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Article

Development of Decadal (1985–1995–2005) Land Use and Land Cover Database for India

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Abstract: India has experienced significant Land-Use and Land-Cover Change (LULCC) over the past few decades. In this context, careful observation and mapping of LULCC using satellite data of high to medium spatial resolution is crucial for understanding the long-term usage patterns of natural resources and facilitating sustainable management to plan, monitor and evaluate development. The present study utilizes the satellite images to generate national level LULC maps at decadal intervals for 1985, 1995 and 2005 using onscreen visual interpretation techniques with minimum mapping unit of 2.5 hectares. These maps follow the classification scheme of the International Geosphere Biosphere Programme (IGBP) to ensure compatibility with other global/regional LULC datasets for comparison and integration. Our LULC maps with more than 90% overall accuracy highlight the changes prominent at regional level, *i.e.*, loss of forest cover in central and northeast India, increase of cropland area in Western India, growth of peri-urban area, and relative increase in plantations. We also found spatial correlation between the cropping area and precipitation, which in turn confirms the monsoon dependent agriculture system in the country. On comparison with the existing global LULC products (GlobCover and MODIS), it can be concluded that our dataset has captured the maximum cumulative patch diversity frequency indicating the detailed representation that can be attributed to the on-screen visual interpretation technique. Comparisons with global LULC products (GlobCover and MODIS) show that our dataset captures maximum landscape diversity, which is partly attributable to the on-screen visual interpretation techniques. We advocate the utility of this database for national and regional studies on land dynamics and climate change research. The database would be updated to 2015 as a continuing effort of this study.

Keywords: remote sensing; land use; land cover; landscape; landsat; resourcesat; South Asia; climate change

1. Introduction

Land-use and land-cover change (LULCC) is a key focus area for the global change community [1,2] because of its significant impacts on climate change [3], biogeochemical cycles [4], biodiversity [5], and water resources [6]. LULCC are driven by changes in multi-scale interacting driving factors such as biophysical conditions of the land, demography, technology, affluence, political structures, economy, and people's attitudes and values [7]. These driving factors vary with geography and time; therefore, LULCC is also heterogeneous both spatially and temporally. Therefore, improved representation of both spatial and temporal dimensions of LULCC is crucial for better understanding human influence on the natural environment. One of the first steps towards this goal is to accurately quantify contemporary and historical LULCC, in a spatially explicit way. During the last 100 years, LULCC in India has been manifested in terms of agricultural expansion at the expense of forests [8]. This process continued until 1960s, when "Green Revolution", for the first time, focused on enhancing agricultural production by means of new high-yielding varieties, extension of irrigation facilities, and use of fertilizers and pesticides [9]. Since the 1960s, modern economic development plans, and their implementation, nonetheless, set new trajectories and pace in the LULCC processes.

In this context, it is pertinent to mention that remote sensing offers an indispensable tool to monitor LULCC at regular time intervals. This technology can provide information on both biological (vegetation and its dynamics) and physical conditions (variations in terrain and morphological features) of LULCC. However, standard LULCC information generated from remote sensing data over the decades continues to be a challenging task, owing to the prevailing variations in spatial resolution of satellite data [10–12]. Numerous recent and on-going studies have improved both the measurements and understanding of factors influencing LULCC at the global scale, which in turn have paved the way to assimilate them in climate models [13–17]. However, at the same time it is observed that there is increased use of satellite remote sensing data has resulted in global, regional [2,3,17,18] and national initiatives to prepare land cover products [19–29]. Coarse resolution satellite data like NOAA-AVHRR, MODIS and SPOT-VGT with their high temporal resolution have been effectively used to provide repeatable land cover maps at regular intervals for LULCC [30,31]. On the other hand, LULC maps at medium to high resolution are limited/project specific and at times, are not available at regular intervals to study the long-term land cover dynamics in India [18,27,32–34]. While coarse resolution land cover products are a valuable resource for global scale assessments of LULCC, the national level assessments invariably require time-series products at much higher spatial resolution for two reasons. First, such products are required to map large scale LULC variability with accuracies more than 85% [31,35] for local governance. Second, the products should be able to delineate and estimate the areas of different cover types such as crop, forest, urban land, fallow land, wastelands, and water bodies. In diverse landscape regions like India, these features are characterized by small-scale fragmented zones having irregular shapes. As a result, such variability can be captured only by using medium and high-resolution satellite images. Moreover, medium-resolution LULC mapping is also crucial for supporting national level agricultural planning, biodiversity conservation, food-supply strategies, watershed development planning, and soil conversation initiatives.

The conventional approach to collect LULCC information in India at the national scale is through compilation of available records from the Directorate/Bureau of Economics and Statistics (DES/BES). Land use information derived from agricultural inventory of individual field plots is also available in nine-fold classification system comprising of land, irrigated area and total area under crops from different states and union territories of the country. In this study, we report for the first time the results of mapping LULCC for India at national scale at medium resolution (~30 m) for three decades (1985–1995–2005). The previous LULCC monitoring at regular intervals for India have been carried out at sub-national scales such as agro-climatic zones, biogeographic regions, meteorological sub-divisions, bioclimatic zones, and different watersheds [20,21,36,37]. National level LULCC mapping for India has received major impetus with the availability of multi-spectral and multi-resolution remote sensing data having synoptic and temporal coverage [19–23,26,27]. Table 1 summarizes the details of earlier initiatives taken by India over the last three decades for mapping and monitoring of LULCC using remote sensing data. These initiatives met the immediate national needs for planning and managing natural resources, agriculture expansion in the catchment, afforestation, eco-development, and preparation of watershed development and irrigation plans [36–44]. Most of these initiatives were one-time efforts and vary in terms of project objectives, classification schemes, methodology of mapping and the satellite data quality. In the present context, landscape dynamics and climate studies need information on phenology and leaf area index of forest; differentiation of cropland, fallow, barren and wasteland; mapping of non-permeable surface like built-up areas; and features like, dams, mining, aquaculture, and wetlands. To delineate these classes with acceptable accuracy, there is a need to use satellite data of high/medium spatial resolution. Besides, time-series maps should be consistent with internationally accepted land cover classification scheme so as to act as surrogate to climate variables.

Table 1. LULC mapping initiatives in India using satellite remote sensing.

Project/Product	Data Used	Scale	Year	Highlights and References
Indian forest cover map	Landsat MSS	1:1M	1972–1975 1982–1985	Maiden effort to detect forest cover change. No spatial change [22]
Bi-Annual State of Forest Report	Landsat, IRS-LISS–III/LISS IV	1:50K	1987–till date	Forest survey of India (FSI) uses satellite data of wet season to map tree cover of India (inside and outside forest areas) biannually [23]
Vegetation type and land cover	Multi-temporal IRS-WiFS	1:500K	1998	Mapping of major vegetation types of India using phenological investigations as a discriminant [24]
Biome level classification	IRS-WiFS and climate database	1:500K	1998	Mapping of major biomes of India using phenology from multi-date WiFS and subsequent spatial modeling using biophysical parameters [25]
Vegetation type and land cover	IRS-LISS III	1:50K	2005–2006	Vegetation type mapping of India using seasonal images, climate data, topographic variations and field sample data as part of Biodiversity characterization project [26,27]
LULC map (annually)	IRS-AWiFS	1:250K	2004–till date	Mapping major LULCC from multidate AWiFS data using hierarchical data mining. Focus was on to identify three cropping seasons for estimating net sown area [28]
LULC map	IRS-LISS-III	1:50K	2005–2006	Level III LULCC maps of India prepared using three season multispectral data [29]

Here, we have generated time-series maps for three decades adopting the hierarchical International Geosphere-Biosphere Programme (IGBP) classification scheme [45]. We have extensively validated the LULC maps using ground truth data, existing maps, and very high-resolution satellite images available on the *Google Earth*. The study brings out the development of medium-resolution temporal LULC datasets of India using visual interpretation of multi-spectral satellite-based remote sensing data.

2. Results and Discussion

Land use and land cover maps from three different decades (1985, 1995 and 2005) have been prepared using three seasons' satellite remote sensing data, vegetation type information and extensive ground truth. The visual interpretation has been carried out using on screen digitization. The flow chart of the approach is shown in Figure 1. The comprehensive satellite data, ground truth surveys, supplementary information and toposheets have been used to prepare the 2005 LULC map (Figure 2), which was subsequently used as a reference to prepare 1995 and 1985 LULC maps (Figures S1 and S2). Our analysis shows that the LULC in India has undergone important changes between 1985 and 2005 (Table 2 and Figures 3 and 4). The total area that has changed during 1985–2005 is 0.10% of the total geographic area of the country (~340,932 km^2). During this period, there has been a continuous decrease in land cover in the form of forests with concomitant increase in cropland and built-up area. Between 1985 and 2005, of the 11 major LULC classes, a considerable increase has been recorded in agriculture (47.55%–49.34%) and built-up areas (1.03%–1.44%), whereas significant decrease was noticed for forests (23.25%–22.18%), and wastelands (2.57%–2.27%). Within different forest classes, areas under mixed forest, savannah/woodlands/scattered trees, and mangroves have shown marginal increase. All the other forest classes remained either unchanged or declined marginally. Other LULC classes including barren land (2.00%–2.13%), plantations (2.36%–2.38%), and shrub land (5.56%–5.65%) also recorded marginal changes in their areas. Grassland remained unchanged, whereas marginal increase in shrub land area was noticed (Table 2).

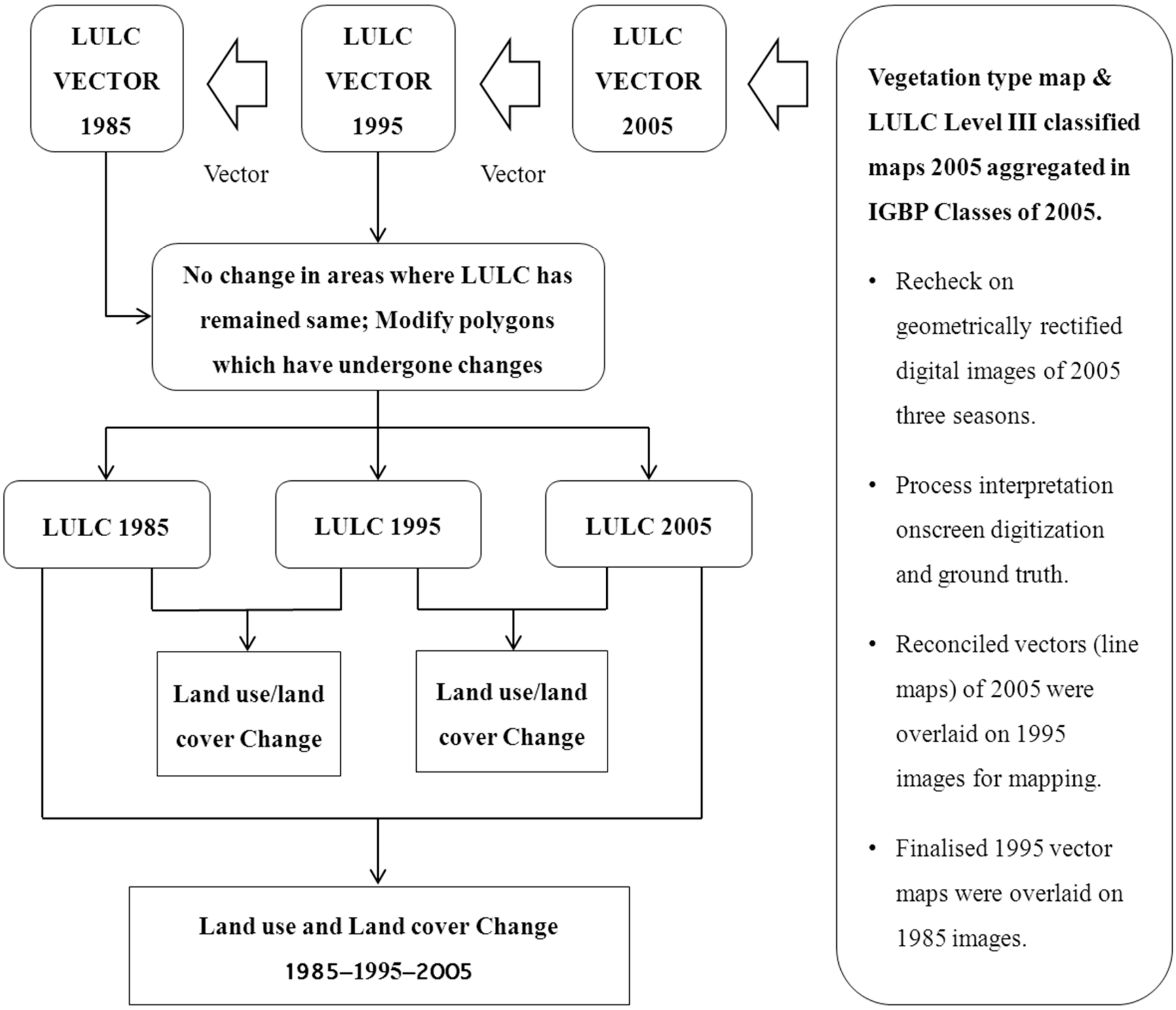


Figure 1. Flow diagram of land use and land cover (LULC) Level-II (IGBP Classification) Mapping using multi-season geometrically co-registered satellite images Satellite images.

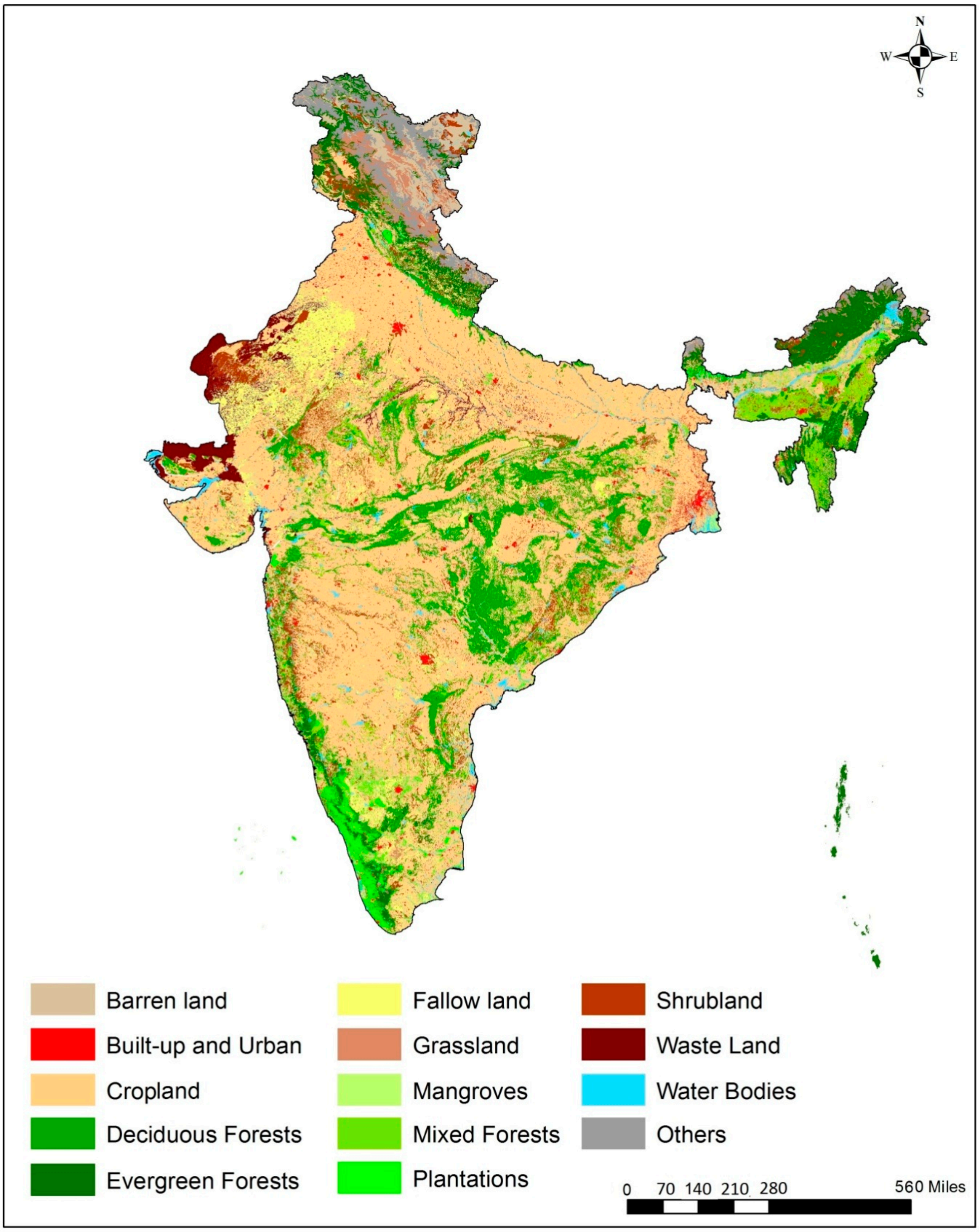


Figure 2. Land use and land cover map of India for 2005. This map serves as a reference for 1995 and 1985 LULC maps (shown in supplementary).

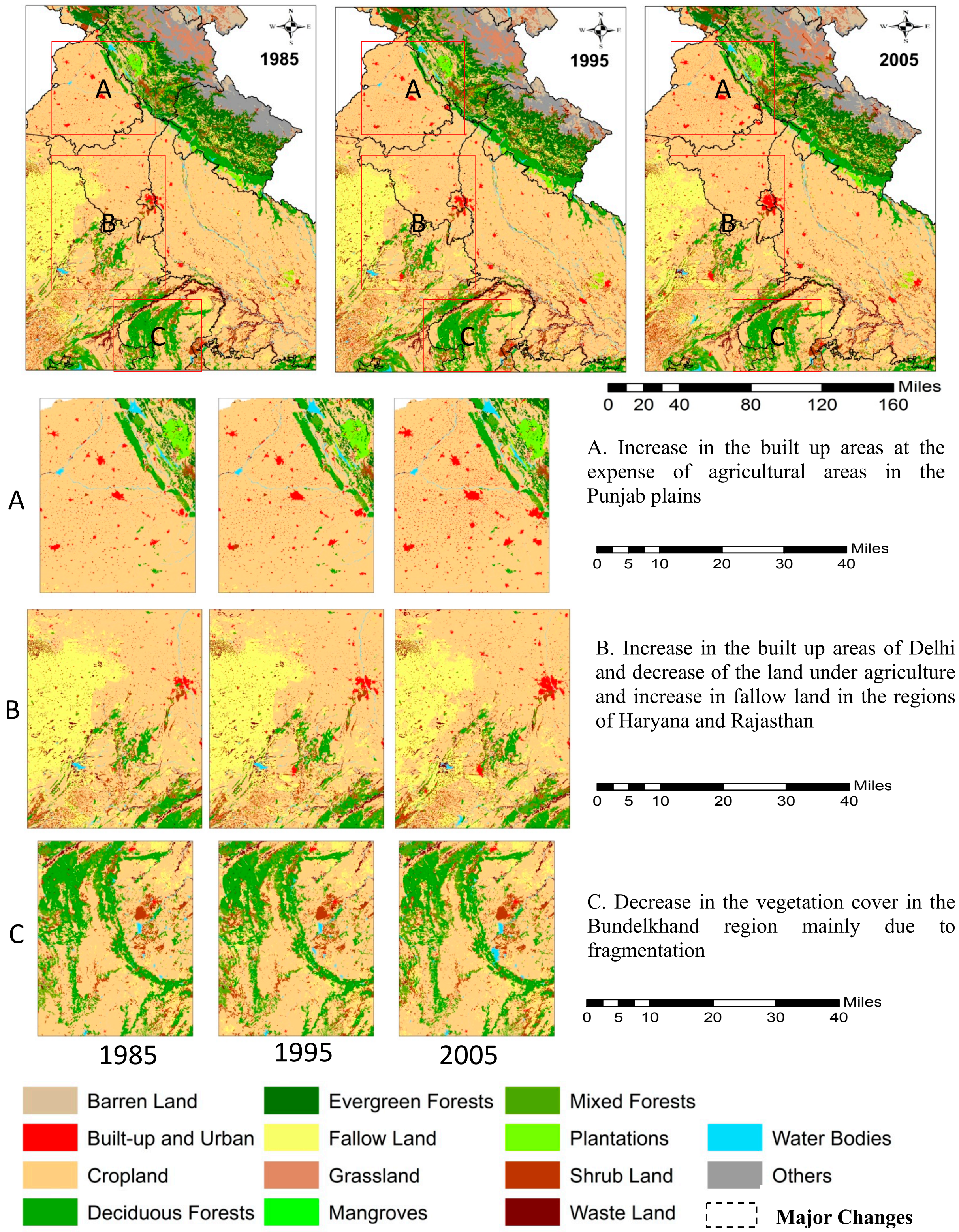


Figure 3. Land-use and land-cover changes in north western India over two decades (1985–2005). (**A**). Increase in the built up areas at the expense of agricultural areas in the Punjab plains. (**B**). Increase in the built up areas of Delhi and decrease of the land under agriculture and increase in fallow land in the regions of Haryana and Rajasthan. (**C**). Decrease in the vegetation cover in the Bundelkhand region mainly due to fragmentation.

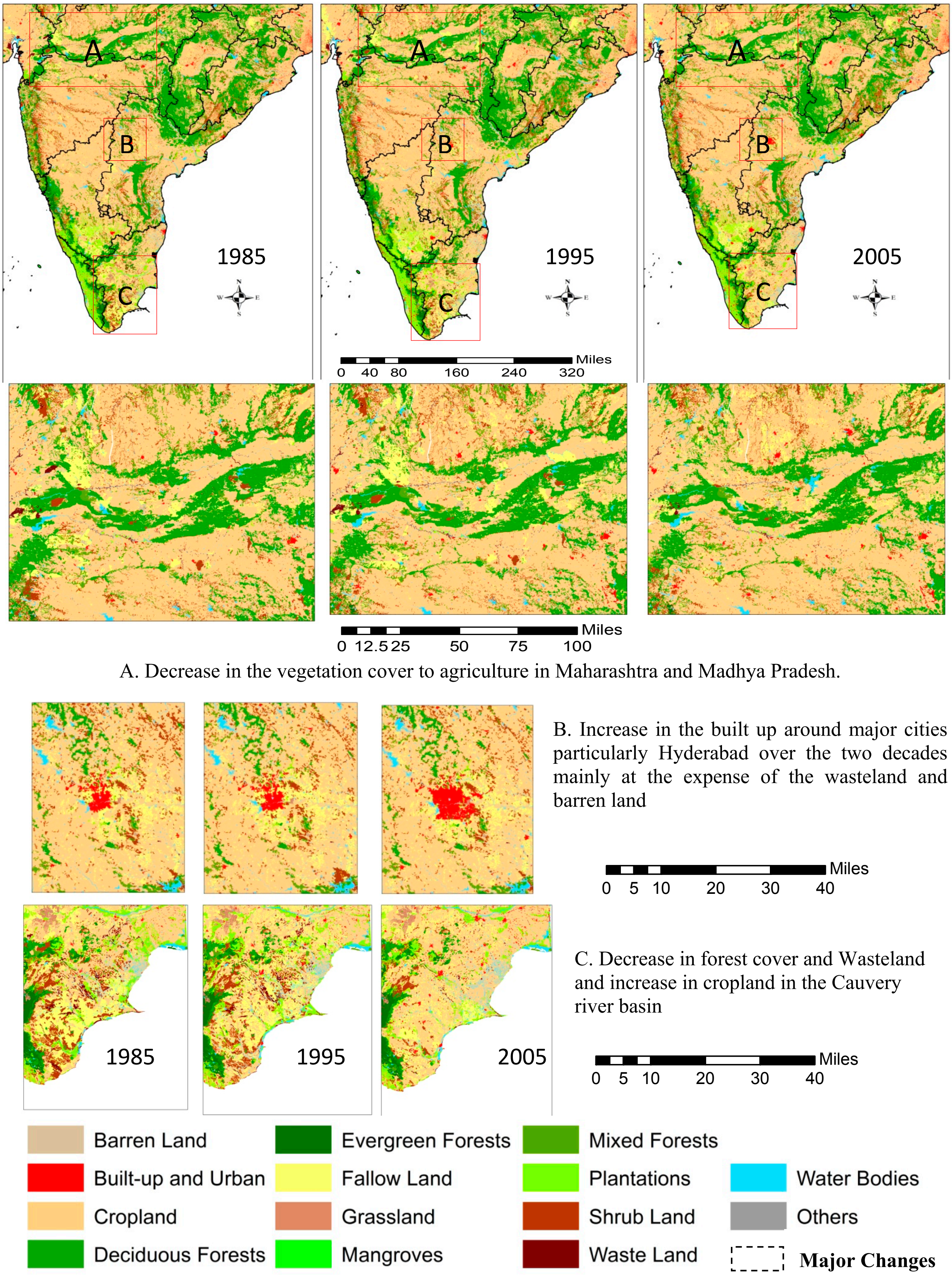


Figure 4. Land-use and land-cover changes in south India over the two decades (1985–2005). (**A**) Decrease in the vegetation cover to agriculture in Maharashtra and Madhya Pradesh. (**B**) Increase in the built up around major cities particularly Hyderabad over the two decades mainly at the expense of the wasteland and barren land. (**C**) Decrease in forest cover and Wasteland and increase in cropland in the Cauvery river basin.

Table 2. Overall extent of land use and land cover classes in India.

Land Use/Land Cover Classes	Area					
	km^2			%		
	1985	1995	2005	1985	1995	2005
Built-up and Urban	34,019	40,090	47,239	1.03	1.22	1.44
Cropland	1,558,712	1,556,346	1,614,921	47.55	47.45	49.34
Fallow land	252,073	266,671	221,136	7.68	8.13	6.77
Forest	764,143	745,173	729,262	23.25	22.67	22.18
-Deciduous broad leaf forest	264,071	241,647	224,101	8.03	7.35	6.82
-Deciduous needle leaf forest	53,358	53,130	56,583	1.62	1.62	1.62
-Evergreen broad leaf forest	187,749	185,083	178,646	5.71	5.63	5.43
-Evergreen needle leaf forest	20,314	20,077	19,346	0.62	0.61	0.59
-Mixed forest	150,163	149,523	147,284	4.57	4.55	4.48
-Mangrove	4120	4525	4579	0.13	0.14	0.14
-Savannah/woodlands/scattered Trees	84,368	91,188	98,723	2.57	2.77	3.01
Plantations	77,493	77,956	78,560	2.36	2.37	2.38
Shrub land	182,860	188,342	192,873	5.56	5.63	5.65
Grass land	54,553	56,604	61,595	1.66	1.62	1.66
Barren land	65,484	71,250	69,855	2.00	2.17	2.13
Waste land	84,414	78,649	74,355	2.57	2.40	2.27
Water bodies [1]	116,119	121,148	114,856	3.55	3.69	3.50
Others [2]	97,152	91,636	92,522	2.96	2.79	2.82

Notes: [1] Includes Aqua Culture, Water bodies, and Permanent Wetlands; [2] Includes Salt Pan, Snow and Ice.

Furthermore, a steady decrease in forest area was recorded in both central India and parts of northeast India between 1985 and 2005 (Figures 3–6). The areas under mangroves show a considerable increase during 1985–1995 and nominal increase during 1995–2005 due to various coastal protection legislations/ordinances formulated by the Government of India. The total area under cropland decreased during 1985–1995 and subsequently increased during 1995–2005 (Table 2). Cropland increase has been observed in the catchment areas of Narmada basin in Central India, Indira Gandhi Canal in Rajasthan and also in parts of Tamil Nadu in southern India (Figure 4). It was also noticed that in 1995, there was higher percentage of fallow and barren land as compared to 1985 and 2005 (Table 2). Besides receiving adequate rainfall during 1995 and 2005, the reason for enhanced agriculture activity could be due to the creation of canal irrigation (under Augmented Irrigation Benefit Programme) and construction of minor/mini irrigation tanks. In addition, a significant increase in plantation is noticed in the peninsular India and western Himalaya (Figure 7). It shows the success of state sponsored programs to meet the resource demand as well as to increase the green cover as per the national forest policy. These plantations are being carried out in forest gaps, wastelands, and on agriculture fields under agro-forestry programs.

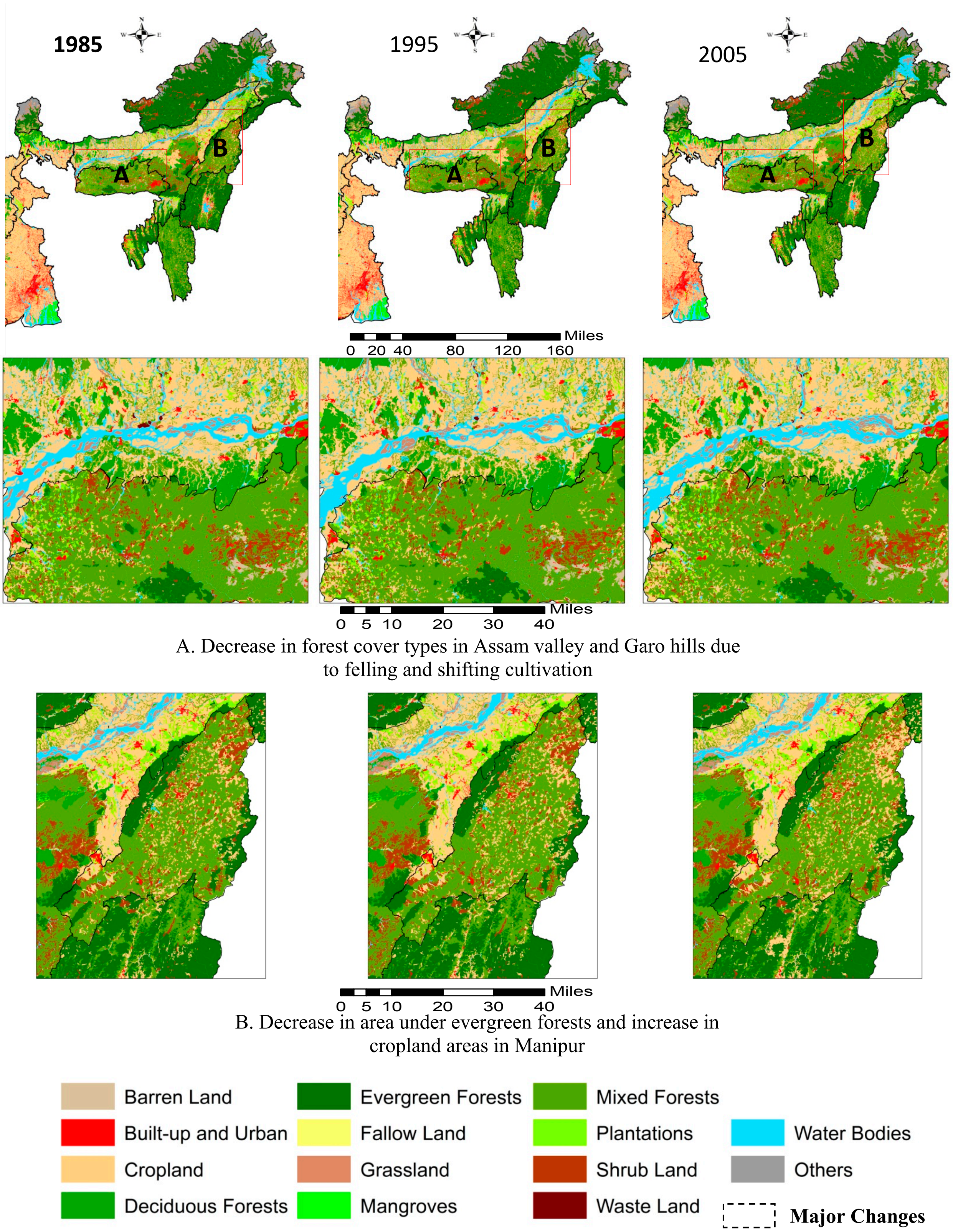


Figure 5. Landscape of North Eastern India presents dominance of forests and shifting cultivation. (**A**) Decrease in forest cover types in Assam valley and Garo hills due to felling and shifting cultivation and (**B**) Decrease in area under evergreen forests and increase in cropland areas in Manipur.

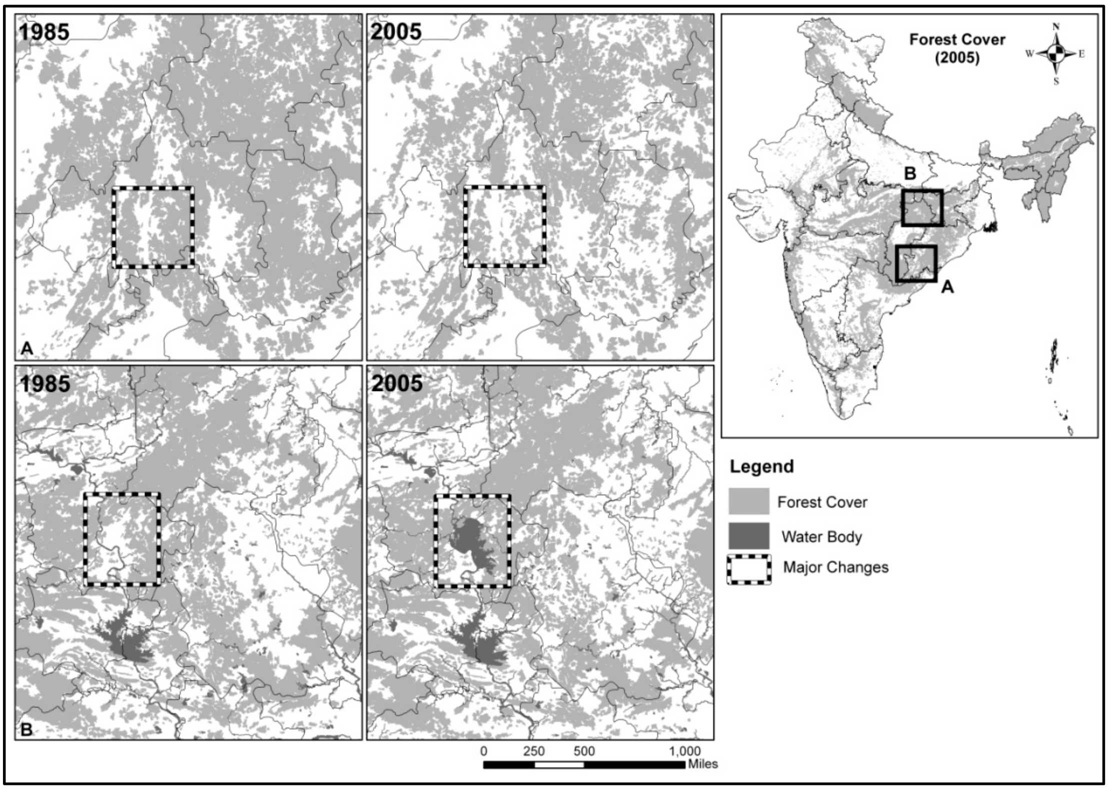


Figure 6. Loss of forest cover in central India during 1985–2005.

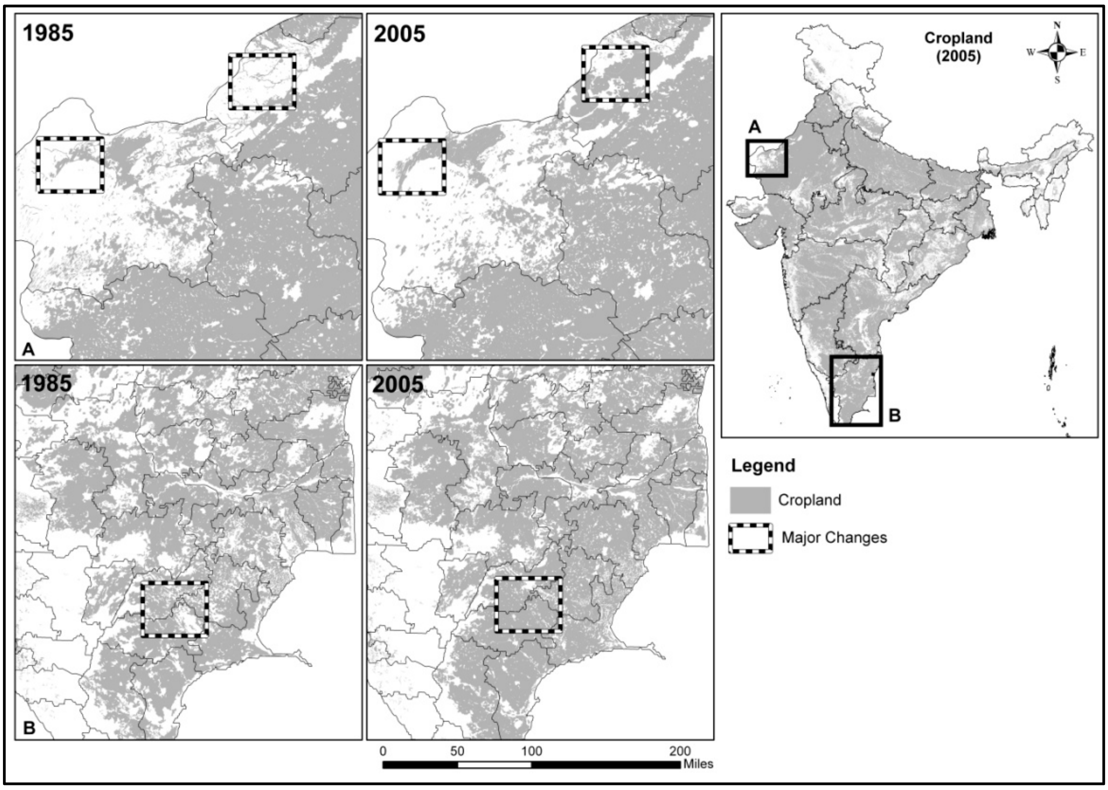


Figure 7. Increase in crop land during 1985 to 2005 in western India and east coast of south India.

Another substantial change in the land use over the decade is the steady increase in built-up area of about 13,219 km^2 at the expense of the agricultural land (Table 2). The built-up area has increased by 6000–7000 km^2 in each decade of the study period. The geographical built-up area has increased from 1.03% in 1985 to 1.22% in 1995 and then to 1.44% in 2005. The changes between 1995 and 2005 are more prominent than the period between 1985 and 1995. The increase in built-up area between 1995 and 2005 is more prominently observed in the north-western plains and in the peninsular India (Figures 3 and 8). Studies on decadal datasets reveal that the built-up area has grown both in circular (radial growth of metropolitan cities) and linear patterns (settlements along the roads). In short, the present study provides important information to assess the changes in urban areas in terms of their spatial dimension and growth [46–48]. The maximum expansion in built-up area is observed around Delhi followed by Surat, Hyderabad, Bangalore, Kolkata, and Mumbai. The emergent urban agglomerations during the study period are Jaipur, Allahabad, Kanpur, Lucknow and Pune. However, the fastest growing urban areas in India are the medium sized settlements at the cost of agriculture land (Figure 3). Furthermore, Western Ghats and Western Himalayas have shown significant increase in plantations from 1985 to 1995 (Figure 9), beyond which no significant changes are noticed.

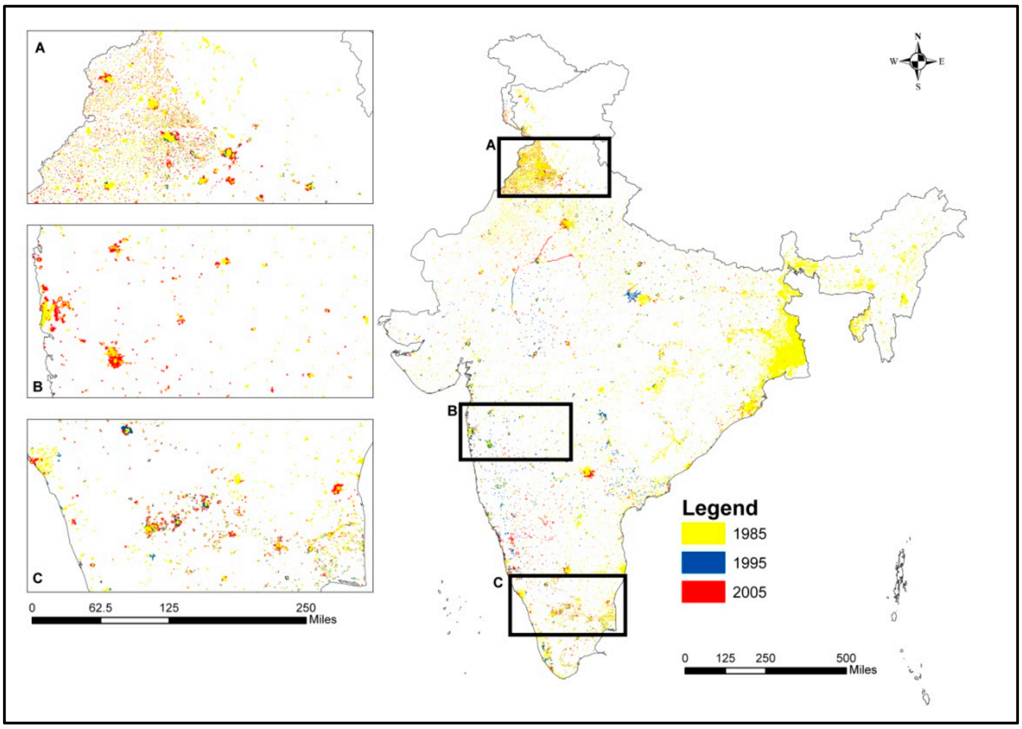


Figure 8. Map showing the urban growth during 1985–1995–2005. Major urban growth centers in north-west Punjab, western India around Mumbai region and Southern India are also shown.

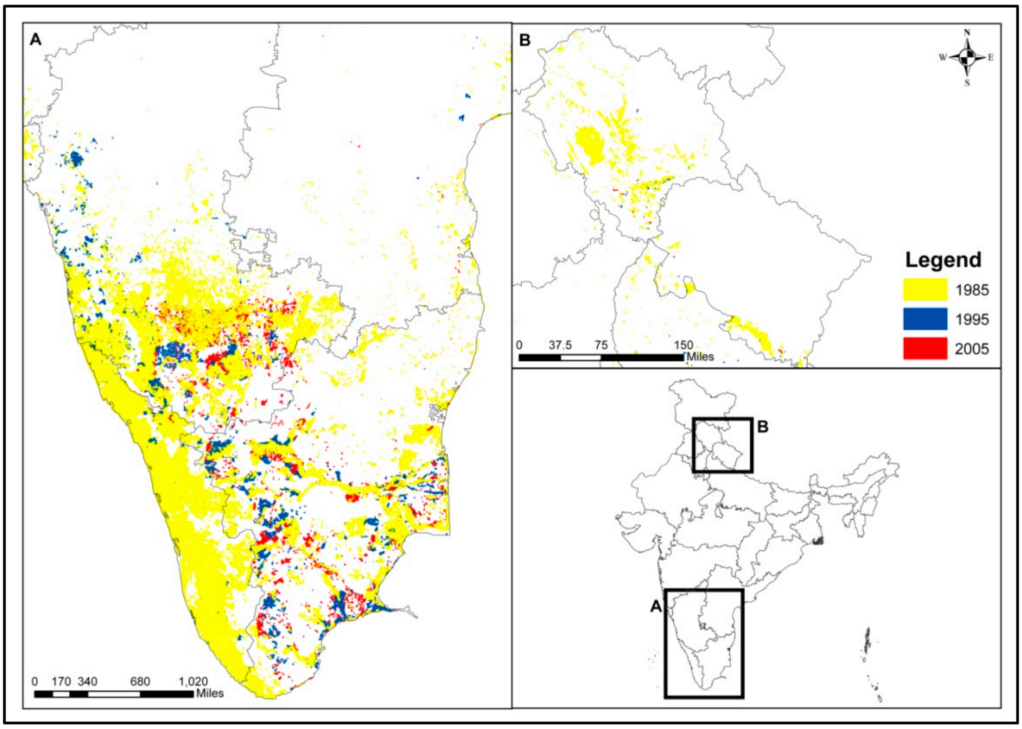


Figure 9. Significant changes in plantation area in Peninsular India and Western Himalaya during 1985–2005.

2.1. Accuracy Evaluation and Consistency between Decadal Trends

We evaluated the accuracy of LULC 2005 map using pre-determined field sample points. We have selected a total of 12,606 stratified random samples to assess the accuracy of the map with the help of ground truth data [26,27]. The above sample points were collected for the project on Biodiversity Characterization project of Indian Space Research Organization (ISRO) and Department of Biotechnology (DBT) [27]. We have used the confusion error matrix created with the mapped and ground reference points to determine the users' accuracy and Cohen's kappa accuracy (Table 3). Most of the LULC classes showed accuracies of more than 90% except for plantation, wasteland, and barren land. However, the accuracies of these three later classes are also within the acceptable limits (Table 3). We achieved an overall mapping accuracy of 94.46% and the Kappa accuracy of 0.9445 for 2005. The migration of classes (LULC change) from one category to another between different years (1985 to 2005) of mapping was found to be only 10.36% of total geographical area, of which it was 5.74% between 1985 and 1995, and 8.55% between 1995 and 2005. Out the changed areas, 5% geographical area between two time periods was verified on the ground using existing land and revenue records to ensure classification accuracy. It can be assumed that the mapping and Kappa accuracies of the 1995 and 1985 maps are similar to that of 2005.

Table 3. Land use/land cover (LULC) classification scheme and description of classes.

S. No.	Land Cover Type (Level I)	Land Use Type (IGBP Classification) (Level II)	Description of Level II classes
1	Built up/Urban	Built up (both urban and rural)	Land covered by buildings and other man-made structures.

Table 3. *Cont.*

S. No.	Land Cover Type (Level I)	Land Use Type (IGBP Classification) (Level II)	Description of Level II classes
2	Agriculture	2.0 Crop land	Temporary crops followed by harvest and a bare soil period (e.g., single and multiple Cropping systems).
		2.1 Fallow land	Land taken up for cultivation temporarily allowed to remain uncultivated for one or more seasons.
		2.3 Plantations	Commercial horticulture plantations, orchards and tree cash crops.
3	Forest	Evergreen Needle forest	Needle leaf woody vegetation with a percent cover >60% and height exceeding 2 m. Almost all trees remain green all year. Canopy is never without green foliage.
		3.1 Evergreen Broad leaf Forest	Broad leaf woody vegetation with a percent cover >60% and height exceeding 2 m. Almost all trees and shrubs remain green year round. Canopy is never without green foliage.
		3.2 Deciduous Needle Forest	Woody vegetation with a percent cover >60% and height exceeding 2 m. Consists of seasonal needle leaf tree communities with an annual cycle of leaf-on and leaf-off periods.
		3.4 Deciduous Broad leaf Forest	Woody vegetation with a percent cover >60% and height exceeding 2 m. Consists of broadleaf tree communities with an annual cycle of leaf-on and leaf-off periods.
		3.5 Mixed forest	Trees with a percent cover >60% and height exceeding 2 m. Consists of tree communities with interspersed mixtures or mosaics of the other four forest types. None of the forest types exceeds 60% of landscape.
		3.6 Savanna/woodland (including woody scattered trees)	Natural Herbaceous and other understory systems, with scattered trees or forest canopy cover between 10% and 30%. The forest cover height exceeds 2 m.
		3.7 Mangrove forest	Evergreen forests in the intertidal areas. These forests are dense and dominated by halophytic plants.
4	Shrub land (closed/open)	Shrub land (closed/open)	Woody vegetation less than 2 m tall and with shrub canopy cover. The shrub foliage can be either evergreen or deciduous.
5	Grassland	5.0 Grassland	Herbaceous types of cover. Tree and shrub cover is less than 10%.
6	Barren/waste land	6.0 Barren land	Exposed soil, sand, rocks, or snow and never have more than 10% vegetated cover during any time of the year.
		6.1 Waste land (sparsely vegetated)	Sparsely vegetated with signs of erosion, Land deformation.

Table 3. *Cont.*

S. No.	Land Cover Type (Level I)	Land Use Type (IGBP Classification) (Level II)	Description of Level II classes
7	Water bodies	7.0 Water bodies	Reservoirs and rivers. Can be either fresh or salt-water bodies, including aquaculture.
		7.1 Permanent wetland	Permanent mixture of water and herbaceous or woody vegetation. The vegetation can be present either in salt, brackish, or fresh water.

2.2. Relevance of LULC Data Sets

As many national governments across the globe are working on policies to mitigate anthropogenic CO_2 emissions, there is an increasing need to improve our understanding of LULCC, and their impacts on the environment [49–54]. Satellite remote sensing has emerged as a vital tool for long-term monitoring of LULCC from local to global scales. The available global datasets on land cover are: MODIS digital classification methods with six-biome classification system [34], 14-class classification system developed at the University of Maryland [55], six-biome classification system developed by Myneni *et al.* [56], the MODIS global land cover map [49] and the MERIS GlobCover with 22 classes [50]. As these maps are of coarser resolution, they often fail to capture the heterogeneous landscapes of India. On the other hand, the previous studies to capture the LULCC pattern in India (Table 1) were solely project specific and lack long-term monitoring with a classification system consistent with global classification system. Our study overcomes the above limitations by providing three decades of medium-resolution LULC maps prepared using a consistent methodology following the IGBP land classification scheme.

As shown in this study, the newly developed spatial datasets captures both major and minor LULCC and hence, these data sets can be incorporated into the available biogeochemical and climate models. The classification scheme has been designed to have two levels: Level I include broad LULC categories, *i.e.*, agriculture, forest, wasteland, water and built up areas, and Level II refers to the objective sub-division of Level I (Table 3). It is possible to merge and segregate the LULC classes as per the scientific and managerial requirements. Further, medium resolution satellite datasets have been found to be extremely useful in capturing the information about specialized ecosystems such as mangroves in India which otherwise, is not possible with the existing global datasets. For countries like India capturing information of such sensitive ecosystems is important, as they are key indicators of climate change.

2.3. Comparison of LULC Maps with Other Global and Conventional LULC Data

We compared our LULC 2005 map with other available global land cover products viz., MODIS land product and GlobCover maps. It is to be noted that these three products vary in spatial resolution. The LULC 2005 map has 30 m spatial resolution, whereas MODIS land products and GlobCover have 500 m and 300 m resolutions respectively. In addition, the MODIS and LULC 2005 India maps are based on IGBP classification scheme, whereas the GlobCover map uses large number of vegetation mosaic classes, irrigated and non-irrigated crops (Table S1). The overall accuracy of GlobCover is

67.10% with Kappa value of 0.656 [38]. The cumulative patch diversity within 10 × 10 km grid indicates that MODIS land product captures the lowest diversity. The GlobCover has higher frequency of lower patch diversity numbers (0–3), while LULC 2005 India map captures highest cumulative patch diversity frequency for more than 3 patch numbers. Therefore, it is evident that the LULC 2005 map of India developed in this present study is able to capture the maximum landscape diversity of LULC classes (Figure 10). As a result of the variations in spatial resolution of the three products, their effect on the mapping details, class definition and generalization are evident (Figure 11) [57].

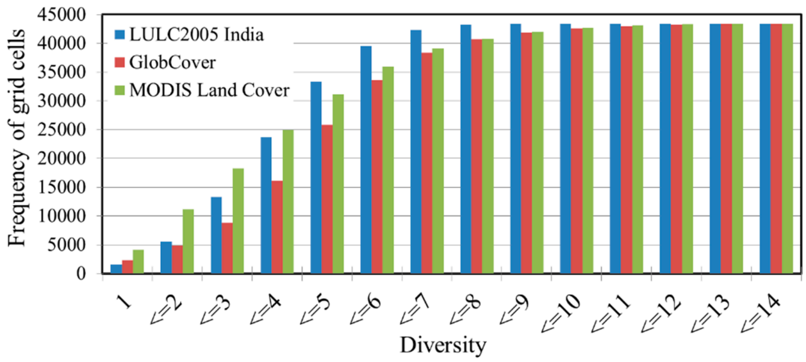


Figure 10. Comparative evaluation of LULC 2005 India product with MODIS Land Product and GlobCover using cumulative diversity of patch classes.

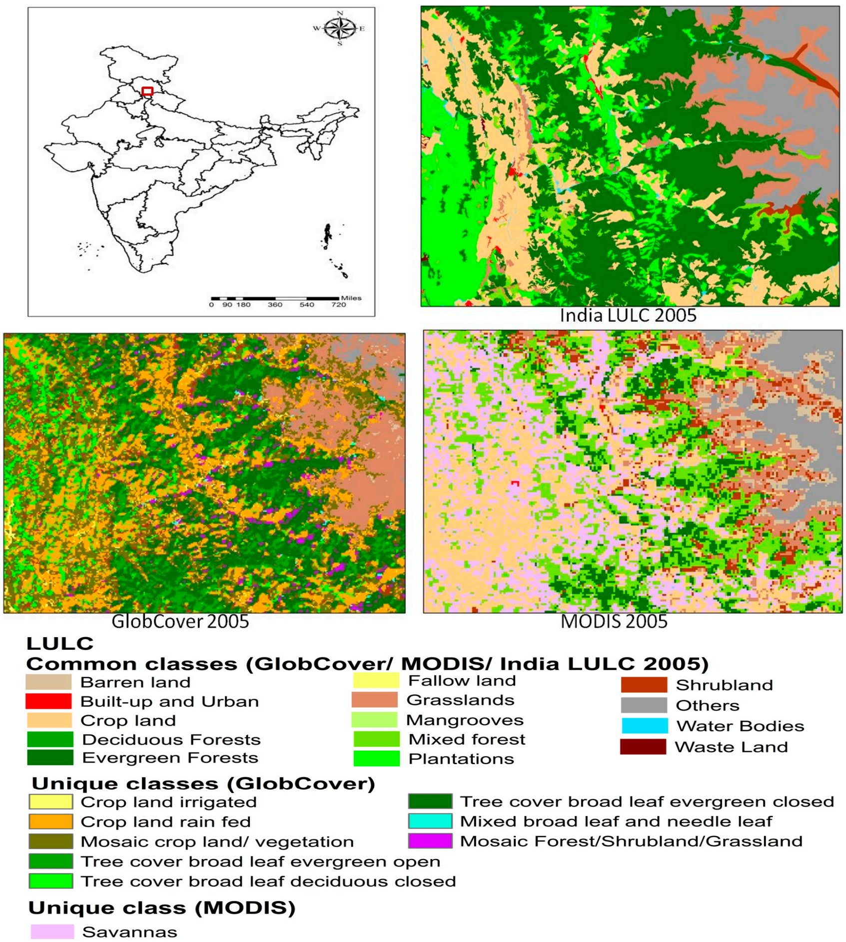
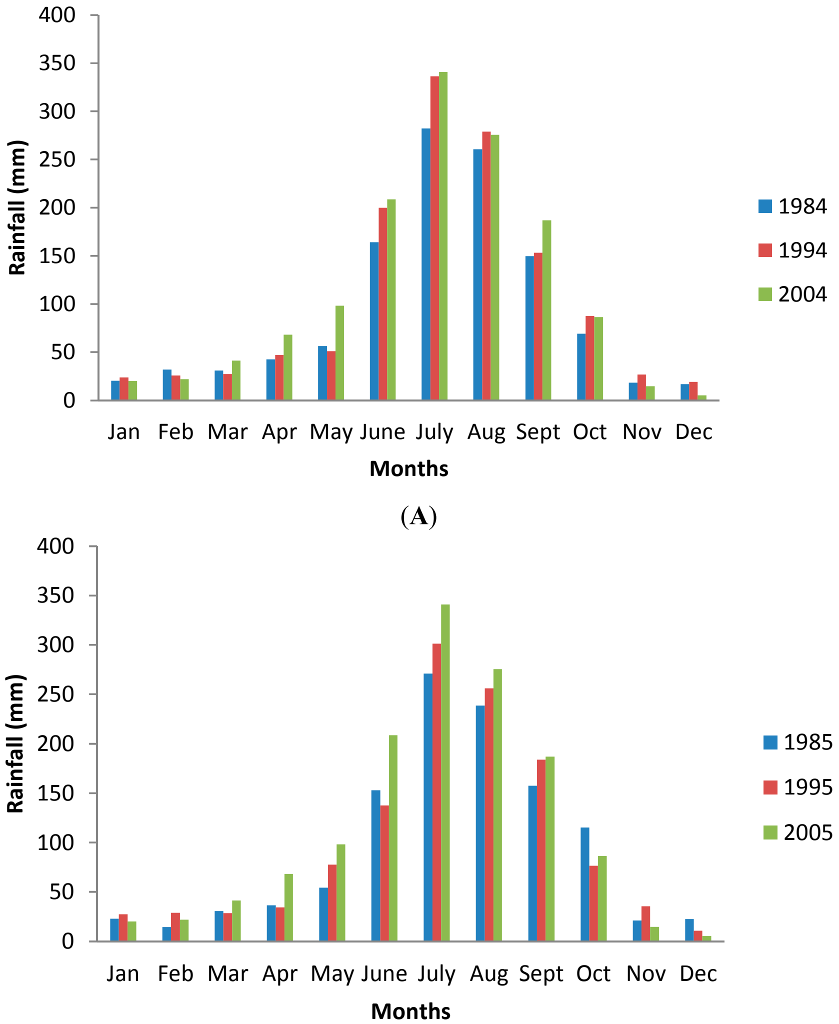


Figure 11. Comparison of resolution of LULC 2005 India product with MODIS Land Product and GlobCover—2005.

2.4. Trend of LULCC

There has been a progressive expansion in agricultural cropland and intensification with management inputs [8,9]. The irrigation projects have contributed to the intensification of agriculture to meet the local and global market demands with more focus on cash crop cultivation [58,59]. The present study reports considerable decrease in cropland area in 1985 due to deficit in rainfall during 1984–1986 compared to 1995 and 2005. During 1995 and 2005, there has been an increase in the crop area due to high number of good monsoon years showing high correlation between cropping area and annual precipitation; thereby, confirming the monsoon-dependent agriculture system in the country (Figure 12).

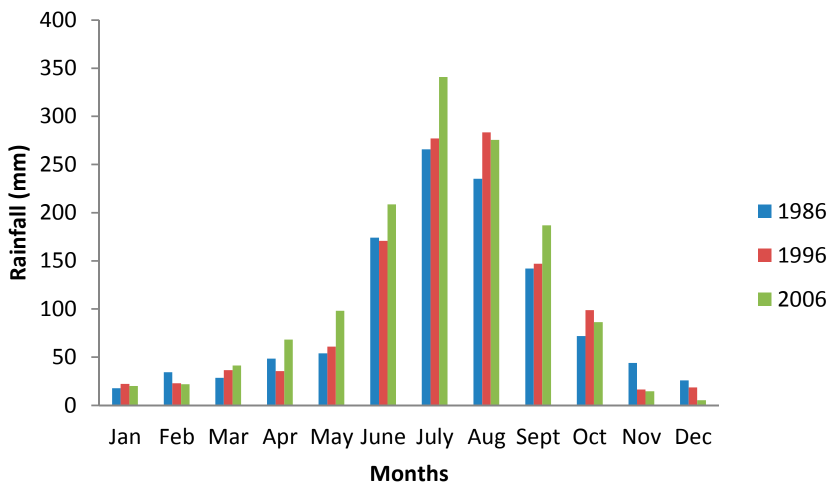
In contrast to the State Forest Reports (SFR) brought out by the Forest Survey of India (FSI) [23], we have observed a consistent decrease in forest cover over the last two decades. The increase in forest area over the years reported by the FSI is attributed to the inclusion of trees outside the forest area in its forest cover mapping. Furthermore, the total area under forest in this study is more than that reported forest area by FSI (SFR, 1987, 1997 and 2009) as woodlands which account for ~1.5% of the total geographical area (TGA) which has been included in our forest category. Besides FSI methodology for mapping vegetation and tree outside forest has also been questioned [60].



(A)

(B)

Figure 12. *Cont.*



(**C**)

Figure 12. The monthly average rainfall pattern was lowest during 1984–1986 (**A**); compared to 1994–1996 (**B**); and 2004–2006 (**C**). The rainfall pattern has affected net cropland area during the mapping periods.

The Indira Gandhi Canal system, Narmada project and other national programs under Accelerated Irrigation Benefit Programme (AIBP) seem to be responsible for the observed increase in cropland area and decrease in fallow land area around these project regions. The progressive deforestation due to mining (coal, iron and aluminum ores) [61–63], illegal felling and encroachment in the central India [64], decrease in forest area during 1985–2005 due to major dams and reservoirs (13,744 ha in Sardar Sarovar Project, Narmada and 4193 ha in Tehri) [64–66], logging and shifting cultivation in North Eastern India [67], mining, conversion of forest land to various land uses are other possible drivers of LULCC [61,62]. One of the positive impacts of government policies has been noticed such as a decline in wasteland in 2005 due to focused watershed schemes for soil and water conservation and linking of Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA) for afforestation [68]. The change patterns observed in the data can be attributed to the socio-economic development in the region. The observations in the central Indian region of Deccan plateau and Chotanagpur plateau indicate progressive increase in deforestation for agriculture.

3. Experimental Section

3.1. Material and Methods

3.1.1 Satellite Data

The study uses multi-temporal data from different satellite systems for LULC mapping. The geometrically co-registered (with sub-pixel accuracy) open source Landsat MSS/TM [69], IRS 1C–LISS III, and Resourcesat1 [70] data for three seasons, viz. winter (January to March); pre-monsoon (April to May) and post-monsoon (mid-October to December) form the main data for our analysis [70]. The Landsat MSS/TM images were downloaded from the United States Geological Survey (USGS) portal. When cloud free Landsat data was unavailable, IRS 1C–LISS III (1994–1995) and Resourcesat 1 (2004–2005) images were used by geometrically correcting them with sub-pixel accuracy, with respect to Landsat data (ortho-rectified) (Table S2; see supplementary material for details on the rectification procedure). We used first order polynomial equation with allowable Root Mean Square (RMS) error of less than one pixel (default) for geometric rectification. The RMS error was found to be 0.4 pixels (less than 9.2 m) in case of LISS-III data, with minimum of 15 Ground Control Points GCPs in each scene having a range of 0.35 to 0.60 pixels (*i.e.*, 8 to 15 m). Highest error was found in the mountainous regions; however, in case of LISS-1 and MSS data, the mean RMS was 0.8 pixels (54 m in case of LISS-1 and ~52 m in case of MSS data). A minimum of 15 GCPs was taken for flat terrains and 30 GCPS for hilly terrain to geo-rectify the satellite images. Parts of eastern Himalaya, for instance, Arunachal Pradesh have perpetual cloud covers; hence, cloud free data of the nearest years have been used for mapping. The details of data from different satellite sensors used in the present study are given in Table 4 and the details of the path and row of the acquired data is presented in the supporting information (Table S2).

Table 4. Satellite remote sensing data used for the LULC mapping.

S. No.	Period	Satellite System	Sensor System	Spatial Resolution of Products Supplied (m)
1	1984–1985	Landsat	MSS	80 (resample to 60 * m)
2	1994–1995	Landsat and IRS 1B	TM, LISS I	30 and 72 m (resample to 56 m *) respectively
3	2004–2005	Landsat and Resourcesat I	TM, LISS III	30 and 23.5 * m respectively

Note: * Finally, all the digital data were re-sampled to 30 m for on screen visual interpretation at 1:50000 scale using nearest neighbor technique.

3.2. Classification Scheme

The hierarchical classification scheme adopted in this study is based on the guidelines formulated by the Anderson classification scheme [31]. The suggested classification offers more consistency owing to its ability to accommodate different levels of information starting from structured broad-level classes to systematic sub-division with more detailed sub-classes. At each level, the defined classes are mutually exclusive (Table 3). The classes, namely, built up/urban, wasteland, and cropland are depicting “land use” that describes the landscapes converted by/for human activities. The remaining six groups, namely, forests, water bodies, wetland, grass land, shrub land, and barren land are “land cover” types, and primarily describing features of the natural environment, although, evidence of human disturbance may be present. Level I category is further classified into Level II classes. Level II categories provide greater details of LULC and structural and functional importance of the respective classes. Level I land use information, for example, is efficiently and economically gathered over large areas by satellite data. Similarly, Level II categories are further refined using satellite images for detailed mapping. The level of classification can be presented at a wider range of scales. The Natural Resource Census Level III classification scheme (Table S3) has been aggregated to Level II and used for mapping.

The IGBP hierarchical classification system for LULC mapping and monitoring requirements using medium-resolution satellite remote sensing data [16,45] was adopted. IGBP classification supports transformation to other classification schemes used globally based on the mapping scale and resolution of the data [16]. This ensures mapping the classes with other classifications schemes while assimilating data for climate and LULCC models (Table 3).

3.3. Temporal LULC Mapping

Figure 1 shows the methodology adopted for the decadal (1985-1995-2005) LULC mapping in India. Vegetation type and land use maps of 2005 generated as a part of the 'Biodiversity Characterization at Landscape Level' (BCLL) project [26,27] and LULC map [29] were used as available resources. The database was aggregated into 18 classes from the available 150 classes (using hierarchical class merging approach) and converted to a vector map using webGIS tool. The 2005 LULC vector map was overlaid on the satellite data (Landsat TM 2005) for three seasons to check for interpretation and aggregated details in vector form. Extensive ground truth data was collected using existing field transects with high-resolution satellite images. The errors and discrepancies in the 2005 LULC map were corrected using the ground truth data and ancillary information supplemented by existing maps to produce the final map. Since 2005, the LULC map was used as a reference for mapping of 1995 and 1985 LULC, utmost care was taken while preparing the 2005 map. The on-screen image interpretation technique was used to prepare the LULC maps with the minimum mapping unit of 2.5 hectares. A standardized methodology was prepared to assist different working groups involved in the mapping exercise. Each working group was given training on how to use the methodology and to bring uniformity. The 2005 LULC map was overlaid on the 1995 satellite data (Landsat TM) and the regions/polygons where the changes had been taken place were realized with respect to 2005 LULC map. The interpretation inconsistencies were also corrected based on the ground information to prepare 1995 LULC map. The final map of 1995 was further overlaid on 1985 satellite data (Landsat MSS/resample resolution 56 m as provided by USGS: http://glovis.usgs.gov) and the same procedure was repeated to produce the 1985 LULC map (Figure S1). The maps were then crossed to generate the change areas. Field surveys were also carried out in 5% of the noted change areas to ascertain the nature of change, their extent and direction of change. The nature and extent of the LULC changes were verified from the ground truth data and records from various revenue and forest departments of the respective states (Figures S2 and S3). Thus, the 2005, 1995, and 1985 LULC maps provide reliable and accurate information on the magnitude of LULCC (Figures 2–5 and 8–11). The LULC India maps of 1995 and 1985 are included as supplementary (Figures S4 and S5).

3.4. Comparison of LULC 2005 Map with Other Global Land Products

The information content of LULC 2005 India map was compared with other two coarser resolution LULC products viz., MODIS [34,71,72] and GlobCover [73,74]. MODIS land cover products have been generated using supervised digital classification using training database of the sites that are distributed globally [71]. The overall accuracy of the MODIS maps is reported to be 75% but higher accuracies range in the class specific categories, at large [35]. More recently, the European Space Agency (ESA) has produced 300 m spatial resolution global land cover product GlobCover [73,74]. The classification process includes unsupervised clustering of selected mosaics using the time series MERIS image mosaics [73].

We have used cumulative diversity index as our metric to compare the three maps. Cumulative diversity is a measure of the number of variety of land cover classes present in a unit landscape. The more classes there are, the more diverse or rich the area is. Therefore, comparing cumulative diversity across three maps indicates which satellite data is better in capturing the compositional makeup of the landscape. To calculate cumulative diversity was overlaid a 10 × 10 km grid mask on the maps, and calculated the number of unique land cover classes (diversity) within each mask grid cell. We then compared the cumulative frequency distribution of the number of grid cells *vs.* landscape diversity across the three maps (Figure 11). While the index is easily calculated and interpreted, it does not render any detail on the size of each class, and therefore its importance. Even if a certain class covers the smallest possible area, it is counted.

Table 5. Accuracy of evaluation of LULC types for the year 2005.

Land Classification *	Bu	Cl	Fl	Fo	Pl	Sl	Gl	Bl	Wl	Wb	Total	UA
Bu	713		21						8		742	96.09
Cl		1478			2	7	11			4	1502	98.40
Fl	12		1116					24	4	5	1161	96.12
Fo		9		1689	23	14					1735	97.35
Pl		11	47	21	527						606	86.96
Sl	23			37		1289	18		32		1399	92.14
Gl		24	36		7	28	1482	2	7		1586	93.44
Bl	49						23	656	36		764	85.86
Wl		57	31	26	8	18	13		1389		1542	90.08
Wb										1569	1569	100.00
Total	797	1579	1251	1773	567	1356	1547	682	1476	1578	12,606	0.936
PA	89.46	93.60	89.21	95.26	92.95	95.06	95.80	96.19	94.11	99.43	0.941	
Overall accuracy = 94.46%; Kappa Accuracy = 0.9445												

* Bu: Built-up/Urban; Cl: Cropland; Fl: Fallow-land; Fo: Forest; Pl: Plantations; Sl: Shrub-land; Gl: Grassland; Bl: Barren-land; Wl: Waste-land; Wb: Water bodies; UA: Users accuracy per cent; PA: Producer accuracy in per cent.

3.5. Accuracy Assessment

During the national BCCL project, ~20,000 sample points were collected to determine species richness, endemism and ecological significance of species, to validate vegetation type and land use maps. Out of ~20,000 sample points, 12,606 were from the years, 2004–2005, distributed uniformly in different LULC classes. In inaccessible areas, the Google satellite images of very high resolution were used to determine Level I LULC class. Post-mapping, ground-verified site-specific accuracy assessment technique was used to evaluate the Level I classes of LULC 2005 map [75,76] using above sample points. The sample points were overlaid on 30 m raster map of 2005 to evaluate the consumer, producer, Kappa and overall accuracies [75] of the Level I classes of LULC 2005 map (Table 5). In the absence of field sample points during 1985 and 1995, no accuracy estimation has been conducted. The LULC 2005 map prepared in this study is a product of detailed visually interpreted vegetation types and LULC maps (Level III) on 1:50K scale (Figure 1). The class-aggregated vectors were overlaid on satellite images and boundaries were refined using new ground truth data and Google Earth images. The interpreted vectors of 2005 were overlaid on 1995 to prepare 1995 maps. The polygons that have undergone changes have been modified using same interpretation key. The same process was repeated to prepare 1985 map from the 1995 map. Hence, the continuity of accuracy levels was ensured.

4. Conclusions

In this article, we have reported a methodology followed by detailed results from national-level LULCC mapping activity for India using multi-temporal and multi-spectral medium resolution satellite data. Our analysis shows that the LULC in India has undergone important changes between 1985 and 2005. The total area that has changed during 1985–2005 is 0.10% of the total geographic area of the country (~340,932 km^2). During this period, there has been a continuous decrease in land cover in the form of forests with concomitant increase in cropland and built-up area. Between 1985 and 2005, of the 11 major LULC classes, considerable increase has been recorded in agriculture (47.55%–49.34%) and built-up areas (1.03%–1.44%), whereas significant decrease was noticed for forests (23.25%–22.18%), and wastelands (2.57%–2.27%). Within different forest classes, areas under mixed forest, savannah/woodlands/scattered trees, and mangroves, have shown marginal increase. All the other forest classes remained either unchanged or declined marginally. Other LULC classes including barren land (2.00%–2.13%), plantations (2.36%–2.38%), and shrub land (5.56%–5.65%) also recorded marginal changes in their areas. Grassland remained unchanged, whereas marginal increase in shrub land area was noticed (Table 2). In the long run, this database can be used for the biogeochemical and hydrological modeling at pan-India scales, and also as an input to regional and global climate models. The follow-on of the present work will investigate: (1) The drivers of observed LULCC between 1985 and 2005; (2) Reconstruct the historical LULCC for India between 1950 and 2011 by combining satellite information with census statistics; (3) Generate scenarios of future LULCC to support national level environmental assessments; and (4) Update the LULC satellite database for 2015 as a continuing effort of this study. The dataset can be used in ecosystem modeling studies including land cover dynamics and global climate change. These maps provide in-depth understanding of LULCC (e.g., degradation, desertification and biodiversity loss and physical and human forces behind these processes). Additionally, they will improve our understanding of the linkages between LULCC and climate change, food production, health, urbanization, coastal zone management, trans-boundary migration, and in identifying sites for renewable energy and availability and quality of water. Furthermore, these maps will enable identification of vulnerable areas of land degradation process, changing patterns of precipitation and temperature, and shifts in the biome boundary distribution.

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Author Contributions

Parth S. Roy	Principal investigator, conceptualizing the research, preparation of manual and writing the article.
Arijit Roy	Mapping, support in methodology manual preparation, and input in manuscript preparation.
Pawan K. Joshi	Mapping, support in methodology manual preparation, and input in manuscript preparation.
Manish P. Kale	Mapping, support in methodology manual preparation, and input in manuscript preparation.
Vijay K. Srivastava	Preparation of methodology manual, mapping and overall coordination.
Sushil K. Srivastav	Coordination of refinement, edge matching, coordination of cleaning data base and editorial inputs in the manuscript.
Ravi S. Dwivedi	Technical guidance for methodology manual, supervising mapping, reviewing the manuscript at various stages and support coordination.
Chitiz Joshi	Edge matching, creation and cleaning of data bases.
Mukund D. Behera	Support in conceptualizing research and preparation of manuscript.
Prasanth Meiyappan	Support in conceptualizing research, comparison of 2005 map with other global data sets, and preparation of manuscript.
Yeshu Sharma	Preparation of national data base, area calculation, and conversion of existing data base to 1 km grid data base.
Atul K. Jain	Conceptualizing and motivating to prepare the research article and support in writing.
Jamuna S. Singh	Reviewed the revised manuscript, classification scheme and advice.
Yajnaseni Palchowdhuri	Mapping and creation of data base.
Reshma. M. Ramachandran	Mapping and creation of data base.
Bhavani Pinjarla	Mapping and creation of data base.
Vishnubhotla Chakravarthi	Support in formulating the research, manuscript preparation and reviewing
Nani B. Battu	Mapping and creation of data base.
Mahalakshmi S. Gowsalya	Mapping and creation of data base.
Praveen Thiruvengadam	Mapping and creation of data base.
Mrinalni Kotteeswaran	Mapping and creation of data base.
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Sandeep Maithani	Internal quality checking of LULC data sets
Gautam Talukdar	Mapping and creation of data base.

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Prasanna Kumar	Mapping and creation of data base.
Deepak Kushwaha	Mapping and creation of data base.

Conflicts of Interest

The authors declare no conflict of interest.

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