water resources, and biogeochemical cycles in India (Ren et al., 2012; Tian et al., 2012b).

4.7. Uncertainties and future needs for LULC data development

In this study, we focused on the development of spatial and temporal LULC patterns at 5 arc minute resolution by integrating remote sensing datasets from Resourcesat-1 and existing inventory archives during 1880–2010. Due to limited availability of the historical archives, our dataset results may not have caught significant fluctuations in LULC changes over short time periods. One of the major uncertainties associated with our newly developed LULC datasets is the estimation of the forest area. Currently, forest area includes any area with more than 10% of the canopy cover. However, canopy cover density has not been provided in the inventory surveys. The built-up area is also based on the assumption as built-up category is not available in the DES datasets (DES, 2010). We derived built-up area from non-agricultural category that includes land occupied by buildings, roads and railways or under water, e.g. rivers and canals, and other lands put to use other than 19-fold classes. From this non-agricultural LULC category, we excluded the area under water-bodies calculated from Resourcesat-1 datasets assuming that area under water-bodies remained constant during 1950–2010. However, this assumption may be fallacious as many man-made reservoirs have been developed during 1880–2010 (Panigraphy et al., 2012). In this case, constant water spread assumption could lead to some under-estimation of the historical built-up area in India.

In order to improve the current understanding of the LULC patterns and their driving forces, further studies are still needed. Firstly, although the new datasets have the most reliable estimations of historical land use, they are still based on the assumption that the current LULC patterns mimic their historical distributions, which may be problematic, as suggested by Houghton and Hackler (2003). Secondly, more data sources especially historical land survey data on forest plantations as well as built-up area are needed to generate more reliable LULC datasets in India. However, it may be very difficult to obtain more information on the historical LULC in India. Therefore, it is essential that long-term historical datasets be reconstructed using validated, spatially explicit land use models. These spatially explicit land use models can be used to reconstruct historical LULC and project future LULC with high spatial resolutions by coupling land survey data, socioeconomic factors, and biophysical and biogeochemical processes (Verburg et al., 1999; Kaplan et al., 2009; Klein Goldewijk and Verburg, 2013). This model is based on a non-linear relationship between population density and land use, which translates into a decrease in per-capita land use over time.

Thirdly, more specific efforts should be made to study the impact of extreme events including droughts and floods as well as political and policy shifts on land use dynamics. These investigations could be made on a national scale or by focusing on small-scale case studies. Quantifying the changes in characteristics of LULC is essential for assessing its impacts on regional climate, biogeochemical cycles, and hydrological processes.

Our results have shown significant alterations in the LULC; however such changes were driven by complex climatic and socio-economic factors during the study period. The major LULC changes include the loss of forests, expansion of cropland, and urbanization during 1880–2010. Greater deforestation occurred during 1880–1950 due to British rule policies to increase income from the timber products and cropland. However, deforestation decreased after the 1980s due to formulation of government policies to protect forests. Cropland expansion rate was greater during 1950 to 1980 primarily due to expansion of irrigation facilities, farm mechanization, electrification, and use of high yielding crop varieties that resulted from Government policies of achieving self-sufficiency in food production. Our results have shown that urbanization which was negligible during 1880–1950 became one of the most important land conversions after the 1950s due to population and economic growth in India. The spatial and temporal information on LULC changes produced in this study can be used by ecosystem, hydrological, and climate models for assessing the impacts of LULC on regional climate, water resources, and biogeochemical cycles in terrestrial ecosystems. To further reduce the uncertainties of LULC data and make reliable projections for the future, we need to advance our understanding of its driving forces and incorporate information from coupling remotely sensed data, vegetation dynamics, and socio-economic factors.

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