Analysing the gross and net deforestation rates in India

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Monitoring of forests has gained vital recognition in the international scenario due to realization of its role in carbon sequestration, biodiversity and global warming. Through advancement of remote sensing and GIS technology it is possible to monitor and analyse gross and net changes in forest ecosystems. This article analyses the deforestation rates and drivers of deforestation in India and summarizes the Government initiatives for conservation of forests based on the published literature. It also reviews gross and net rate of deforestation from the national level to locale scale. At the national level, Forest Survey of India has been carrying out mapping of forest cover on a biennial basis. The current estimate of gross deforestation in India is quite low (–0.43%) for 2009–2011 compared to the global average of –0.6%. Even though considerable progress has been made in the protection of forests, gross deforestation rate continues as a focal hindrance. The deforestation studies carried out in various parts of India are found to be fragmentary and far from being comprehensive. From the regional analysis carried out, it can be seen that the overall net rate of deforestation was relatively high in the North East region (–0.90 to –5.29) and Deccan Peninsula (–0.19 to –3.2) followed by the Western Ghats. For precise estimation of gross and net deforestation, consistency in definitions, uniform methodology and new techniques for quantifying forest cover have been realized.

Keywords: Deforestation, forest cover, gross and net rate, national and regional scale.

WITH the realization of an ever-increasing pressure on forests, loss of biodiversity due to changes in land use/land cover and the impact of forests on climate change, monitoring of forest cover is being appreciated more than ever before all over the world[1,2]. The definition of forest varies across countries. FAO Global Forest Resource Assessment 2005 has used parameters of minimum tree height 5 m, canopy cover more than 10% and minimum land area 0.5 ha (ref. 3). The threshold of 10% is key in this definition. In many countries, forest is typically defined as an area with substantially higher levels of canopy closure, for example, 30–40% depending on age in Russia[4] and 60% in South Africa[5]. In Australia, forest is defined as a vegetation type dominated by woody species having a mature stand height exceeding 5 m, with an overstorey canopy cover greater than 20%. In the classification of forests introduced by UNEP WCMC, all forest classes have a minimum threshold of 30%, except for the class including sparse trees and woodlands, for which canopy closure is from 10% to 30% (ref. 6). Forest cover analysis by the Forest Survey of India (FSI) using satellite data, defines forest as an area of more than 1 ha and >10% of tree canopy cover[7]. The scale of current man-made destructions is the prime concern of the day, as it leads to deforestation which has been ranked as the greatest global environmental problem[8,9]. Deforestation can be defined as the process of change of land use with depletion of tree crown cover to less than 10% (ref. 3). The effects of deforestation on biodiversity are mainly destruction of habitat, fragmentation and creating edge effects between the boundary of a forest and deforested land[10].

The FAO estimated the total area of the world's forests in 2005 to be 3.8 billion hectares or 30% of the global land area[3]. According to FAO, the global rate of deforestation is reported to be 0.7% per year from 1990 to 1995 (ref. 11). The net rate of forest loss in the tropics is 21 m ha, which means that about 1.2% of all remaining tropical forests were cleared annually[12]. Nearly 1.8% of the forests is estimated to be degraded every year, the major cause being deforestation[13]. If the current rate of deforestation continues, the world's tropical forests will vanish within 100 years – causing unknown effects on global climate and eliminating majority of the species[14]. Yet, the estimates are uncertain, that is why it is important to monitor and assess the forest resources with a more practical approach[15]. A report estimates that the Earth's total forest area continues to decrease at about 13 M ha yr^{-1} (ref. 16). Overall, there was a net decrease in global forest area of 1.7% between 1990 and 2005, at an annual rate of change of 0.11%. The rate of forest loss was reported as 3 M ha per year between 1990 and 2000 and 6 M ha per year between 2000 and 2005 (ref. 16). In addition, the global gross forest cover loss was reported to be 0.6% per year during 2000–2005 (ref. 17).

Absence of reliable spatial datasets on deforestation is a major obstacle for modelling global environmental change[18]. Monitoring of deforestation is perceived as the most important contribution of remote sensing technology to the study of global change[19]. The combination of remote sensing as well as GIS techniques with ground surveys can go a long way in the management of critical

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areas and contribute to the ecological interpretation of remote sensing data. Globally, AVHRR, MSS and TM data have been widely used for estimating deforestation[20]. Considerable accuracy can be achieved through the combination of high-resolution satellite data, automated methods and high level of human expertise[21]. Through multi-temporal remote sensing data, change detection can be monitored and gross and net changes in forest ecosystems can be analysed. Remote sensing technology can be further applied to monitor the status of conservation targets and to evaluate the conservation effectiveness. A global level study for 198 of the protected areas indicated that nearly 70% of the surrounding buffers has shown decline, and 25% has experienced decline within its very own administrative boundaries[22].

India is one of the mega-biodiversity nations and seventh largest in the world and second largest in Asia having an area of 328.72 m ha. It has about 17,000 species of flowering plants and about 5400 endemic species[23]. India is considered to be one of the 12 centers of origin and diversity of several plant species in the world. The country's rich vegetation wealth and diversity is undoubtedly due to the immense variety of climatic and altitudinal variations coupled with varied ecological habitats. Champion and Seth[24] have recognized 16 major forest types comprising 221 minor types in India. Deforestation was in the form of tree felling during the pre-colonial era in India, when tribal folks were more hunter-gatherers and who subsequently practised shifting cultivation for their living. This was followed by settled form of agriculture where forest lands were cleared for cultivation and later, gradually forests came to be cleared for commercial purposes, as raw material sources and use in forest-based industries[25]. The major drivers of forest cover changes in India are shifting cultivation along with encroachment for agricultural land, mining, quarrying, expansion of settlements, dam construction and illegal logging[26,27]. A study by Jha and Bawa[28] has quantified the effect of human population growth, human development index (HDI; which measures income, health and education) 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, and rate of deforestation was low, population growth was still high. Few international agreements such as the Ramsar Convention, the World Heritage Convention and the UNESCO MAB programme advocate the concept of setting up of 'Protected Areas' (PAs) whereas others such as Convention on Biological Diversity, European Natura 2000 network and many national policies support the establishment of a comprehensive system or network of PAs[29,30].

The Indian Forest Act, 1927, the first such act, failed to address many contemporary issues related to forest management. Deforestation was realized as a critical threat to the existence of endangered species while the Endangered Species Act of 1973 was being drafted[31]. The Wildlife Protection Act, 1972, provided protection to wild animals, birds, plants as well as their habitat and envisaged setting up of PAs. The Forest Conservation Act aimed at lowering the rate of deforestation by controlling conversion of forest land to non-forestry purposes. National Forest Policy, 1988, envisaged in making forest management participatory and conservation-oriented[32].

The Supreme Court of India has banned all kinds of clear-felling in the forests of India from 1996 onwards, which has resulted in greater protection and a decreasing trend of deforestation[33]. The Biodiversity Act, 2002, primarily focused on the conservation of biological resources by facilitating access to local communities by a sustainable approach. The National Environment Policy, 2006, addressed the issue of empowerment of the local communities to avoid forests from becoming open access in nature and degrading gradually. 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[34]. Presently, India has 590 PAs – 500 wildlife sanctuaries and 90 national parks covering an area of 156,700 sq. km. 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 ecosystems[30].

NRSA (now NRSC) had carried out nation-wide mapping of forest cover using Landsat MSS data in 1972–75 and later in 1980–82 for the first time on 1 : 1 M scale[35]. Consequently, FSI, an operational agency of Ministry of Environment and Forests, Government of India started mapping forest cover in the country using remote sensing data. Reliable quantification of deforestation necessitates satellite images of IRS LISS III (spatial resolution of 23.5 m) or finer spatial resolution. Despite the source and degree of deforestation, the forest cover change analysis needs to be carried out during annual/biennial period at the national level to sub-annual level for deforestation and degradation hotspots. The biennial forest cover assessment was initiated by FSI at 1 : 250,000 scale and later on at an improved scale, i.e. 1 : 50,000 (since 2001). According to the recent State of Forest Report, forest cover of India was 692,027 sq. km (21% of TGA) during 2009 (ref. 7). NRSC has initiated spatial database preparation for Indian forests as part of the National Carbon Project in order to detect the changes that have taken place, particularly in the forests and subsequently to analyse trends that have taken place over a period from 1920 to 2010/11 (ref. 36). This study aims to present rates and patterns of deforestation in India based on the published literature from FSI, FAO, etc.

Methods

The present work uses published information primarily from FSI, FAO and other regional level/locale-specific

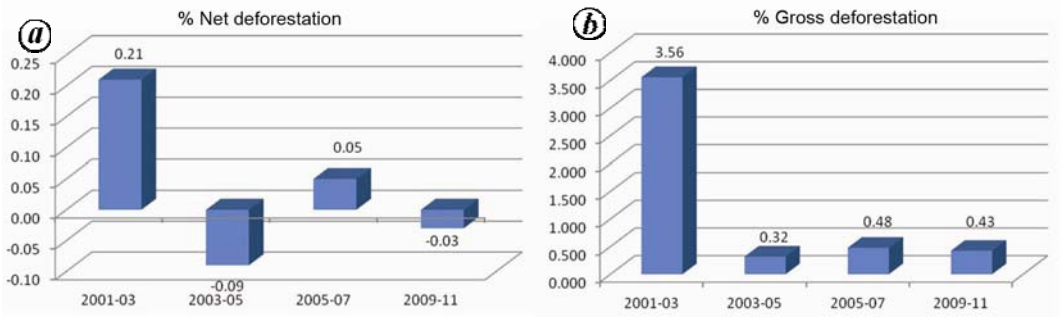

Figure 1. Net deforestation rate (***a***) and gross deforestation rate (***b***) in India during 2001–11 (source: FSI).

Table 1. Net and gross deforestation rate in India during 2001–2011 (source: FSI)

t_1	t_2	a_1 (area in sq. km)	a_2 (area in sq. km)	Net rate	a_1 (area in sq. km)	a_2 (area in sq. km)	Gross rate
2001	2003	675,538	678,333	+0.21	675,538	629,146	–3.56
2003	2005	678,333	677,088	–0.09	678,333	674,022	–0.32
2005	2007	690,171	690,899	+0.05	690,171	683,583	–0.48
2009	2011	692,394	692,027	–0.03	692,394	686,519	–0.43

case studies. The causative factors of deforestation in different parts of India are discussed. Forest area loss can be measured using spatial analysis. In order to analyse deforestation, the annual rate of change is calculated by comparing the area under forest cover in the same region at two different times. According to FAO, the annual rate of forest change is derived from the compound interest formula due to its explicit biological meaning[37,38]. This is as follows

$$r = 1/(t_2 - t_1) \times \ln a_2/a_1,$$

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.

Discussion

National-level deforestation rates

Consistent estimates of deforestation rates in India are lacking. The first estimate by FAO calculated an annual gross deforestation rate of 0.6% between 1981 and 1990 for India, where the scale of reporting is unknown and areas of afforestation were not included[11]. The second estimate by Ravindranath and Hall[39] suggested India's annual net deforestation to be 0.04% between 1982 (1 : 1 million scale) and 1990 (1 : 250,000 scale). Another estimate by Ravindranath *et al.*[40] suggested India's annual net deforestation to be 0.07% between 1981–83 and 1985–87 based on FSI assessment. These estimates are widely dissimilar due to scale, definition, methodology of classification, quality of hard copy images and inclusion/exclusion of afforestation. Such inequality in estimates of the rate and extent of deforestation calls for more careful regional level or locale-specific studies[11]. Even though significant progress has been made in the protection of forest cover, gross deforestation continues as a major impediment. However, the speed of deforestation is likely to be less compared to the period 1970–90.

The net and gross deforestation estimates of Indian forests by FSI are shown in Table 1. Figure 1 *a* and *b* shows the percentage of net deforestation and gross deforestation respectively. It should be noted here that although the percentage of net rate of deforestation shows both negative and positive values, the gross rate of deforestation constantly shows negative values due to ongoing human-induced land-use changes for various economic purposes. The current estimate of gross deforestation in India is low (–0.43) for 2009–11 compared with the global average of –0.6%.

Regional/locale-specific deforestation rates

The regional level/locale-specific studies on deforestation have been reviewed herewith to analyse rates of deforestation and to prioritize deforestation hotspots for effective conservation strategies. Various studies have identified the regions of higher to lower risk of deforestation in different parts of the country. We have identified five major bio-geographic zones of high conservation value for regional-level assessment based on the availability of the published literature. It should be noted that the gross rate of deforestation was missing in many of these studies and was also not possible to calculate, since the change area matrix of land use/land cover itself was absent in the published work (Table 2).

Table 2. Net and gross deforestation rates in regional level/local-specific studies in India

	Study area	State	T_1	T_2	$T_2 - T_1$	Area (sq. km) T_1	Area (sq. km) T_2	Net area loss/gain	% Deforestation Net rate	% Deforestation Gross rate	Major drivers identified	Reference
Himalaya	Kuchgad, Almora	Uttarakhand	1967	1988	21	29.7	27.5	–2.2	–0.37	NA	Agricultural expansion	43
			1988	1997	9	27.5	26.1	–1.4	–0.6	NA		
			1967	1997	30	29.7	26.1	–3.6	–0.48	NA		
	Himalaya	Indian Himalayas	1970	2100	130	157,050	82,920	–74,130	–0.49	NA	Various anthropogenic factors	41
			1970	2000	30	157,050	133,410	–23,640	–0.54	NA		
			2000	2100	100	133,410	82,920	–50,490	–0.48	NA		
		Western Himalayas	1970	2100	130	81,260	28,130	–53,130	–0.82	NA		
			1970	2000	30	81,260	63,120	–18,140	–0.84	NA		
			2000	2100	100	63,120	28,130	–34,990	–0.81	NA		
		Eastern Himalayas	1970	2100	130	75,790	54,790	–21,000	–0.25	NA		
			1970	2000	30	75,790	70,300	–5,490	–0.25	NA		
			2000	2100	100	70,300	54,790	–15,510	–0.25	NA		
	Pithoragarh	Uttarakhand	1976	1990	14	1,161.8	1,138.4	–23.4	–0.15	–0.24	Expansion of agriculture and settlements	42
			1990	1999	9	1,138.4	1,137.6	–0.8	–0.01	–0.37		
			1999	2006	7	1,137.6	1,118	–19.5	–0.25	–0.93		
			1976	2006	30	1,161.8	1,118	–43.8	–0.13	–0.52		
	Doodhganga Range	Jammu & Kashmir	1994	2004	10	61.4	57.3	–4.1	–0.69	–0.96	Expansion of agriculture	44
Northeast	Sonitpur	Assam	1994	2001	7	810.4	578.2	–232.2	–4.82	NA	Logging, encroachment for agriculture	45
	North-East	North-East India	1989	1993	4	165,777	164,359	–1,418	–0.21	NA	Shifting cultivation, mining, forest fires, logging, infrastructure development	27
			1989	1999	10	165,777	166,173	396	0.02	NA		
	Part of Barak valley, North Tripura	Tripura	2000	2006	6	175.6	127.8	–47.8	–5.29	NA	Shifting cultivation	46
Western Ghats	Agasthyamalai region	Kerala and Tamil Nadu	1920	1990	70	1626	1,423	–203	–0.19	NA	Dams, expansion of plantations and agriculture	47
	Southern Western Ghats	Kerala and Tamil Nadu	1973	1995	22	10,669.2	7,939.6	–2,729.6	–1.34	NA	Dams, expansion of plantations and agriculture	48
	Northern Western Ghats	Maharashtra	1987	2005	18	9,663.5	9,400.3	–263.3	–0.15	–0.37	Infrastructure development, dams, mining	51

Table 2. (*Contd*)

	Study area	State	T_1	T_2	$T_2 - T_1$	Area (sq. km) T_1	Area (sq. km) T_2	Net area loss/gain	% Deforestation Net rate	% Deforestation Gross rate	Major drivers identified	Reference
Coasts and islands	Bhitarkanika	Odisha	1973	1988	15	180	178.7	–1.3	–0.05	–0.28	Anthropogenic activities by local villagers	52
			1988	2004	16	178.7	164.6	–14	–0.55	–0.76		
			1973	2004	31	180	164.6	–15.3	–0.29	–0.54		
	Balasore	Odisha	1973	2004	31	3.2	3.3	0.2	0.18	–0.69	Expansion of agriculture	56
	Mangroves of Godavari delta	Andhra Pradesh	1977	2000	23	194.8	185.2	–9.6	–0.22	NA	Encroachment for aquaculture, agriculture	54
			2000	2005	5	185.2	186.1	0.9	0.1	NA		
			1977	2005	28	194.8	186.1	–8.7	–0.16	–0.94		
	North Andaman	Andaman	1976	1999	23	1,347.9	1,273	–74.9	–0.25	–0.68	Logging, encroachment for agriculture, tsunami	53
			1999	2005	6	1,273	1,222.2	–50.8	–0.68	NA		
			1976	2005	29	1,347.9	1,222.2	–125.7	–0.34	NA		
	Point Calimere Wildlife Sanctuary	Tamil Nadu	1991	2010	19	13	13.5	0.5	0.19	NA	–	57
Deccan Peninsula	Pranahita Wildlife Sanctuary	Andhra Pradesh	1993	2004	11	82.7	80.2	–2.5	–0.28	–1.46	Logging, encroachment for agriculture	58
	Nawarangpur	Odisha	1973	2004	31	2,122.4	783.6	–1,338.8	–3.22	–4.11	Logging, dams, encroachment of agriculture and settlements, infrastructure development	26
			1973	1990	17	2,122.4	1,329.5	–792.9	–2.75	–3.15		
			1990	2004	14	1,329.5	783.6	–545.9	–3.78	–4.77		
	Ranchi	Jharkhand	1996	2008	12	52.5	46.8	–5.7	–0.95	NA	Urbanization	59
	R.V. Nagar	Andhra Pradesh	1988	2006	18	258.9	223.7	–35.2	–0.81	–1.04	Shifting cultivation	60
	Malkangiri	Odisha	1973	2004	31	3,003.4	2,125.4	–878	–1.12	–1.83	Logging, encroachment for agriculture, dams, infrastructure development, expansion of settlements	61
	Odisha	Odisha	1935	2010	75	81,786	48,669	–33,117	–0.69	–0.74	Mining, logging, encroachment for agriculture, shifting cultivation, dams	36
			1935	1975	40	81,786	56,661	–25,125	–0.92	–0.92		
			1975	1985	10	56,661	51,642	–5,019	–0.93	–1.15		
			1985	1995	10	51,642	49,773	–1,869	–0.37	–0.4		
			1995	2010	15	49,773	48,669	–1,104	–0.15	–0.4		
	Singrauli	Madhya Pradesh	1978	1991	13	1,730.7	1,352.9	–377.8	–1.89	–3.69	Mining	62
			1991	2010	19	1,352.9	1,044	–308.9	–1.36	–2.38		
			1978	2010	32	1,730.7	1,044	–686.7	–1.63	–3.04		

Himalaya

A net deforestation rate of –0.54 has been recorded in the Indian Himalaya during 1970 to 2000 (ref. 41). This study hypothesized that the ongoing anthropogenic forest conversion could be aggravated by global warming. Another study by Munsi *et al.*[42] in Pithorgarh district, Uttarakhand, found a net deforestation rate of –0.13 and a gross deforestation rate of –0.52 over a period of 30 years (1976–2006). The study showed that the area under open forest has increased due to degradation of evergreen dense forests and concluded that with increasing human activities, the deforestation rate has increased over the years. Net deforestation rate of –0.48 was estimated for Kuchgad micro-watershed in Almora district, Uttarakhand from 1967 to 1997 (ref. 43). The study observed agricultural expansion along with over-exploitation of broad leaved forests for economic purposes as a cause of deforestation in that area. A study in Dudhganga range of Jammu and Kashmir reported a net rate of –0.69 and a gross rate of –0.96 within a period of 10 years from 1994 to 2004 (ref. 44). Areas with major open forest cover were observed to have been converted to blank areas, whereas significant change of very dense forests to moderately dense forests was also seen, the transition having been attributed to human intervention.

The North East region

A time series analysis of satellite imagery of 1994 to 2001 was carried out in Sonitpur district, Assam, which highlights extensive deforestation in the moist deciduous and other forest areas[45]. The drivers which lead to large-scale deforestation are insurgency problem, encroachment and the increasing human and livestock population. The net deforestation rate was found to be as high as –4.82. The area analysis shows that 97,875 sq. km (40%) of the forest in NE India falls in the dynamic areas where rapid forest cover changes have been taking place since 1972. The analysis reported that overall dynamic areas are highest in Tripura (56%), Meghalaya (54%), Mizoram (48%), Nagaland (52%), Manipur (38%) and Assam (33%). Overall, the net deforestation rate in NE India was found to be slightly positive, i.e. 0.02 from 1989–1999 due to regrowth of vegetation in abandoned shifting cultivation areas and protection measures. Major causes of deforestation in Meghalaya are attributed to extensive mining, shifting cultivation and permanent agriculture. In Tripura and Nagaland, uncontrolled exploitation of forests, extensive cutting of bamboo and conversion of forests to permanent agriculture are the main threats for forests[27]. Arunachal Pradesh, compared to all other North East states, is maintaining more forest cover due to complexity of the terrain and inaccessibility by humans in interior areas of forests[27]. A very high net deforestation rate of –5.29 was reported in parts of North Tripura district, which is the deforestation hotspot in the whole of Barak basin. The altered pattern of land use, particularly increasing shifting cultivation was identified as the cause of forest cover change[46].

The Western Ghats

Ramesh *et al.*[47] have found the rate of net deforestation in Agasthyamalai region, Western Ghats between 1920 and 1960 to be –0.19 and concluded that several areas of high biodiversity value were not included in the PA network. The authors have observed that the peripheral areas are more threatened by human impact and if this continues, the whole PA network would be threatened in the long run. Menon and Bawa[15] estimated the rate of deforestation in the Western Ghats to be 0.57% annually during the period 1920–90. A study on changes in forest cover between 1973 and 1995 in the southern part of the Western Ghats was carried out using satellite data that showed rate of net deforestation as –1.34 over 22 years[48]. The authors have accounted for the decrease in forest area due to the increase in spatial extent of plantations and agricultural fields. They have also noted that the most rapid change has occurred in Kerala due to its high population density. Studies in Kerala indicate the loss of forest between 1961 and 1988 to be 8.4%, at an average annual rate of 0.28% (ref. 49). During 1960–90, forest loss was found to be 9.9% in the same area, with an annual deforestation rate as 0.33% (ref. 50). Joseph *et al.*[51] have reported net rate of deforestation as 0.04% in the Indira Gandhi Wildlife Sanctuary, Anamalais during 1973–2006, which is the minimum rate in the Western Ghats. Panigrahy *et al.*[52] analysed the pattern of change in forest cover and calculated the net rate of deforestation as –0.15 and that of gross deforestation as –0.37 in the northern Western Ghats of Maharashtra. They reported that the degradation of forest cover is due to the increase in population pressure for forest resources and also due to disasters like forest fires.

Coasts and islands

Assessment of forest cover loss was carried out in the North Andaman Islands, Andaman which revealed the net rate of deforestation as –0.34 from 1978 to 2005; the forest change being primarily due to the prevailing anthropogenic pressure and also due to natural disturbances to some extent[53]. A net rate of –0.16 and a gross rate of –0.94 of deforestation was estimated for the mangroves of Godavari delta, Andhra Pradesh for a period of 28 years from 1977 to 2005. The loss of mangroves was attributed to encroachment by agriculture, aquaculture and coastal erosion[54]. The study in Bhitarkanika Wildlife Sanctuary, Odisha, has shown net rate of deforestation

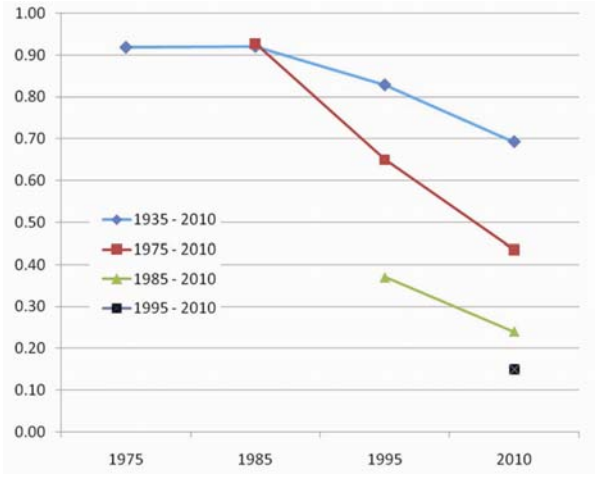

Figure 2. Declining trend of annual rate of net deforestation in Odisha (source: Reddy *et al.*[36]).

to be –0.29 and gross rate to be –0.54 for the mangroves during 1973–2004, the reason for deforestation being the anthropogenic activities by local villagers. There was an increased rate of net deforestation during 1973–88 and 1988–2004 (ref. 55). A rate of afforestation, i.e. 0.18 was found for a study in Balasore, Odisha, whereas the gross deforestation rate for the same study was found to be –0.69, within a period of 31 years from 1973 to 2004 (ref. 56). In contrast to most other tropical forests, dry evergreen forests of Point Calimere sanctuary, Tamil Nadu showed positive changes in forest cover, i.e. afforestation rate of 0.19 for a period of 19 years from 1991 to 2010 (ref. 57).

Deccan Peninsula

Forest cover change analysis carried out in Pranahita Wildlife Sanctuary, Andhra Pradesh for 11 years from 1993 to 2004 showed net and gross deforestation rates to be –0.28 and –1.46 respectively ascribing this loss to illegal logging and expansion of agricultural fields[58]. Reddy *et al.*[26] have recorded the net rate of deforestation as –3.2 and –4.11 as gross rate of deforestation in Nawarangpur district, Odisha during 1973–2004. The main causes of forest change were identified as encroachment for agriculture and settlements, illegal logging, dams, infrastructure development, etc. A study focusing on the monitoring of deforestation in Ranchi, Jharkhand was carried out. It was found that from 1996 to 2008, net rate of deforestation was –0.95 due to urbanization[59]. A study for a period of 18 years from 1988 to 2006 showed a net deforestation rate of –0.81 and a gross deforestation rate of –1.04 in R.V. Nagar range, Visakhapatnam, Andhra Pradesh[60]. Anthropogenic activities, mainly shifting cultivation and expansion of agricultural fields, were identified as drivers of forest change in that area. Dynamics of tropical forest cover assessment revealed the net rate of deforestation as –1.83 from 1973 to 2004 in Malkangiri district, Odisha[61]. The authors reported that various factors with varying intensities like over-grazing, illegal encroachments, unsustainable practices, forest fires, shifting cultivation and indiscriminate logging were responsible for the ongoing deforestation and advocated an urgent need for rational management of the remaining forest for its future survival. A study on the historical forest cover change over a period of 75 years (1935–2010) was carried out in Odisha, which brought out the spatio-temporal changes in forests and spatial variation in forest types. The net rate of deforestation was –0.69 and gross rate was –0.74 during 1935–2010. The trend of deforestation observed in the long-term forest cover change in Odisha is shown in Figure 2. It can be seen that the net rate remains almost same (–0.9) between 1975 and 1985, while it decreased to –0.37 for the period 1985–95 and further to –0.15 for 1995–2010. In the context of forest type, large-scale deforestation of dry deciduous forest was observed[36]. The gross rate for the period 1935–75 was –0.92 and –0.92 respectively; for 1975–85 it was –0.93 and –1.15 respectively; for 1985–1995 it was –0.37 and –0.40 respectively and for the period of 1995–2010 it was 0.15 and –0.40 respectively. Land-use change analysis was carried out in Singrauli district, Madhya Pradesh from 1978 to 2010, highlighting the severity of mining as a forest change driver. The net and gross rates of deforestation were –1.63 and –3.04 respectively[62].

The analysis of different cases confirm continued destruction and degradation of forests in spite of afforestation measures and protection. The deforestation hotspots are found in southern Odisha, Sonitpur in Assam and North Tripura. From the above analysis, it can be concluded that the overall net rate of deforestation in the Himalaya ranges from –0.13 to –0.69; in the North East region from 0.90 to –5.29; in the Western Ghats from to –0.04 to –1.34; in the coasts and islands from –0.16 to –0.34 and in the Deccan Peninsula from 0.19 to –3.2. Analysis of the trend of net rate in deforestation studies of Pithoragarh district, Uttarakhand (Figure 2) showed a decline in the net rate from –0.15 to –0.01 during 1976–90 and 1990–99, whereas a steep rise to –0.25 is seen during 1999–2006. The gross rate of deforestation for the same study, however, showed a gradual increase from –0.24 in 1976–99 and –0.37 in 1990–99 to a considerable increase of –0.93 in 1999–2006.

Conclusions and recommendations

Understanding of deforestation rates in various parts of India is far from complete due to selective studies across the country. However, the present review provides an apparent representation of the ongoing gross deforesta-

tion. The prime drivers of deforestation can be considered as shifting cultivation along with increasing demand for agricultural land, mining, quarrying, expansion of settlements, urbanization, dam construction, illegal logging, infrastructure development, forest fire and over-grazing. The spatial resolution is of interest because forest systems are sensitive to varying resolutions which are used to study ecological processes at different scales. Much research on forest cover change has been carried out using coarse spatial resolution imagery on 1 : 1 M scale. The coarse-scale mapping of forest extent is difficult because each pixel may represent two or more land-cover classes. Some studies have shown that the extent of forest cover may be underestimated because of this problem, while other image classifications tend to overestimate forest extent[63]. Visual corrections have a large impact on the results of automated land-cover classification and the final reviewed results for the tropics indicated that about 20% of the forest patch labels were improved[63,64]. The visual refinement had a notable effect on estimates of forest area change for Southeast Asia, where the net rate of change in forest cover loss from 1990 to 2000 was assessed at 0.9% before and 1.6% after visual control[65]. The areas mapped as forests may be under degradation process, invisible from observations of IRS LISS III and Landsat satellite imagery. In this context, forest cover information at very high spatial resolution and scales is required to assess the impacts of forest cover change and degradation[65]. The integration of both visible and invisible forest degradation based on very high resolution satellite data and field observations is necessary for effective conservation strategies. Consistency in definitions, and new methodologies and techniques for quantifying forest cover at global to regional level are likely to be a challenging area of research. A new national action plan is strongly recommended in the areas where large-scale deforestation and forest degradation have affected majority of forests, especially in NE India, parts of the Eastern Ghats and islands.

1. SCBD, Biodiversity issues for consideration in the planning, establishment and management of protected area sites and networks. The Secretariat, Montreal, CBD Technical Series No. 15, 2004, pp. 164.
2. Forest Survey of India, India State of Forest Report. Ministry of Environment and Forests (MoEF), Government of India (GoI), 2009.
3. FAO, State of the world's forests, Food and Agriculture Organisation of the United Nations, Rome, 2012.
4. FFSR, *Manual for Forest Inventory in Russian Forest Fund. Part 1. Organization of Forest Inventory. Field Works*, Federal Forest Service of Russia, Moscow, 1995, p. 174.
5. Scholes, R. J. and Biggs, R., Ecosystem services in southern Africa: a regional assessment, Council for Scientific and Industrial Research, Pretoria, South Africa, 2004.
6. United Nations Environment Programme World Conservation Monitoring Centre, 2004. Available on-line at www.unep-wcmc.org/forest/data
7. Forest Survey of India, India State of Forest Report, MoEF, GoI, 2011.
8. Martinez, K. E., Social determinants of deforestation in developing countries: a cross-national study. *Soc. Forces*, 1998, **77**, 567–586.
9. Williams, M., Dark ages and dark areas: global deforestation in the deep past. *J. Hist. Geogr*., 2000, **26**, 28–46.
10. Whitmore, T. C., Tropical forest disturbance, disappearance, and species loss. In *Tropical Forest Remnants: Ecology, Management, and Conservation of Fragmented Communities* (eds Laurance, W. F. and Bierregaard, R. O.), University of Chicago Press, Chicago, 1997, pp. 3–12.
11. FAO, State of the world's forests, Food and Agriculture Organisation of the United Nations, Rome, 1997.
12. Myers, N., Tropical forest: the main deforestation fronts. *Environ. Conserv*., 1993, **20**, 9–16.
13. Skole, D. and Tucker, C., Tropical deforestation and habitat fragmentation in the Amazon: satellite data from 1978 to 1988. *Science*, 1991, **260**, 1905–1910.
14. NASA, Tropical deforestation. NASA facts, FS-1998-11-120-GSFC, National Aeronautics and Space Administration, Goddard Space Flight Center, 1998.
15. Menon, S. and Bawa, K. S., Deforestation in the tropics: reconciling disparities in estimates for India. *Ambio*, 1998, **27**, 576–577.
16. FAO, State of the world's forests, Food and Agriculture Organisation of the United Nations, FAO, Rome, 2005.
17. Hansen, M. C., Stehman, S. V. and Potapov, P. V., Quantification of global gross forest cover loss. *Proc. Natl. Acad. Sci. USA*, 2010, **107**, 8650–8655.
18. Murai, S. (ed.), Development of global eco-engineering using remote sensing and geographic information systems. In *Towards Global Planning of the Sustainable Use of the Earth Resources*, Proceedings of 8th Toyota Conference, Elsevier, 1995.
19. Chape, S., Harrison, J., Spalding, M. and Lysenko, I., Measuring the extent and effectiveness of protected areas as an indicator for meeting global biodiversity targets. *Philos. Trans. R. Soc. London, Ser. B.*, 2005, **360**, 443–455.
20. Wiens, J. *et al.*, Selecting and conserving lands for biodiversity: the role of remote sensing. *Remote Sensing Environ.*, 2009, **113**, 1370–1381.
21. Townshend, J. R. G. *et al.*, The NASA Landsat Pathfinder Humid Tropical Deforestation Project. In Proceedings of the ASPRS Conference on Land Satellite Information in the Next Decade, Vienna, 25–28 September 1995, pp. IV76–IV87.
22. Defries, R., Hansen, A., Newton, C. and Hansen, M. C., Increasing isolation of protected areas in tropical forests over the past twenty years. *Ecol. Appl*., 2005, **15**, 19–26.
23. Hajra, P. K. and Mudgal, V., Plant diversity hotspots in India – an overview. BSI, 1997.
24. Champion, H. G. and Seth, S. K., *A Revised Survey of the Forest Types of India*, Manager of Publications, Government of India, 1968, p. 404.
25. Gadgil, M., India's deforestation: patterns and processes. *Soc. Nat. Resour*., 1990, **3**, 131–143.
26. Reddy, C. S., Rao, P. R. M., Pattanaik, C. and Joshi, P. K., Assessment of large-scale deforestation in Nawarangpur district, Orissa, India: a remote sensing based study. *Environ. Monit. Assess*., 2009, **154**, 325–335.
27. Lele, N. and Joshi, P. K., Analyzing deforestation rates, spatial forest cover changes and identifying critical areas of forest cover changes in North-East India during 1972–1999. *Environ. Monit. Assess*., 2009, **156**, 159–170.
28. Jha, S. and Bawa, K. S., Population growth, human development, and deforestation in biodiversity hotspots. *Conserv. Biol*., 2006, **3**, 906–912.
29. Hockings, M. and Phillips, A., How well are we doing? Some thoughts on the effectiveness of protected areas. Management

effectiveness of protected areas. In *Protected Areas Programme, Parks* (ed. Goriup, P.), IUCN, 1999, vol. 9, pp. 1–64.
30. Bridgewater, P., Biosphere Reserves – a network for conservation and sustainability. International Agreements and Programmes. In *Protected Areas Programme, Parks* (eds Harrison, J. and Simpson, K.), IUCN, 2002, vol. 12, pp. 1–58.
31. Davison, S. G., Alteration of wildlife habitat as a prohibited taking under the Endangered Species Act. *J. Land Use Environ. Law*, 1995, **10**, 155–239.
32. Aggarwal, A., Das, S. and Paul, V., Is India ready to implement REDD Plus – A preliminary assessment. The Energy Research Institute, New Delhi for COP 15, 2009, pp. 2–15.
33. Rosencranz, A. and Lele, S., Supreme Court and India's forests. *Econ. Polit. Wkly*, 2008, pp. 11–14.
34. National Biodiversity Action Plan, MoEF, GoI, 2008, p. 100.
35. NRSA, Report of nationwide mapping of forest and non-forest areas using Landsat False Color Composite for period 1972–75 and 1982–85. National Remote Sensing Agency, 1983.
36. Reddy, C. S., Jha, C. S. and Dadhwal, V. K., Assessment and monitoring of long-term forest cover changes in Odisha, India, using remote sensing and GIS. *Environ. Monit. Assess.*, 2013, **185**, 4399–4415.
37. FAO, State of the world's forests, Food and Agriculture Organisation of the United Nations, Rome, 1995.
38. Puyravaud, J. P., Standardizing the calculation of the annual rate of deforestation. *For. Ecol. Manage.*, 2003, **177**, 593–596.
39. Ravindranath, N. H. and Hall, D. O., Indian forest conservation and tropical deforestation. *Ambio*, 1994, **23**, 521–523.
40. Ravindranath, N. H., Somoshekhar, B. S. and Gadgil, M., Carbon flow in Indian forests. *Climatic Change*, 1997, **35**, 297–320.
41. Pandit, M. K., Sodhi, N. S., Koh, L. P., Bhaskar, A. and Brook, B. W., Unreported yet massive deforestation driving loss of endemic biodiversity in Indian Himalaya. *Biodivers. Conserv*., 2007, **16**, 153–163.
42. Munsi, M., Malaviya, S., Oinam, G. and Joshi, P. K., A landscape approach for quantifying land-use and land-cover change (1976–2006) in middle Himalaya. *Reg. Environ. Change*, 2009, **10**, 145–155.
43. Wakeel, A., Rao, K. S., Maikhuri, R. K. and Saxena, K. G., Forest management and land use/cover changes in a typical micro watershed in the mid elevation zone of Central Himalaya, India. *For. Ecol. Manage.*, 2005, **213**, 229–242.
44. Farooq, M. and Rashid, H., Spatio-temporal change analysis of forest density in Doodhganga Forest Range, Jammu & Kashmir. *Int. J. Geomatics Geosci*., 2010, **1**, 132–140.
45. Srivastava, S., Singh, T. P., Singh, H., Kushwaha, S. P. S. and Roy, P. S., Assessment of large-scale deforestation in Sonitpur district of Assam. *Curr. Sci*., 2002, **82**, 1479–1484.
46. Chakraborty, K., Vegetation change detection in Barak Basin. *Curr. Sci*., 2009, **96**, 1236–1242.
47. Ramesh, B. R., Menon, S. and Bawa, K. S., A vegetation based approach to biodiversity Gap analysis in the Agastyamalai region, Western Ghats, India. *Ambio*, 1997, **26**, 529–536.
48. Jha, C. S., Dutt, C. B. S. and Bawa, K. S., Deforestation and land use changes in Western Ghats, India. *Curr. Sci*., 2000, **79**, 231–238.
49. Prasad, S. N., Conservation planning for the Western Ghats of Kerala: II. Assessment of habitat loss and degradation. *Curr. Sci*., 1998, **75**, 228–235.
50. Ramesh, B. R., Danny, L. S. and Gurkkal, R., Forest landscape analysis and management plan for Kerala, funded by World Bank, Kerala Forest Department and French Institute of Pondicherry, 2005.
51. Joseph, S., Blackburn, G. A., Gharai, B., Sudhakar, S., Thomas, A. P. and Murthy, M. S. R., Monitoring conservation effectiveness in a global biodiversity hotspot: the contribution of land cover change assessment. *Environ. Monit. Assess*., 2009, **158**, 169–179.
52. Panigrahy, R. K., Kale, M. P., Dutta, U., Mishra, A, Banerjee, B. and Singh, S., Forest cover change detection of Western Ghats of Maharashtra using satellite remote sensing based visual interpretation technique. *Curr. Sci*., 2010, **98**, 657–664.
53. Chandra Prasad, P. R., Reddy, C. S., Rajan, K. S., Raza, S. H. and Dutt, C. B. S., Assessment of tsunami and anthropogenic impacts on the forest of the North Andaman Islands, India. *Int. J. Remote. Sensing*, 2009, **30**, 1235–1249.
54. Reddy, C. S. and Roy, A., Assessment of three decade vegetation dynamics in mangroves of Godavari Delta, India using multitemporal satellite data and GIS. *Res. J. Environ. Sci*., 2008, **2**, 108–115.
55. Reddy, C. S., Pattanaik, C. and Murthy, M. S. R., Assessment and monitoring of mangroves of Bhitarkanika Wildlife Sanctuary, Orissa, India using remote sensing and GIS. *Curr. Sci*., 2007, **92**, 1409–1415.
56. Reddy, C. S. and Pattanaik, C., Mangrove vegetation assessment and monitoring in Balasore district, Orissa using remote sensing and GIS. *Natl. Acad. Sci. Lett*., 2007, **30**, 377–381.
57. Prabhadevi, V. and Reddy, C. S., The use of remote sensing to quantify spatio-temporal land cover changes in Point Calimere, a Ramsar Site. *Natl. Acad. Sci. Lett*., 2012, **35**, 85–90.
58. Giriraj, A., Babar, S. and Reddy, C. S., Monitoring of forest cover change in Pranahita Wildlife Sanctuary, Andhra Pradesh, India using remote sensing and GIS. *J. Environ. Sci. Technol*., 2008, **1**, 73–79.
59. Kumar, P., Rani, M., Pandey, P. C., Majumdar, A. and Nathawat, M. S., Monitoring of deforestation and forest degradation using remote sensing and GIS: a case study of Ranchi in Jharkhand (India). *Report Opinion*, 2010, **2**, 14–20.
60. Reddy, C. S., Prachi, U., Shilpa, B., Giriraj, A. and Sudhakar, S., Assessment of fragmentation and disturbance patterns in Eastern Ghats: a case study in R.V. Nagar Range, Visakhapatnam district, Andhra Pradesh, India. *J. Indian Soc. Remote Sensing*, 2010, **38**, 632–639.
61. Pattanaik, C., Reddy, C. S. and Reddy, P. M., Assessment of spatial and temporal dynamics of forest cover in Malkangiri district of Orissa, India. *J. Geogr. Sci*., 2011, **21**, 176–192.
62. Areendran, G., Rao, P., Raj, K., Mazumdar, S. and Puri, K., Land use/land cover change dynamics analysis in mining areas of Singrauli district in Madhya Pradesh, India. *Trop. Ecol*., 2013, **54**, 239–250.
63. Foody, G. M., Lucas, R. M. and Curran, P. J., Mapping tropical forest fractional cover from coarse spatial resolution remote sensing imagery. *Plant Ecol*., 1997, **131**, 143–154.
64. Laurance, W. F. and Bierregaard, R. O., *Tropical Forest Remnants: Ecology, Management, and Conservation of Fragmented Communities*, The University of Chicago Press, Chicago, Illinois, USA, 1997.
65. Rasi, R. *et al.*, An automated approach for segmenting and classifying a large sample of multi-date Landsat-type imagery for pan-tropical forest monitoring. *Remote Sensing Environ.*, 1997, **115**, 3659–3669.

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