

# Quantification and monitoring of deforestation in India over eight decades (1930–2013)

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**Abstract** There is still large uncertainty over the status of global forest cover owing to the paucity of comprehensive and holistic studies related to long term forest cover change. The aim of the present work is to prepare a nation-wide multi-date forest cover database which describes and quantifies historical and recent changes in natural forests of India. This analysis facilitated the determination of the state of Indian forest cover changes over last eight decades. Here, we have mapped the total area under forest cover, evaluated the spatial tracking of changes in natural forests, estimated the rate of deforestation and afforestation, analysed the biogeographic zone wise and state wise forest cover change, existing land use in deforested area, influence of environmental factors such as terrain on deforestation and implication of different definitions of forest used by agencies reporting deforestation in India. The results indicated that forests covered an area of 869,012 km<sup>2</sup> in 1930 which has decreased to 625,565 km<sup>2</sup> in 2013, a net loss of 243,447 km<sup>2</sup> (28 %) in eight decades. The highest annual average forest loss was found to be 4795 km<sup>2</sup> during 1930–1975, 1476 km<sup>2</sup> during 1975–1985, 767 km<sup>2</sup> during 1985–1995, 356 km<sup>2</sup> during 1995–2005 and 209 km<sup>2</sup> during 2005–2013. Between 1930 and 1975, forest experienced large scale deforestation at gross annual rate of 0.77 % which has declined to 0.29 % and 0.14 % for the 1975–1985 and 1985–1995 periods respectively. Quantification of annual rate of gross deforestation for the recent period indicates 0.07 % during 1995–2005 and 0.05 % during 2005–2013. The lower rates of deforestation during recent period support effectiveness of conservation measures taken at national level. It was found that deforestation rate has decreased in many biogeographic zones by 2005, except for Andaman &

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Nicobar Islands and North East. The major deforestation has mostly occurred due to conversion of forests to agriculture. The construction of reservoirs contributed to 4.1 % of forest loss. The tropical forests have experienced large scale deforestation followed by subtropical forests. The findings of the study will be useful to prioritize conservation and protection of forest cover at the regional level. It shall also provide a base for future research on the impacts of deforestation on carbon flux and biodiversity.

**Keywords** Deforestation · Monitoring · Forest · Conservation · Remote sensing · India

## Introduction

There is an increasing concern that tropical deforestation continues to be a major contributor to climate change. Deforestation is estimated to be responsible for 90 % of the CO<sub>2</sub> emissions caused by land-use changes (IPCC 2001). The Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report revealed the relatively poor understanding of the impact of land use changes on the long-term trends in environmental variables (Pielke et al. 2002). This knowledge gap was reemphasized and recommended for an original approach by Pielke et al. (2002) and Roy et al. (2007) to quantify changes in vegetation cover. Net carbon emissions from deforestation during the past decade are estimated at 3.3 billion tonnes of CO<sub>2</sub> emissions annually (<http://www.ipcc.ch>). Tropical forests contain high levels of biodiversity, being particularly significant in terms of both species richness and concentration of endemic species (Brooks et al. 2006). Biodiversity change through the loss of ecosystem services slows down the economic development of a nation and thus intricately linked to poverty which has been identified by the United Nations as the greatest challenge to the humankind (Díaz et al. 2006). Thus, deforestation has impacts on carbon stocks, biodiversity, ecosystem services and livelihoods. India is one of the mega-biodiversity nations. It is the seventh largest country in the world and the second largest in Asia having an area of 328.72 Mha (<http://india.gov.in/india-glance/profile>). India has the second largest population in the world and accounts for 17.5 % of the global population. The population of India was only 238.4 million in 1901 having increased by more than four times to reach 1277 million in 2013 (<http://censusindia.gov.in>).

Deforestation has been linked to demographic changes, socio-economic and environmental factors and forest management. Population growth and agricultural expansion have been identified as the underlying driving forces of deforestation which not only operate at the local or regional level but also have indirect national and global level consequences (Geist and Lambin 2002). The relationship between population growth and deforestation becomes apparent as local people clear land to provide more area for farming. In the case of developed countries, the relationship is much more complex as the population begins to shift away from dependence on agriculture as a livelihood. In addition, food, fuel and timber needs are met through imports from other areas of the country and world (Meyerson 2004). At the same time, population growth increases with increasing deforestation pressure as more the cleared land, more the population it can support (Díaz et al. 2006). DeFries et al. (2010) found that forest loss was positively correlated with urban population growth and agricultural products exports across 41 countries in the humid tropics.

In the pre-colonial era, humans were of the hunter-gatherer nature and later gradually progressed as settled cultivators (Gadgil 1990). In the seventeenth century British India, the forests were over-exploited and destroyed for timber extraction and expansion of agriculture. In the early eighteenth century, though the hazards of deforestation were realized, it was linked solely to change in rainfall patterns (Ribbentrop 1990). In the past, forest cover has been decreasing in India constantly due to the lack of foresight and priorities of the policy makers. It was only in the 1880's that exploitation of forests by people was curtailed by the then Governor General, Lord Dalhousie by issuing the Charter of the Indian Forests (Ribbentrop 1990). The major concern of the Government up to and even after independence was to meet the growing demand for food. As a response to this, large areas of forested lands were cleared for agriculture and other developmental activities which resulted in the increase of agricultural land between 1951 and 1976 (Ribbentrop 1990). Following this, dams were built to aide to the irrigation needs of the agricultural lands and large tracts of forests were destroyed in the process (Ribbentrop 1990). Relocation of villagers in other places further added to the process of deforestation. Wildlife Protection Act, 1972 envisaged protection to wild animals, birds, plants as well as their habitat through setting up of protected areas in India. Forest Conservation Act, 1980 aimed at lowering the rate of deforestation by controlling conversion of forest land to non-forestry purposes. National Forest Policy, 1988 envisaged making forest management participatory and conservation-oriented (Aggarwal et al. 2009).

In spite of significant human population increase, India has added over 4 Mha of forest cover through tree plantation programs during 1990–2010 (FAO 2010). For India, the increase in plantations was greater than the loss of natural forests (Houghton 2005). An assessment by Puyravaud et al. (2010) has shown that there is loss of India's native forests. Gilbert (2012) has highlighted the disagreement over the area under forests in India. Ravindranath et al. (2014) reported that India could be potentially over-reporting the forest cover by including many plantation categories. Since 1997, the total forest cover seems to have steadily increased from 63 to about 69 Mha in 2013 (FSI 2013). Approximately 5.4 Mha of the natural forests have been diverted to commercial plantations (MoEF 2009). Orchards and commercial plantations which could be potentially classified as 'forest' account for about 8.79 Mha or 12.7 % of the total forest cover (Ravindranath et al. 2014). If dominant orchards and commercial plantations such as coconut, coffee, mango, cashew-nut, etc. are excluded as forests, the area under forests could reduce from 69.2 Mha (21.05 %) to 60.4 Mha (Ravindranath et al. 2014).

It is important to note that plantations are very different from natural forest cover in terms of species composition, ecosystem functions and their ability to support a wide range of species and withstand stress such as drought and disease (Meyerson 2004). The natural forest definition is indicated to potentially become important in the conservation policies and UNFCCC REDD + negotiations (Romijn et al. 2013; Ravindranath et al. 2014). The study in Western Ghats by comparing satellite data of 1973 and 1995 indicated 25.6 % of forest cover loss (Jha et al. 2000). The reported annual net deforestation rate for Odisha state of India for the period of 1995–2010 was 0.15 % (Reddy et al. 2013a). The study in Andhra Pradesh has reported annual net rate of deforestation as 0.02 % during 2005–2011 (Hari Krishna et al. 2014). Spatial patterns are usually scale specific. Depending upon the scale of observation processes that appear homogeneous at a small scale may become heterogeneous at a larger scale. The optimum resolution depends upon the study objectives, the type of environment and the kind of information required (Lam and Quattrochi 1992). Consistent estimates of deforestation rates in India have not been analysed very comprehensively so far (Reddy et al. 2013b). The lack of an objective system for periodical

monitoring of the natural forests to update changes prevents obtaining actual deforested area. Huge quantity of carbon and environmental services may get negatively affected when natural forests are substituted by plantations but technically by definition they remain forests. Thus, the loss of forest and associated biodiversity extend far beyond the simple statistics of deforestation due to inclusion of plantations and orchards (Jha et al. 2000; Romijn et al. 2013). There is a requirement of consistent and spatio-temporally explicit quantification of natural and managed forest change (Hansen et al. 2013). This study objective is to assess and monitor the spatial extent and trends in forest cover change of India (1930–2013). Multi-source and multi-temporal data from earliest possible topographical maps and satellite remote sensing datasets were used to map the Indian forest cover.

## Definitions

There are no globally agreed definitions of forest and deforestation. In the present study, forest is defined as land spanning more than 1 ha, dominated with native tree species having a minimum stand height of 5 m with an overstorey canopy cover greater than 10 %. Our study considers deforestation as replacement of forest by other land use and/or depletion of forest canopy cover to less than 10 %.

FAO (2010) includes timber and rubber plantations as forests. United Nations Framework Convention on Climate Change (2001) includes young natural stands and all plantations under forest. In the study by Hansen et al. (2013) the term “forest” refers to tree cover. FSI defines forest cover as all lands more than one hectare in area, with a tree canopy density of more than 10 %, irrespective of ownership and legal status (FSI 1987–2013).

## Methods

This study is primarily based on classification and spatial grid cell analysis of multi-source and multi-temporal data.

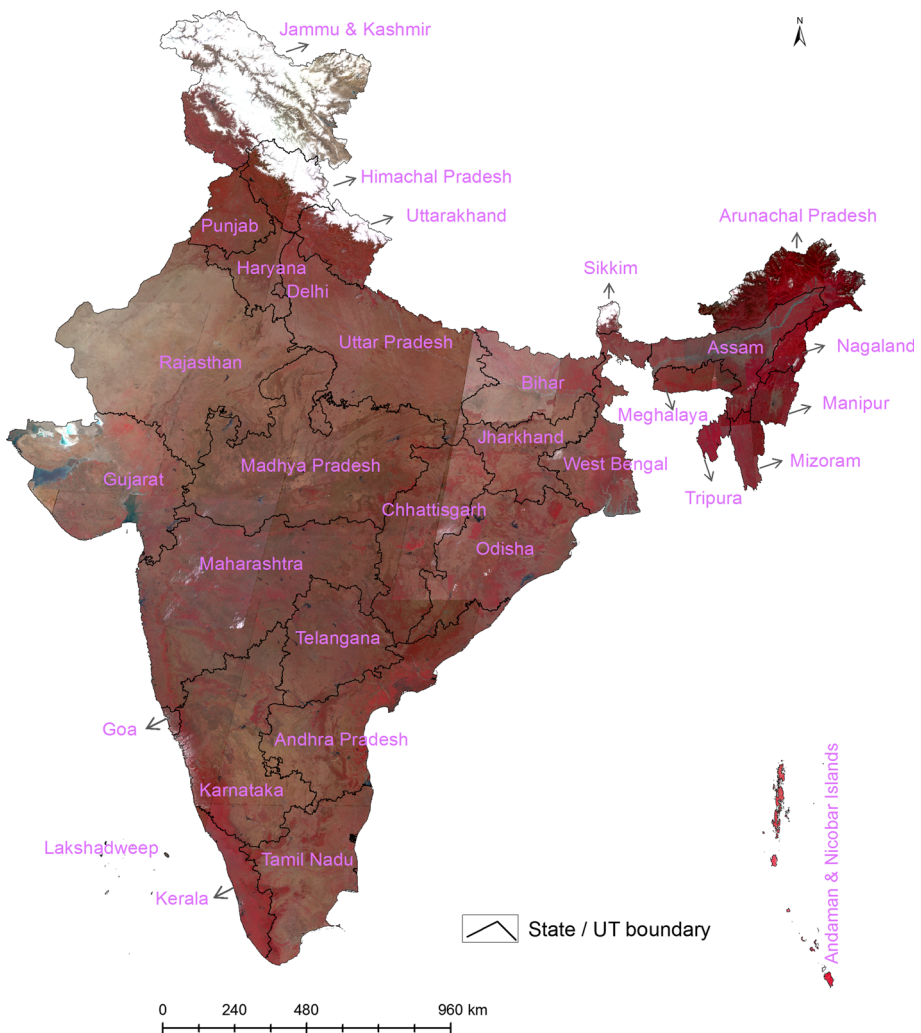
**Table 1** Details of spatial data used in the study

Sl. no	Type	Period	Scale/ resolution*	No. of maps/ satellite scenes
1	Topographical maps	1920–1940	1:250,000	251
2	Landsat MSS	1972–1977	80 m	356
4	Landsat MSS	1985	80 m	452
5	IRS 1A/1B LISS-I	1995	72.5 m	470
6	IRS P6 AWiFS	2005	56 m	64
7	Resourcesat-2 AWiFS	2013	56 m	64

\* Scale for topographical maps; spatial resolution for satellite datasets

## Data sources

To generate maps of forest cover across India, the topographical maps (1:250,000 scale) prepared by Army Map Service, U.S. Army, Washington surveyed during 1920–1940 (<http://www.lib.utexas.edu/maps/ams/india>) were acquired. Remote sensing data pertaining to Landsat MSS (1972–1977) provided by Global Land Cover Facility Programme was downloaded from the website (<http://glcftp.umiacs.umd.edu:8080/esdi>). Landsat MSS (1985) was procured through National Remote Sensing Centre (NRSC), ISRO, Hyderabad. Remote sensing data of IRS 1A/IB LISS I (1995), IRS P6 AWiFS (2005) and Resourcesat-2 AWiFS (2013) were obtained from NRSC, ISRO, Hyderabad (Table 1). We have considered 1930 as the base year for our temporal analysis for the 1920–1940 period. For



**Fig. 1** IRS Resourcesat-2 AWiFS False Colour Composite image of India (January 2013)

Andaman and Nicobar Islands and in gap areas of survey for the 1930's period, the topographical maps (1:250,000 scale) prepared by Survey of India (1950–1960) were used. All the satellite scenes had negligible (less than 5 %) cloud cover. Cloud cover areas were interpreted based on subsequent year of mapping (i.e. 2006 data for 2005). False colour composite image of Resourcesat-2 AWiFS of 2013 is shown in Fig. 1.

## Ancillary data

This study combined use of very high resolution images from Google Earth (<http://earth.google.com>) and extensive field surveys to aid in interpretation of forest cover. The multi-season IRS P6 AWiFS data of 2012, multi-season IRS P6 LISS III data of 2005/2006, Landsat ETM+ data of 2000/2001, land use/land cover map of 1:250,000 scale (2012) generated by NRSC and forest cover map of 1:50,000 scale (2005) of FSI were used as reference.

## Total area under forest

Satellite data was acquired and preprocessed, followed by image extraction, noise removal and geometric correction. Following the availability of orthorectified Landsat TM data, the common ground control points were selected on the raw satellite data with proper spatial distribution covering the entire study area. This process of geometric correction of raw satellite data was achieved using first order polynomial transformation fit. A nearest-neighbor algorithm was used to perform the resampling procedure and the image-to-image registrations, which yielded a root-mean-square error of <1 pixels for all data (Jensen and Lulla 1987). The study area was extracted from the multiple satellite data scenes by subsetting. To reduce the error due to various atmospheric conditions at different dates of image acquisition conversion of digital number to Top-of-Atmosphere reflectance algorithm as suggested by Chavez (1996) was applied. The images were georeferenced to the Albers Conformal Conic coordinate system and WGS84 datum. For interpretation of topographical maps, on-screen visual interpretation technique was used. In remote sensing data analysis, spectral and temporal characterization for land cover mapping was done by multi-season data which masked the vegetation cover for further visual interpretation. The forest cover map produced from the Resourcesat-2 AWiFS image of 2013 was used as a template for classifying the other four periods (1975, 1985, 1995, 2005) by on-screen visual interpretation for change between forest and non forest cover. Change areas were added to the spatial data of the corresponding period. The main advantage of using this technique, rather than classifying all images independently, is to minimise the changes that are associated with sensor differences as well as with phenological, atmospheric and environmental variability. The hybrid method of digital and visual interpretation of the satellite imagery for forest change supports identifying areas of deforestation and afforestation/reforestation and will reduce the inconsistencies. Calculation of forest cover dynamics comprised of analysis of changes for the time periods, 1930–1975, 1975–1985, 1985–1995, 1995–2005 and 2005–2013.

## Spatial change analysis

A grid cell of 5 km × 5 km (each 25 km<sup>2</sup>) was generated for time series assessment and to analyse the trends in spatial distribution of forest cover (1930–1975, 1975–1985, 1985–1995, 1995–2005 and 2005–2013). The distribution of transitions and persistence of forest was calculated and the change evaluated for any trend (negative change, positive change and unchanged area) across the identified classes i.e. <1, 1–5, 5–10, 10–15, 15–20 and >20 km<sup>2</sup>.

## Rate of deforestation and afforestation/reforestation

Spatial analysis plays an important role in estimating the forest cover change. The annual rate of forest cover change is calculated by comparing the area under forest cover in the same region at two different times. Areas that have undergone change from non forest to forest were treated as ‘reforestation’. The annual rate of change which was derived from the compound interest formula was calculated following Puyravaud (2003).

$$r = \frac{1}{(t_2 - t_1)} \times \ln \frac{a_2}{a_1}$$

where  $r$  is the annual rate of change (percentage per year),  $a_1$  and  $a_2$  are the forest cover estimates at time  $t_1$  and  $t_2$  respectively.

## Land use in deforested areas

An understanding of land use in deforested area is necessary to interpret the influence of land use drivers. Forest land altered by deforestation process has been quantified for 1930–2013. The present work seeks to provide spatial distribution of various types of land use/land cover in deforested land.

## Biogeographic zone wise forest cover change analysis

Topography, climate, flora and fauna of biogeographic zones are unique. Rodgers and Panwar (1988) have divided India into 10 biogeographic zones. The present study considered ‘biogeographic zones’ as a standard stratum for forest cover analysis. In India, Himalayas (both Western and Eastern), Western Ghats, North East, Andaman Islands (Indo-Burma) and Nicobar Islands (Sundaland) are the global biodiversity hotspots.

## Influence of elevation on deforestation

Biophysical factors such as terrain play major role in acceleration of deforestation. Landscape of India represents elevation from zero to 8586 m (MSL). We have used the NASA SRTM Digital Elevation Model to understand influence of elevation on deforestation (Rabus et al. 2003). We categorised nine elevation-based categories on the basis of altitude which has been further divided into four climatic zones. Deforested areas have been examined at different elevation levels: <100, 100–200, 200–500, 500–1000, 1000–1500, 1500–2000, 2000–2500, 2500–3000 m, and >3000 m.

## Validation of maps

The accuracy of the maps was validated independently of the mapping. Field data of NRSC comprising of 8500 sample points was used to validate the map of 2013. Validation of forest cover maps for 1975, 1985, 1995 and 2005 was done based on visual assessment of satellite images and the temporal consistency of ground control points. Land use/land cover map of 1:250,000 scale (2010) and vegetation type map of 1:50,000 scale (2004) available at National Remote Sensing Centre were consulted for corroboration of spatial distribution of forest cover. The overall accuracy of the forest cover maps derived for the years 1975, 1985, 1995, 2005 and 2013 were 89.2, 90.5, 92.4, 93.2 and 93.2 % respectively. All the kappa values were more than 0.85.

The high accuracy of the classified maps of 2005 and 2013 revealed that hybrid image interpretation (which was supported by field data and visual key elements of image), has provided an appropriate delineation of forest cover. Further, the accuracy has increased for 2005 and 2013 maps due to availability of more detailed reference datasets. The mapping for the oldest data of 1975–1995 was carried out carefully considering ground control points (as invariant objects) that had not changed over time. In case of topographical maps, the maximum positional error of theme reaches up to 1 mm at the scale of map. The study on historical land-use reconstructions has highlighted uncertainty in long term forest cover change analysis with topographic maps and results proving that 5–10 % errors are inherent at various stages of analysis (Kaim et al. 2014). In this research, results of trajectory analysis show that in the Swiss Alps only around 5 % of mapped areas and less than 7 % in the Polish Carpathians may be considered uncertain, which is an optimistic result for the reliability of forest cover change mapping and further research (Kaim et al. 2014). In the present study, it is important to stress that forest patches were presented according to theme boundaries. The inaccuracy in mapping was minimised by visual interpretation of forest cover in topographical maps. Overlay analysis has included all forest ground control points matched with forest cover map of 1930. In order to manage mapping errors propagated through the analyses of change, all the digital datasets were resampled to 56 m before proceeding for analysis.

## Results

### Key findings

The present study

1. Identified the total area under forest cover over eight decades.
2. Identified the spatial tracking of changes in natural forests.
3. Involved estimation of rate of deforestation and afforestation.
4. Carried out biogeographic zone wise forest cover change analysis.
5. Carried out state wise forest cover change analysis.
6. Analysed the existing land use in deforested area.
7. Identified the influence of elevation on deforestation.



### *Major changes in forest cover*

The forests covered an area of 869,012 km<sup>2</sup> in 1930 which has decreased to 625,565 km<sup>2</sup> in 2013, a net loss of 243,447 km<sup>2</sup> (28 %) in eight decades (Table 2). Forest showed the largest decline in relation to its area during 1930–1975. The first forty five years of study (1930–1975) account for major forest loss (215,792 km<sup>2</sup>) and only 27,655 km<sup>2</sup> was lost in the next thirty eight years. In the present study based on natural definition, forest cover decline was 3614 km<sup>2</sup> during 1995–2005 and 1668 km<sup>2</sup> during 2005–2013. The highest forest loss was noticed with 4795 km<sup>2</sup> per year during 1930–1975, 1476 km<sup>2</sup> per year during 1975–1985, 767 km<sup>2</sup> per year during 1985–1995, 356 km<sup>2</sup> per year during 1995–2005 and 209 km<sup>2</sup> per year during 2005–2013. Table 2 shows the forest cover of India in various periods.

### *Spatial Change analysis*

The vectorised datasets were analyzed to identify the extent and rate of change. There are total 130883 grids identified to visualize the change in spatial patterns of forest cover (Table 3). The forest cover change map of India for the period of 1930–2013 is shown in Fig. 2. Grid wise analysis exhibits that the highest number of grids has undergone negative changes during 1930–1975 followed by 1985–1995 and 1995–2005 (Table 4). There are total 6231 grids that have shown loss of forest cover during 2005–2013. Large scale deforestation of >15 km<sup>2</sup> is mainly attributed to expansion of agriculture.

At the same time, positive changes were observed in 2329 grids during 2005–2013. It is an indication of regrowth of forests along with afforestation/reforestation programmes taken up by State Forest Departments that may have contributed to the increase in forest cover. The Supreme Court of India, on 10th July 2009, had issued orders that there would be a Compensatory Afforestation Fund Management and Planning Authority (CAMPA) for monitoring, technical assistance and evaluation of compensatory afforestation activities (<http://forestclearance.nic.in/>).

### *Rate of deforestation and afforestation/reforestation*

Forest cover changes did not occur at the same rate during all time intervals studied. Between 1930 and 1975, large scale deforestation at the gross annual rate of 0.77 % has been estimated, which has however declined to 0.29 and 0.14 % for the 1975–1985 and 1985–1995 periods, respectively. Annual rate of deforestation indicates gross loss of 0.07 % during 1995–2005 and 0.05 % during 2005–2013. The highest net annual rate of deforestation was 0.63 % during 1930–1975 and the lowest net rate was 0.03 % during

**Table 2** Areal extent of forest cover in India

Period	Area (km <sup>2</sup> )	% of total geographical area
1930	869,012	26.4
1975	653,220	19.9
1985	638,460	19.4
1995	630,795	19.2
2005	627,233	19.1
2013	625,565	19.0

**Table 3** Grid wise analysis of forest cover (number of grids)

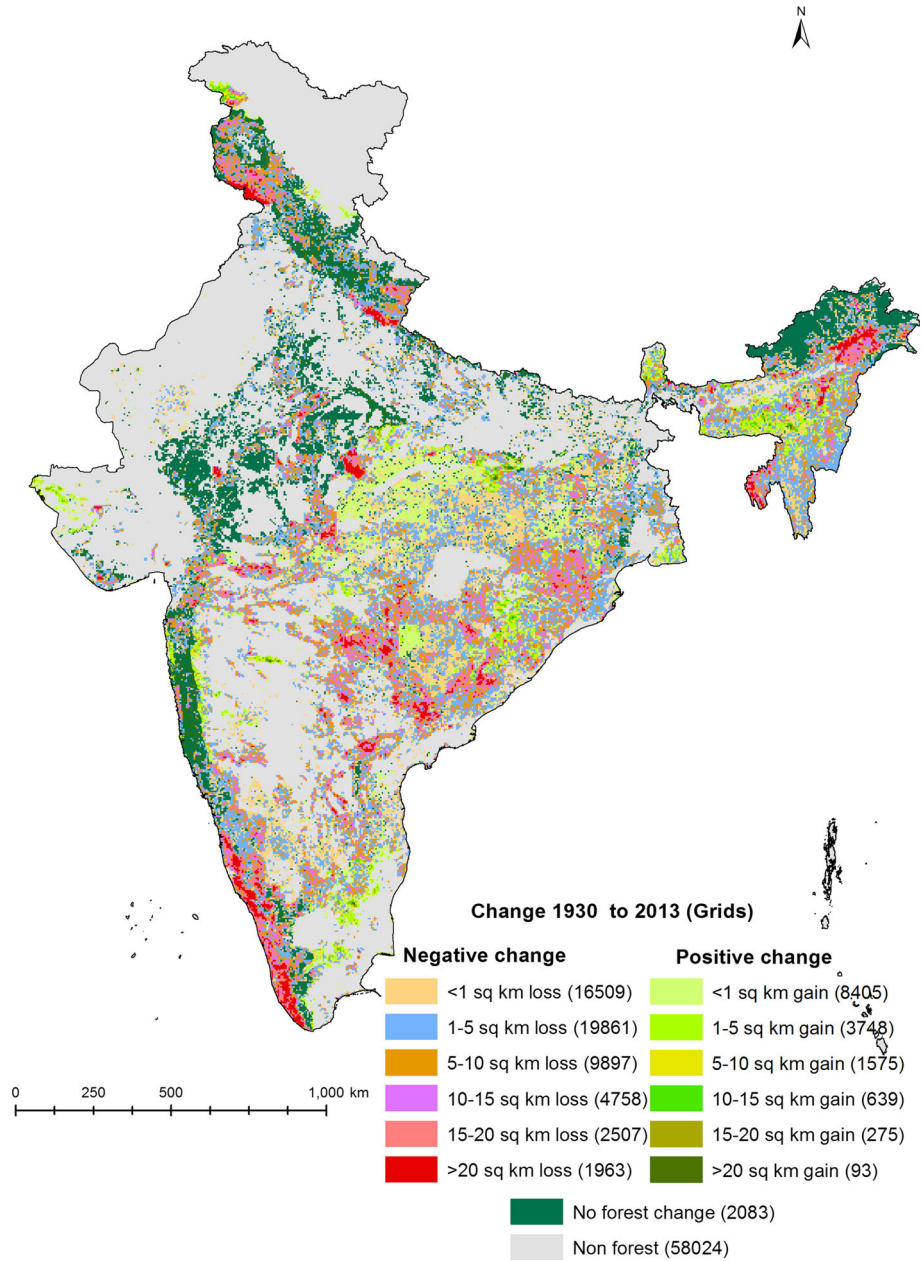
Class	1930	1975	1985	1995	2005	2013
<1 km <sup>2</sup>	9526	9271	9359	9359	9361	9376
1–5 km <sup>2</sup>	12,775	10,411	10,529	10,603	10,678	10,665
5–10 km <sup>2</sup>	9038	8758	8799	8877	8907	8949
10–15 km <sup>2</sup>	7760	7565	7682	7721	7704	7733
15–20 km <sup>2</sup>	7768	7820	7897	7756	7766	7778
>20 km <sup>2</sup>	22,278	14,151	13,425	13,156	12,996	12,890
Total	69,145	57,976	57,691	57,472	57,412	57,391

2005–2013. In spite of forest conservation policies, the trend of deforestation has continued, though there is obvious decline in the rate of annual deforestation from 1975 (Table 5; Fig. 3). More importantly, the net deforestation rate has been very low during 2005–2013 indicating management interventions for conservation of forests at national level. Even though the deforestation rate has decreased in India since the time period 1975–2013, the forest is still disappearing than it is afforested/reforested and thus the crisis with deforestation remains.

#### *Biogeographic zone wise forest cover change analysis*

Deccan biogeographic zone supports highest forest cover followed by North East, Western Ghats, Eastern Himalayas and Western Himalayas. Coasts, Desert and Trans Himalayas represents least forest cover among the biogeographic zones (Table 6). Since there are five time phases of historical annual deforestation rate to compare, it is now possible to determine trend in different biogeographic zones (Fig. 4; Table 7). Overall, it is apparent that deforestation rate has decreased in many biogeographic zones by 2005, except for Andaman & Nicobar Islands and North East. An observation of population statistics of Andaman & Nicobar Islands from 1931 to 2011 showed a continuous population increase of 19,223 to 3,81,000 and the population growth was more than 90 % (<http://censusindia.gov.in>).

Expansion of agriculture and settlements led to the forest conversions that occurred in the Himalayan region. The major driver of deforestation in North East is shifting cultivation along with logging and mining. In the Western Ghats, construction of dams, expansion of plantations and agriculture as well as infrastructure development are responsible for deforestation. Coasts and islands witnessed deforestation mainly due to various anthropogenic activities, expansion of agriculture, aquaculture, logging and also due to occurrence of natural calamities like tsunami in Andaman & Nicobar Islands. Expansion of agriculture is the primary cause of deforestation in Deccan followed by logging, mining, shifting cultivation, urbanization, construction of dams and infrastructure development (Reddy et al. 2013b). The analysis reveals that much of the forests in Western Himalayas and Eastern Himalayas show evidence of decreasing trend of deforestation due to inaccessibility and conservation effectiveness. Satellite image chips of selected large-scale deforestation sites are shown in Fig. 5.



**Fig. 2** Forest cover change map of India: 1930–2013

*State/Union Territory (UT) wise forest cover change*

The trend of forest cover loss is significant in ten states, i.e. Assam, Odisha, Telangana, Andhra Pradesh, Karnataka, Manipur, Meghalaya, Mizoram, Nagaland and Tripura.

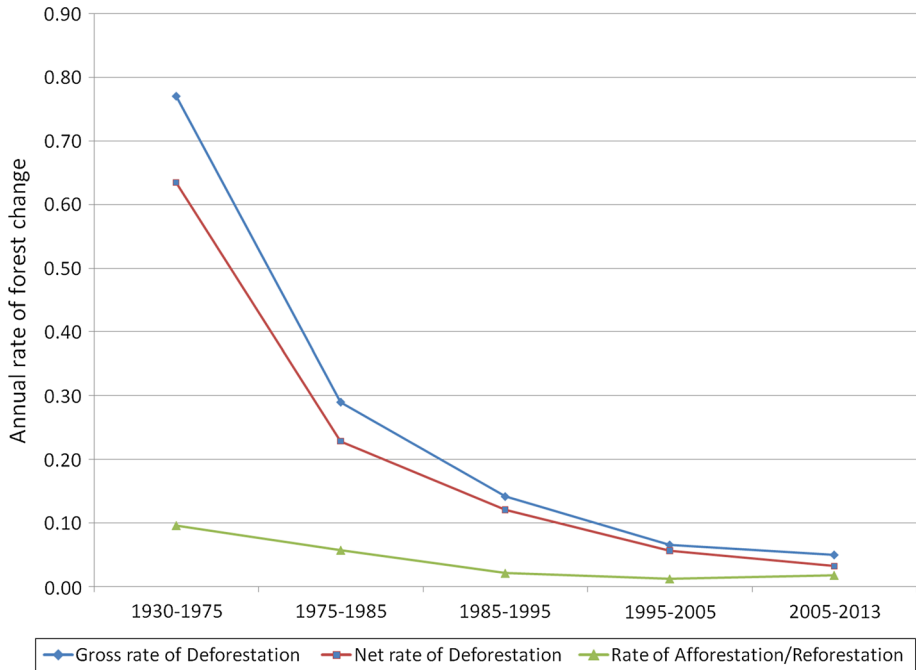
**Table 4** Analysis of grid-wise negative and positive changes in India (No. of  $5 \times 5$  km cells)

Change	1930–1975	1975–1985	1985–1995	1995–2005	2005–2013
Forest loss					
<1 km <sup>2</sup>	17511	3233	12538	4069	5689
1–5 km <sup>2</sup>	18721	3798	2368	948	478
5–10 km <sup>2</sup>	9295	586	171	143	52
10–15 km <sup>2</sup>	4200	112	9	23	11
15–20 km <sup>2</sup>	2214	29	4	6	1
20–25 km <sup>2</sup>	1755	16	0	2	0
Total	53,696	7774	15,090	5191	6231
Forest gain					
<1 km <sup>2</sup>	10125	735	862	1248	2058
1–5 km <sup>2</sup>	3959	711	447	212	268
5–10 km <sup>2</sup>	1641	73	23	10	3
10–15 km <sup>2</sup>	665	15	2	1	0
15–20 km <sup>2</sup>	279	0	1	0	0
20–25 km <sup>2</sup>	96	1	0	0	0
Total	16,765	21,648	1335	1471	2329

**Table 5** Annual rate of forest cover change in India

Time period	Gross rate of deforestation	Net rate of deforestation	Rate of afforestation/ reforestation
1930–1975	0.77	0.63	0.1
1975–1985	0.29	0.23	0.06
1985–1995	0.14	0.12	0.02
1995–2005	0.07	0.06	0.01
2005–2013	0.05	0.03	0.02

Andaman & Nicobar Islands, biodiversity hotspot of India shows continual forest loss during the study period (Table 8). The major forest covered states (>30 % forest cover in India), i.e. Arunachal Pradesh, Chhattisgarh and Madhya Pradesh have undergone very low deforestation during 2005–2013. Of the seven union territories of India, there is no natural forest cover found in Lakshadweep. Rapid changes in forest cover in the past decades were observed in North East states of India. The increasing rate of deforestation was found in two states i.e. Assam (0.32) and Meghalaya (0.21) (Table 9). The forest cover owned mostly by village communities and individuals in the states of North East India. In Nagaland, 91 % of forest land is under control of communities, followed by 90 % in Meghalaya, 68 % in Manipur, 62 % in Arunachal Pradesh, 41 % in Tripura, 33 % in Mizoram and Assam (Manhas et al. 2006).



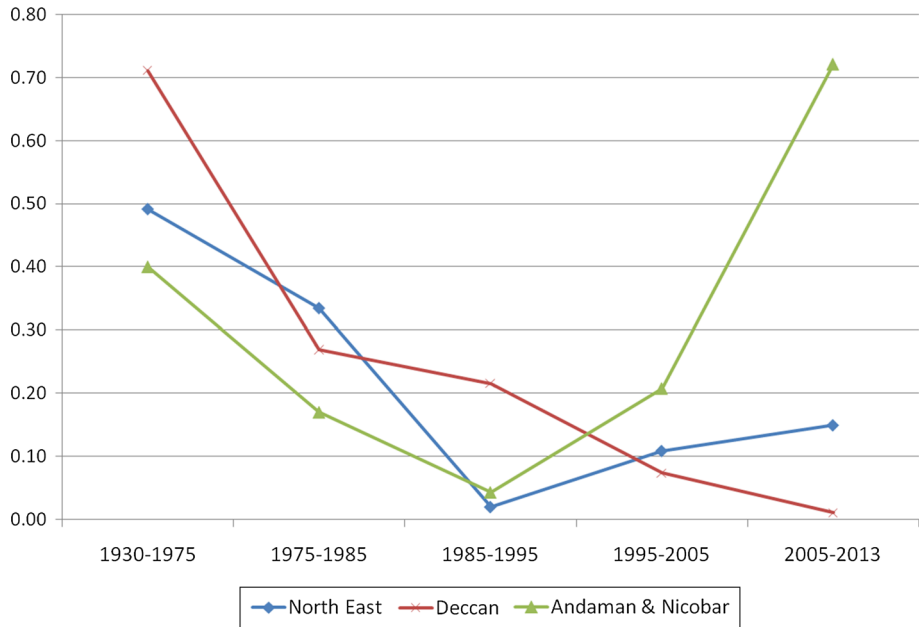
**Fig. 3** Annual rate of forest change in India

**Table 6** Areal extent of forest cover in Biogeographic zones (area in km<sup>2</sup>)

Biogeographic zone	1930	1975	1985	1995	2005	2013
Trans Himalayas	1695	1695	1695	1695	1695	1695
Western Himalayas	52,166	44,092	43,999	43,999	43,982	43,982
Eastern Himalayas	68,815	63,690	62,823	62,822	62,713	62,706
Gangetic Plains	29,458	16,353	15,967	15,898	15,875	15,870
Semi Arid	68,491	47,465	46,591	46,111	45,986	45,986
Desert	1279	1279	1121	1121	1121	1121
North East	114,550	91,842	88,823	88,998	88,038	86,994
Deccan	430,507	312,716	304,421	297,935	295,771	295,521
Coasts	9555	3875	3765	3725	3744	3763
Western Ghats	84,968	63,123	62,286	61,551	61,511	61,511
Islands (Andaman & Nicobar)	7530	7090	6970	6940	6797	6416
Total	869,012	653,220	638,460	630,795	627,233	625,565

*Land use in deforested areas*

According to FAO (2009), the deforested areas have mainly been converted into agriculture. Among the land use change determinants, agriculture and plantations were



**Fig. 4** Net rate of deforestation in Andaman & Nicobar, Deccan and North East

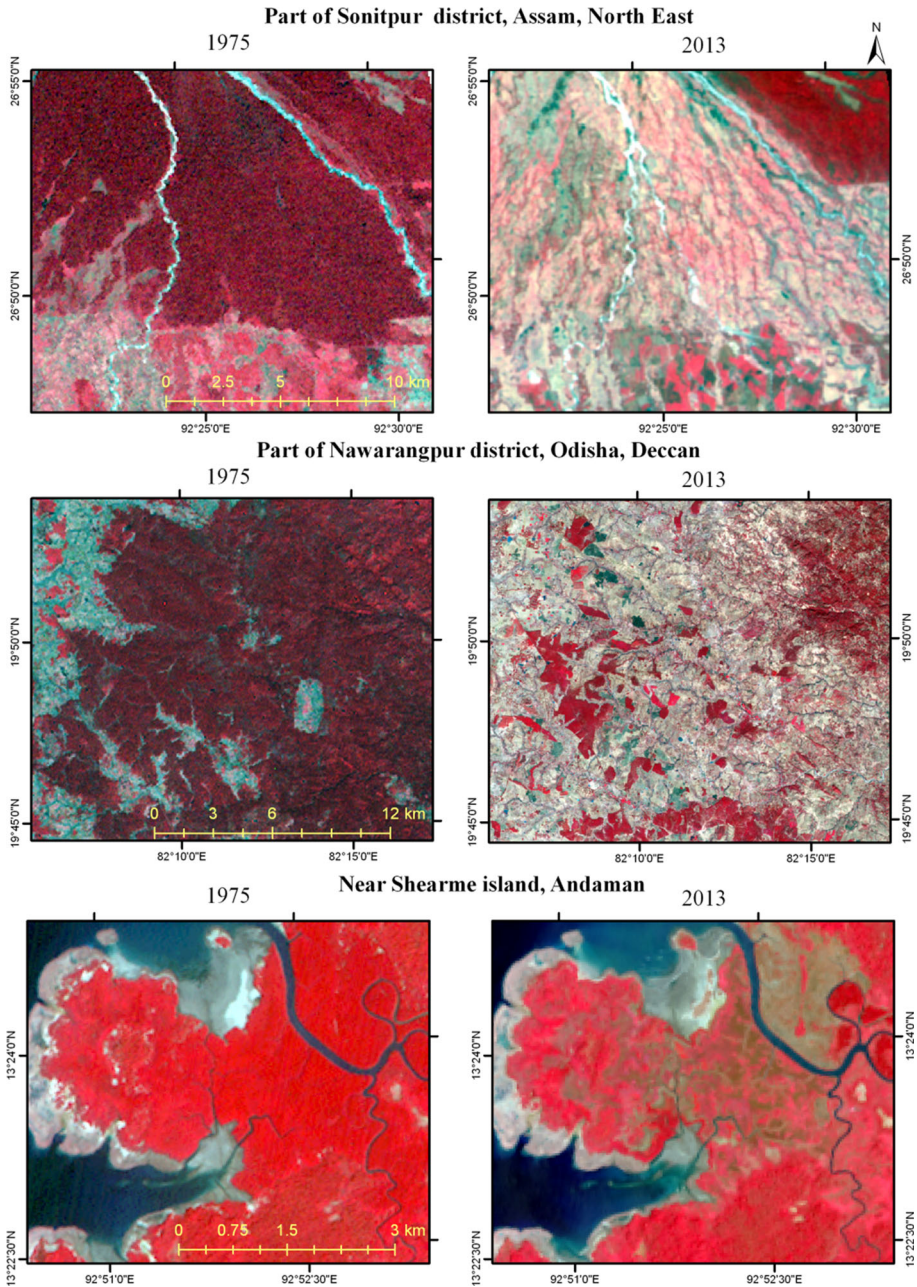
**Table 7** Net rate of deforestation in Biogeographic zones

Biogeographic zone	1930-1975	1975-1985	1985-1995	1995-2005	2005-2013
Trans Himalayas	0	0	0	0	0
Western Himalayas	0.37	0.02	0	0	0
Eastern Himalayas	0.17	0.14	0	0.02	0
Gangetic Plains	1.31	0.24	0.04	0.01	0
Semi Arid	0.81	0.19	0.1	0	0
Desert	0	1.32	0	0	0
North East	0.49	0.33	0.02	0.11	0.15
Deccan	0.71	0.27	0.22	0.07	0.01
Coasts	2.01	0.29	0.11	0	0
Western Ghats	0.66	0.13	0.12	0.01	0
Andaman & Nicobar Islands	0.40	0.17	0.04	0.21	0.72

responsible for major forest loss in India. Scrub is one of the predominant land use change drivers, which is mainly due to overexploitation of forest cover and shifting cultivation. Water bodies contribute for 4.1 % of total forest loss which is mainly attributed to construction of reservoirs (Table 10).

#### *Influence of elevation on deforestation*

Among the Indian forests, tropical zone has experienced large scale deforestation followed by subtropical zone. These two zones have high population growth and forests are



**Fig. 5** Large scale deforestation as evidenced by False colour composite satellite images (1975 and 2013)

close to the disturbance sources i.e. roads and settlements. Deforestation is low in alpine zone followed by temperate zone due to low population pressure, inaccessible topography and least infrastructure development (Table 11). Forests potentially ends at the timberline (>4000 m) where snow persists is known as ‘nival zone’. Beyond timberline,

**Table 8** Areal extent of forest cover in states/union territories (area in km<sup>2</sup>)

Sl. no.	State/UT	1930	1975	1985	1995	2005	2013
1	Andhra Pradesh	44,580	28,282	27,147	26,400	26,017	26,003
2	Arunachal Pradesh	64,937	59,797	58,933	58,932	58,824	58,822
3	Assam	36,323	23,749	22,479	22,268	21,805	21,250
4	Bihar	6983	5530	5479	5457	5454	5454
5	Chhattisgarh	64,106	59,747	57,588	55,312	55,135	55,116
6	Delhi	41	40	34	34	34	34
7	Goa	1627	1371	1292	1279	1279	1279
8	Gujarat	14,427	10,825	10,672	10,701	10,698	10,737
9	Haryana	1445	876	866	866	866	866
10	Himachal Pradesh	14,762	14,418	14,354	14,354	14,354	14,354
11	Jammu & Kashmir	28,986	18,712	18,679	18,679	18,662	18,662
12	Jharkhand	29,372	23,857	23,358	23,060	22,766	22,766
13	Karnataka	53,592	34,511	33,942	33,857	33,781	33,750
14	Kerala	30,161	11,267	11,029	10,483	10,465	10,462
15	Madhya Pradesh	93,857	79,046	78,550	78,011	77,601	77,590
16	Maharashtra	67,117	50,717	50,563	50,229	50,225	50,213
17	Manipur	18,465	16,581	15,378	15,434	15,308	15,246
18	Meghalaya	15,891	16,047	16,112	16,279	15,953	15,691
19	Mizoram	20,253	17,915	17,870	17,905	17,827	17,768
20	Nagaland	14,676	12,806	12,162	12,375	12,464	12,333
21	Odisha	78,855	55,084	51,648	49,436	48,910	48,757
22	Punjab	1913	1312	1286	1286	1286	1286
23	Rajasthan	24,679	16,563	15,716	15,359	15,358	15,358
24	Sikkim	2917	2819	2819	2819	2819	2819
25	Tamil Nadu	24,397	21,925	21,885	21,870	21,867	21,861
26	Telangana	40,746	18,652	18,368	18,006	17,556	17,520
27	Tripura	9081	4852	4914	4829	4775	4802
28	Uttar Pradesh	17,628	10,417	10,416	10,416	10,413	10,415
29	Uttarakhand	24,729	19,604	19,291	19,291	19,291	19,292
30	West Bengal	14,670	8580	8541	8509	8524	8524
31	Andaman & Nicobar	7530	7090	6970	6940	6797	6416
32	Chandigarh	6	6	6	6	6	6
33	Dadra & Nagar Haveli	249	218	109	109	109	109
34	Daman & Diu	2	2	2	2	2	2
35	Lakshadweep	0	0	0	0	0	0
36	Puducherry	9	2	2	2	2	2
	Total	869,012	653,220	638,460	630,795	627,233	625,565

vegetation cover is represented in the form of scrub and meadows. The present analysis shows inverse relationship of deforestation with increasing elevation level. Hence, it is apparent that the low elevation forests with better accessibility are more vulnerable to deforestation (Fig. 6).



**Table 9** Net rate of deforestation in states/union territories (UT)

Sl. no.	State/UT	1930–1975	1975–1985	1985–1995	1995–2005	2005–2013
1	Andhra Pradesh	1.01	0.41	0.28	0.15	0.01
2	Arunachal Pradesh	0.18	0.15	0.00	0.02	0.00
3	Assam	0.94	0.55	0.09	0.21	0.32
4	Bihar	0.52	0.09	0.04	0.01	0.00
5	Chhattisgarh	0.16	0.37	0.40	0.03	0.00
6	Delhi	0.05	1.63	0.00	0.00	0.00
7	Goa	0.38	0.59	0.10	0.00	0.00
8	Gujarat	0.64	0.14	0.00	0.00	0.00
9	Haryana	1.11	0.10	0.00	0.00	0.00
10	Himachal Pradesh	0.05	0.04	0.00	0.00	0.00
11	Jammu & Kashmir	0.97	0.02	0.00	0.01	0.00
12	Jharkhand	0.46	0.21	0.13	0.13	0.00
13	Karnataka	0.98	0.17	0.03	0.02	0.01
14	Kerala	2.19	0.21	0.51	0.02	0.00
15	Madhya Pradesh	0.38	0.06	0.07	0.05	0.00
16	Maharashtra	0.62	0.03	0.07	0.00	0.00
17	Manipur	0.24	0.75	0.00	0.08	0.05
18	Meghalaya	0.00	0.00	0.00	0.20	0.21
19	Mizoram	0.27	0.03	0.00	0.04	0.04
20	Nagaland	0.30	0.52	0.00	0.00	0.13
21	Odisha	0.80	0.64	0.44	0.11	0.04
22	Punjab	0.84	0.20	0.00	0.00	0.00
23	Rajasthan	0.89	0.52	0.23	0.00	0.00
24	Sikkim	0.08	0.00	0.00	0.00	0.00
25	Tamil Nadu	0.24	0.02	0.01	0.00	0.00
26	Telangana	1.74	0.15	0.20	0.25	0.03
27	Tripura	1.39	0.00	0.17	0.11	0.00
28	Uttar Pradesh	1.17	0.00	0.00	0.00	0.00
29	Uttarakhand	0.52	0.16	0.00	0.00	0.00
30	West Bengal	1.19	0.05	0.04	0.00	0.00
31	Andaman & Nicobar	0.40	0.17	0.04	0.21	0.72
32	Chandigarh	0.00	0.00	0.00	0.00	0.00
33	Dadra & Nagar Haveli	0.30	6.93	0.00	0.00	0.00
34	Daman & Diu	0.00	0.00	0.00	0.00	0.00
35	Lakshadweep	0.00	0.00	0.00	0.00	0.00
36	Puducherry	3.34	0.00	0.00	0.00	0.00

## Discussion

### Comparison of implication of forest definitions on reporting of deforestation

Through this study, we also emphasize the need to discuss the implication of forest definitions on reporting of forest area, change and rate of deforestation (Fig. 7). The Forest Survey of India (FSI), the official organization of Ministry of Environment and Forests &

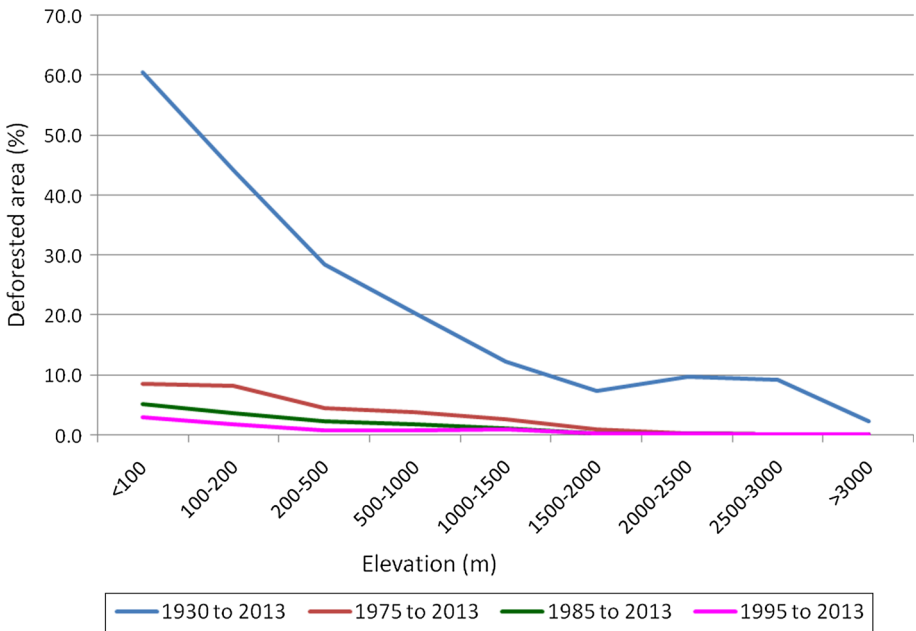
**Table 10** Land use in deforested areas (area in km<sup>2</sup>)

Forest to	1930–2013		1975–2013		1985–2013		1995–2013		2005–2013	
	Area	%	Area	%	Area	%	Area	%	Area	%
Agriculture	145,235	57.1	15,171	50.5	5098	37.2	1639	26.6	329	13.6
Plantations	34,977	13.7	2192	7.3	918	6.7	381	6.2	224	9.3
Scrub	34,652	13.6	8904	29.7	6376	46.5	3579	58.1	1766	72.9
Barren	15,233	6	1180	3.9	403	2.9	143	2.3	32	1.3
Water	10,310	4.1	1651	5.5	607	4.4	330	5.4	36	1.5
Grasslands	9503	3.7	663	2.2	222	1.6	89	1.4	34	1.4
Settlements	4473	1.8	268	0.9	77	0.6	0	0	0	0
Total	254,383	100	30,028	100	13,700	100	6162	100	2422	100

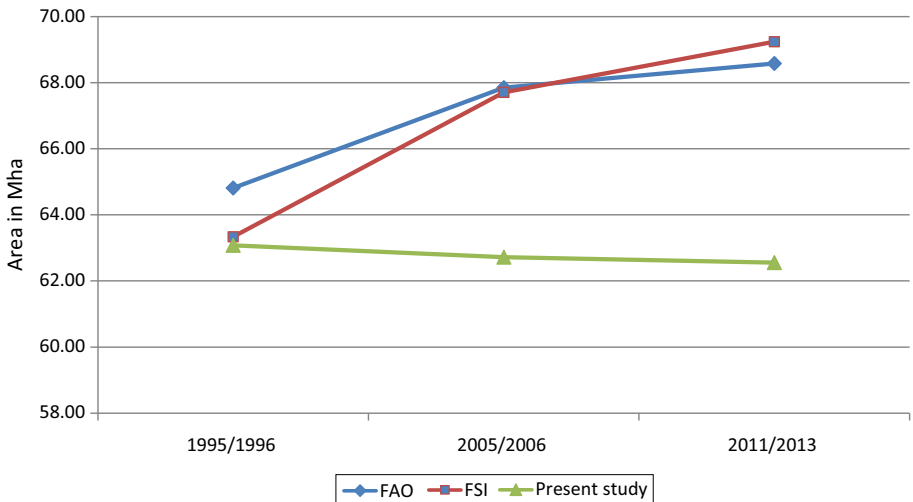
**Table 11** Elevation wise representation of forest cover and deforested area (area in km<sup>2</sup>)

Climatic zone	Elevation level (m)	1930	1975	2013	Change: 1930–2013	%	Change: 1975–2013	%
Tropical	<100	78146	33,710	30,836	47,310	60.5	2874	8.5
Tropical	100–200	97,085	59,062	54,214	42,872	44.2	4848	8.2
Tropical	200–500	322,032	240,981	230,105	91,927	28.5	10,876	4.5
Tropical	500–1000	238,286	197,086	189,469	48,817	20.5	7617	3.9
Subtropical	1000–1500	49,014	44,075	42,951	6063	12.4	1124	2.6
Subtropical	1500–2000	28,729	26,816	26,575	2154	7.5	241	0.9
Temperate	2000–2500	23,445	21,215	21,163	2283	9.7	53	0.2
Temperate	2500–3000	17,912	16,592	16,583	1329	7.4	9	0.1
Alpine	>3000	14,362	13,682	13,670	692	4.8	12	0.1
		869,012	653,220	625,565	243,446	28	27,655	4.2

Climate Change, forest definition for national forest reporting is being used in India for forest monitoring purposes that brings out state of forest report biennially since 1980's. As per state forest reports of FSI, the total forest cover of India was 640,819 km<sup>2</sup> (64.08 Mha) in 1987 which has increased to 697,898 km<sup>2</sup> (69.78 Mha) by 2013 with net positive change of 57,079 km<sup>2</sup> (FSI 2013). FSI recorded forest cover to be 638,879 km<sup>2</sup> in 1995 and 677,088 km<sup>2</sup> in 2005. Hansen et al. (2013) mapped global tree cover extent for the period from 2000 to 2012. In India, the total tree cover loss is estimated at 8971 km<sup>2</sup> and total gain area at 2549 km<sup>2</sup>. Based on this study total net loss of tree cover is accounted as 6422 km<sup>2</sup> (Hansen et al. 2013). However, according to FAO (2012), forest cover was 64.81 Mha in 1996, 65.85 Mha in 2001, 67.85 Mha in 2006 and 68.58 Mha in 2011 assessment periods. Annual growth rate between 1996 and 2000 was 0.32 %; between 2000 and 2006 was 0.6 %, between 2006 and 2011 was 0.21 % (FAO 2012). The present study has estimated forest area of 62.56 Mha similar to land use/land cover map of NRSC (NRSC, 2012; Tian et al. 2014). Another study by Roy et al. (2015) has estimated a forest area of 729,262 km<sup>2</sup> in 2005, a higher estimate to that reported by FSI.



**Fig. 6** Elevation wise representation of deforested area



**Fig. 7** Comparison of forest cover as per FAO, FSI and present study

### Deforestation trends

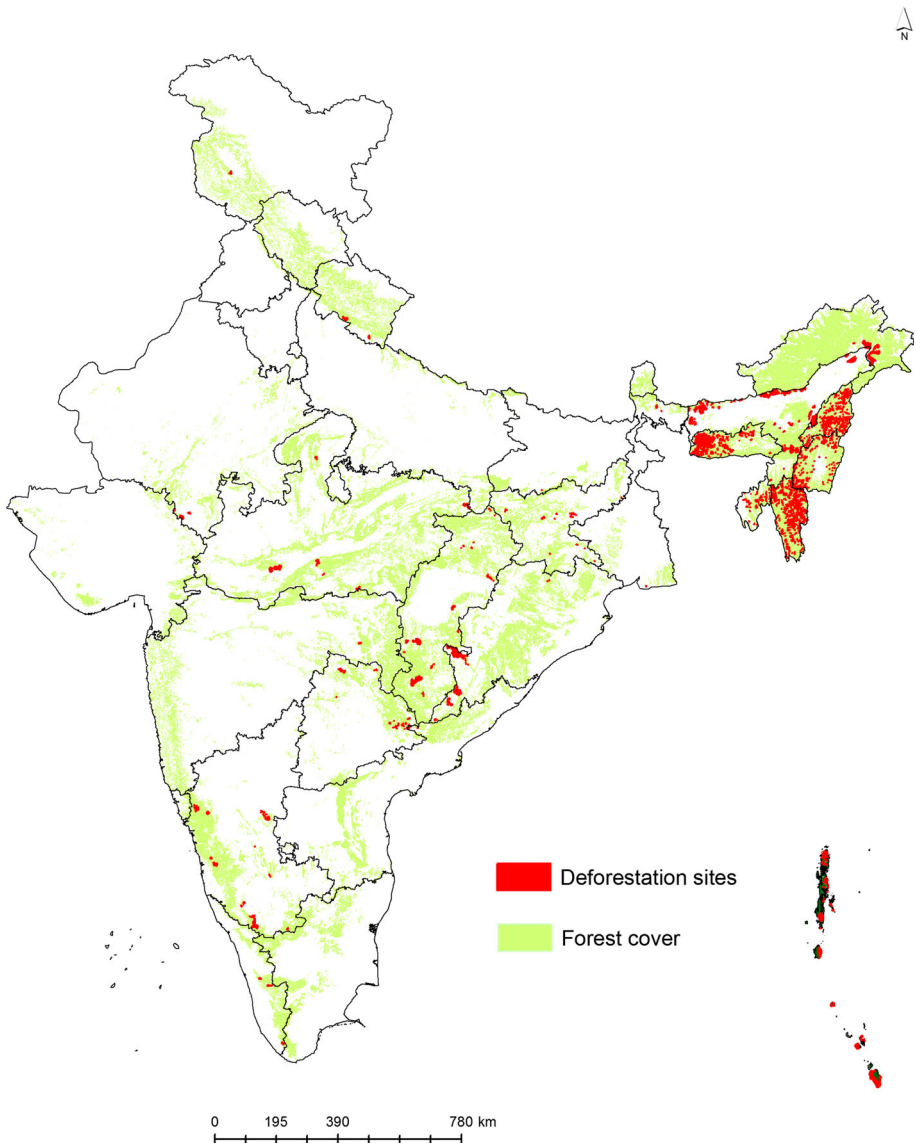
This study has analysed spatial forest cover changes and deforestation rates in India during 1930–1975, 1975–1985, 1985–1995, 1995–2005 and 2005–2013. All the five study periods that were investigated showed evidence of significant trends in forest change associated

with the loss of forest cover. It has provided deforestation rates at national level and regional level. When the annual change of deforestation is compared, there is a clear evidence of large scale deforestation during 1930–1975. During the 1930–1975, the reduction of forests was 4795 km<sup>2</sup> per year. The annual loss of forest is 866 km<sup>2</sup> between 1975 and 2005. Presently, the forest loss has decreased to 209 km<sup>2</sup> per year (2005–2013). The deforestation rate might have been low at present (2005–2013) because of development and implementation of forest management policies. Another reason might be that many accessible forests were already logged in the past. But even if the loss of forests is decreasing in many biogeographic zones, it still continues at a high rate in Andaman & Nicobar Islands and North East. The results depict that deforestation is highly concentrated in parts of North East India, Andaman & Nicobar, Deccan covering southern Odisha, northern Telangana and northern Andhra Pradesh. Analysis showed that agriculture and plantations have replaced the natural forests in the deforested areas and contributed to 57.1 and 13.7 % respectively.

Several studies have combined contemporary remote sensing datasets with historical land use and land cover (LULC) archives to construct the distributions of cropland and forest cover over several centuries (Ramankutty and Foley, 1999; Ramankutty et al. 2008; Goldewijk 2001). For India, global scale studies have used the LULC records at state level (N = 30) to reconstruct the historic LULC datasets which have produced significant discrepancies (Ramankutty and Foley 1999). Richards and Flint (1994) have reported that total forest area decreased from 100 Mha to 81 Mha during 1880–1950. The temporal pattern of deforestation during 1880–2000 had a major control over temporal pattern of carbon emissions due to land use change (Chhabra and Dadhwal 2004). The forest cover changes have been observed to serve as the basis for calculating the emissions of carbon associated with deforestation. Over the past decades, national policies of India have aimed at conservation and sustainable management of forests being responsible for declining trend of deforestation in India. These results demonstrate the value of utilizing historical topographical maps and remote sensing to detect changing scenario of natural forest areas. Remote sensing data in combination with GIS have been observed to have potential value in understanding the changes in forests. We recommend that natural forest be differentiated from plantations following Sasaki and Putz (2009). This will facilitate prioritization for conservation of biodiversity and contribute to sustainable forest resource development.

A study on environmental predictors of deforestation in the Pacific Islands during the pre-European era revealed that there was a statistical decrease in deforestation with increasing rainfall, elevation and other relief features (Rolett and Diamond 2004). Nagendra et al. (2003) analysed landscape transformation in western Honduras and indicated that areas at lower elevation and closer to roads determinates high fragmented areas, whereas areas of high elevation located further away from roads had a predominant forest cover and less fragmented. Mitsuda and Ito (2011) found through their study that lower elevation and gently sloping land was preferred for deforestation.

A study by Jha and Bawa (2006) has quantified the effect of human population growth, human development index (HDI) and deforestation rate and found that when population growth was high and HDI was low there was a high rate of deforestation, but when HDI was high, rate of deforestation was low, population growth was still high. These results support low deforestation in Western Ghats of Kerala, Karnataka, Maharashtra, Tamil Nadu in the recent past. Deforestation rate decreased in India which shows population growth of 1.92 % per year, human development index was 0.69 and deforestation rate was 0.51 % per year (Jha and Bawa 2006).



**Fig. 8** Major deforestation sites in India

The Supreme Court of India has banned all kinds of clear-felling in the forests of India from 1996 onwards which has resulted in more protection and a decreasing trend of deforestation along with strict conservation practices and community forest management (Rosencranz and Lele 2008). The Green India Mission under the National Action Plan on Climate Change, 2008 advocated bringing one third of the nation's geographic area under forest cover by afforestation of wastelands and degraded forest areas (Rosencranz and Lele 2008). India has 590 protected areas—500 wildlife sanctuaries and 90 national parks covering an area of 156,700 km<sup>2</sup>. At present, under the provisions of the act, 4.7 % of the

total geographic area of the country is devoted to in-situ conservation of habitats and ecosystem (MoEF 2008). Greater deforestation occurred during 1880–1950 due to British rule policies to increase income from the timber products and cropland. However, deforestation decreased after 1980's due to formulation of government policies to protect forests (Tian et al. 2014). George and Chattopadhyay (2001), highlighted four distinct phases of deforestation; viz., (1) extensive conversion of forestlands to plantations following a Royal Proclamation in the late nineteenth century, (2) the “Grow More Food” campaign of the mid–1940s when substantial areas of forests were opened up for the cultivation of food crops, (3) colonization during the 1950s and 1960s which created new settlements in the deforested areas and (4) infrastructure development of the post-independence era (1947) during which projects in power, irrigation and transportation sectors were set up on forest lands (George and Chattopadhyay 2001). The prime drivers of deforestation can be listed as agricultural expansion along with increasing demand for wood, expansion of settlements, dam construction and infrastructure development. Shifting cultivation in the North East has been responsible for the loss of 10 Mha of forests (MoEF 2009).

Information on spatial distribution of natural forests is critical to stop the progress of deforestation and degradation. Working at the broad scale of this study has the advantage of providing general trends at the regional scale that are useful for landscape planning and serve as a basis for analyzing drivers of land cover change (Schulz et al. 2010).

Major deforestation sites (>1 km<sup>2</sup>) derived through multi-temporal remote sensing data are highlighted in Fig. 8. In conclusion, the rate of deforestation is relatively low at national level during 2005–2013. The continuing forest cover loss might have significant conservation implications for endemic species of Andaman & Nicobar Islands, Deccan and North East. Conservation practices and afforestation programmes may minimize the ongoing forest losses. The major challenge is to focus on vulnerable areas of deforestation for effective conservation of biodiversity, enhancement of carbon stocks and sustainable management of forests.

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