of carbon dioxide and water vapour exchange in an ecotonal boreal forest. *Global Change Biol*., 1999, **5**, 891–902.
31. Anthoni, P., Law, B. E. and Unsworth, M. J., Carbon and water vapor exchange of an open-canopied ponderosa pine ecosystem. *Agric. For. Meteorol*., 1999, **95**, 151–168.
32. Schmid, H. P., Grimmond, C. S. B., Cropley, F., Offerle, B. and Su, H. B., Measurements of $CO_2$ and energy fluxes over a mixed hardwood forest in the mid-western United States. *Agric. For. Meteorol.*, 2000, **103**, 357–374.
33. Collatz, G. J., Ball, J. T., Grivet, C. and Berry, J. A., Regulation of stomatal conductance and transpiration: a physiological model of canopy processes. *Agric. For. Meteorol*., 1991, **54**, 107–136.
34. Stannard, D. I., Blanford, J. H., Kustas, W. P., Nichols, W. D., Amer, S. A., Schmugge, T. J. and Weltz, M. A., Interpretation of surface flux measurements in heterogeneous terrain during the Monsoon'90 experiment. *Water Resour. Res*., 1994, **30**(5), 1227–1239.
35. Twine, T. E. *et al.*, Correcting eddy-covariance flux underestimates over a grassland. *Agric. For. Meteorol*., 2000, **103**, 279–300.
36. Jarvis, P. G. and Leverenz, J. W., Productivity of temperate, deciduous and evergreen forests In *Encyclopaedia of Plant Physiology*, *New Series* (eds Lange, O. L. *et al.*), Springer-Verlag, Berlin, 1983, vol. 12D, pp. 233–280.
37. Haszpra, L., Bareza, Z., Davis, K. J. and Tarczay, K., Long-term tall tower carbon dioxide flux monitoring over an area of mixed vegetation. *Agric. For. Meteorol*., 2005, **132**, 58–77.
38. Pathre, U. V., Sinha, A. K., Shirke, P. A. and Sane, P. V., Factors determining the mid-day depression of photosynthesis in trees under monsoon climate. *Trees*, 1998, **12**, 472–481.
39. Gilmanov, T. G., Verma, S. B., Sims, P. L., Meyers, T. P., Bradford, J. A., Burba, G. G. and Suyker, A. E., Gross primary production and light response parameters of four Southern Plains ecosystems estimated using long-term $CO_2$-flux tower measurements. *Global Biogeochem. Cycle*, 2003, **17**(2), 1071.
40. Ruimy, A., Javis, P. G., Baldocchi, D. D. and Saugier, B., $CO_2$ fluxes over plant canopies and solar radiation: a review. *Adv. Ecol. Res*., 1995, **26**, 1–69.
41. Zhang, L. M. *et al.*, Seasonal variations of ecosystem apparent quantum yield ($\alpha$) and maximum photosynthesis rate ($P_{max}$) of different forest ecosystems in China. *Agric. For. Meteorol*., 2006, **137**, 176–187.
42. Thornley, J. H. M. and Johnson, I. R., *Plant and Crop Modelling: A Mathematical Approach to Plant and Crop Physiology*, Clarendon, Oxford, England, 1990, p. 669.
43. Massman, W. J. and Lee, X. H., Eddy-covariance flux corrections and uncertainties in long-term studies of carbon and energy exchanges. *Agric. For. Meteorol*., 2002, **113**, 121–144.
44. Baldocchi, D. D., Assessing ecosystem carbon balance: problems and prospects of the eddy-covariance technique. *Global Change Biol.*, 2003, **9**, 478–492.

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# Assessment and monitoring of deforestation from 1930 to 2011 in Andhra Pradesh, India using remote sensing and collateral data

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**Deforestation is one of the greatest threats to the world's forest ecosystems. The present study has utilized remote sensing and GIS techniques to quantify changes in forest cover and to map patterns of deforestation in Andhra Pradesh, India during 1930–2011. Andhra Pradesh has the second largest recorded forest area and ranks sixth with an actual forest cover amongst all Indian states. Forest cover maps from seven temporal datasets were prepared based on interpretation of multi-source topographical maps and satellite data. A representative set of landscape indices has been used to study landscape-level changes over time. The mapping for the period of 1930, 1960, 1975, 1985, 1995, 2005 and 2011 indicates that the forest cover accounts for 85,392, 68,063, 46,940, 45,520, 44,409, 43,577 and 43,523 sq. km of the study area respectively. The study found the net forest cover declined as 49% of the total forest area during the last eight decades. The annual rate of estimated deforestation during 2005–2011 was 0.02%. Annual rate of deforestation of teak mixed forests was relatively higher (0.76) followed by mangroves (0.58%), semi-evergreen forests (0.43%), dry deciduous forests (0.21%), moist deciduous forests (0.09%) and dry evergreen forests (0.07%) during 1975–2011. The landscape analysis shows that the number of forest patches was 3,981 in 1930, 5,553 in 1960, 8,760 in 1975, 9,412 in 1985, 9,646 in 1995 and 10,597 in 2011, which indicates ongoing anthropogenic pressure on the forests. The mean patch size (sq. km) of forest decreased from 21.5 in 1930 to 12.3 in 1960 and reached 3.9 by 2011. The analysis of historical forest cover changes provides a basis for management effectiveness and future research on various components of biodiversity, climate change and accounting of carbon.**

**Keywords:** Collateral data, deforestation, landscape metrics, remote sensing.

THERE is increasing attention on the protection of tropical forests for the future of mankind[1]. Deforestation has been identified as the primary threat for loss of biodiversity[2], responsible for 18% of global carbon dioxide emissions, impacts on climate[3] and livelihoods of people dependent on forests[4]. Deforestation is defined as an event in a

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geographic area associated with a change in land use from forest to non-forest category. As a process, deforestation is the change in land use with depletion of tree crown cover to less than 10% (ref. 5). A major challenge is to understand the historical trends in forest cover and thereby to identify opportunities for management intervention[6].

The quantification of forest cover extent and change is valuable for distinguishing deforestation and afforestation, accounting of carbon, land-use planning and conservation monitoring[7,8]. Fragmentation is defined as a process during which a large expanse of habitat is transformed into a number of smaller patches of smaller total area, isolated from each other by a matrix of habitats unlike the original[9]. Calculation of landscape pattern measurements has the potential to quantify and interpret aspects of deforestation and fragmentation[10,11].

Since the launch of the first earth resource technology satellite (Landsat) in 1972, remote sensing has established its contribution in the monitoring of forest resources. Remote sensing data with its temporal coverage and along with Geographical Information System (GIS), facilitate the analysis of historical forest cover changes and relate such changes to environmental and human factors[12]. Multi-temporal satellite images and GIS techniques permit the quantification of forest cover changes[13] and fragmentation[14]. India is one of the top 12 mega-biodiversity nations and accounts for 6% of the world's forests. According to the Forest Survey of India, the country's forest cover is 692,027 sq. km, which represents 21% of the total geographical area[15].

Reddy *et al.*[16] analysed long-term forest cover change over Odisha, India and observed that information on historical changes in Indian forests is scarce. Reddy *et al.*[17] analysed the deforestation rates, drivers of deforestation and summarized the Government initiatives for conservation of forests in India. A long-term forest cover change dataset in a geospatial format is required to model net carbon emissions covering phytomass-related studies. Globally, forest cover loss at very coarse scale data has been generated[18]. In contrast to short-period forest change, historical datasets need to integrate multiple sources of historical topographical maps and remote sensing datasets. In the present study, we attempted to generate such spatial data for Andhra Pradesh (AP). It ranks second amongst states of India in terms of recorded forest area, i.e. 63,814 sq. km after Madhya Pradesh, and sixth in India with an actual forest cover, i.e. 46,389 km. This amounts to 16.9% of the total geographic area of the state and 6.5% of the total forest cover of the country[15].

The Forest Survey of India (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'[15]. Thus forest cover as reported by FSI does not make any distinction between natural or man-made forests, thereby including all plantations, orchards, etc. and all areas meeting the above defined criteria, irrespective of whether it is forest, public park, private community or institutional land. In the present study forest is a 'land spanning more than 1 ha, dominated with natural tree vegetation with an overstorey canopy cover greater than 10%'. The uniqueness of natural forest is being dominated by a composition of a variety of indigenous species. The 'natural forest definition' is indicated to potentially become significant for the biodiversity conservation and UNFCCC REDD$^+$ negotiations[19,20].

India could be potentially under-reporting deforestation by reporting only the gross forest changes at the national and state levels[20]. India could also be over-reporting the area under forests by including non-forest tree categories. Thus, there is need for a new approach for monitoring and reporting of forest area, to meet the challenges of forest conservation, research and reporting to UN agencies such as FAO, UNFCCC (National Communications, CDM and REDD$^+$) and CBD[19,20]. This study focuses on preparation of spatial database of forest cover map from the earliest possible topographical map records to recent remote sensing data to detect the changes through time series over the period 1930–2011. Landscape metrics (indices) have been used as indicators to quantify pattern of deforestation and forest fragmentation in the study area.

AP is situated in the middle of eastern half of the Indian Peninsula, lying between 12°41′–19°54′N lat. and 76°46′–84°45′E long. It is bounded by the Bay of Bengal in the east, Tamil Nadu in the south, Karnataka in the west and Maharashtra, Chhattisgarh and Odisha in the north. The total geographical area of the state is 275,045 sq. km. Geographically, the state is categorized into three regions, namely (1) the Coastal Plains (along the east coast, a low-lying area from Srikakulam to Nellore) consisting of mainly of agricultural land; (2) the Eastern Ghats, forming a chain of discontinuous range of hills along the coast with good forest vegetation, and (3) the Deccan Plateau consisting of agricultural lands, scrub and deciduous forests which cover part of Kurnool (excl. Nallamalais), Anantapur district and the major part of Telangana. The wide range of topography and other physical features of the state, provided by the hills rising from almost sea level to about 1500 m altitude, shaped the land to harbour varied flora and fauna[18]. The forests in the state are broadly classified into dry deciduous, moist deciduous, semi-evergreen and mangroves[21]. The population of AP was 4.35 crores in 1971, which increased to 8.46 crores in 2011; thus it is one of the most populous states in India[22].

The temporal historical maps and remote sensing datasets were acquired from different sources. The Survey of India topographical maps (1 : 250,000 scale) prepared by Army Map Service, US Army, Washington surveyed during 1917–1938 were used[23]. Remote Sensing data pertaining to Landsat MSS (1972–1977) and Landsat MSS

**Table 1.** Historical maps and satellite datasets used in the study

| Type | Period | Scale/resolution* | Source | Classification technique |
|---|---|---|---|---|
| Topographical maps | 1917–1938 | 1 : 250,000 | US Army Map Service | Feature capture |
| Topographical maps | 1950–1965 | 1 : 250,000 | SOI | Feature capture |
| Landsat MSS | 1972–1977 | 80 m | Geocover | Hybrid classification |
| Landsat MSS | 1985 | 80 m | Geocover | Hybrid classification |
| IRS 1A LISS-I | 1995 | 72.5 m | ISRO | Hybrid classification |
| IRS P6 AWiFS | 2005 | 56 m | ISRO | Hybrid classification |
| IRS P6 AWiFS | 2011 | 56 m | ISRO | Hybrid classification |

*Scale for topographical maps; spatial resolution for satellite datasets. SOI, Survey of India; ISRO, Indian Space Research Organisation.

(1985) provided by Global Land Cover Facility Programme was downloaded from the relevant website[24]. The data of IRS 1B LISS-I (1995) and IRS P6 AWiFS (2005 and 2011) have been acquired from NRSC Data Centre, Hyderabad, India. Data sources are summarized in Table 1. Satellite remote sensing datasets of the oldest period pertaining to 1972–1977 are referred to as 1975 period. The images were georeferenced to the Albers conformal conic coordinate system and WGS84 datum. Visual interpretation technique was used to map forest cover from historical topographical maps. Hybrid classification techniques were adopted to map forest cover and forest types for the satellite data. All major forest types described by Champion and Seth[21] were mapped from satellite data. All the datasets were converted into vector form. Then, forest cover polygons were converted to a spatial dataset. ERDAS Imagine and ArcGIS were used for digital image processing and GIS respectively.

The annual rate of forest cover change was calculated by comparing the area under forest cover in the same region at two different times. Puyravaud[25] has suggested a formula derived from the compound interest law. It can also be derived from the mean annual rate of change. Both for mathematical reasons as well as its explicit biological meaning, the following formula has been preferred to calculate the annual rate of forest change[25]

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

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.

After determining the forest cover changes, landscape metrics were used to quantify spatial variation of landscape structure and composition of AP. For this, five landscape metrics were selected based on the literature review and calculated using Fragstats, ArcInfo and Excel[10,13].

(i) *Number of patches:* It measures the extent of fragmentation of the entire landscape. It represents the number of patches for the class. Comparisons are obtained by differences in values.

(ii) *Patch density (per 100 ha):* This has the same basic utility as the number of patches as an index, except that it expresses the number of patches on a per unit area basis that facilitates comparisons among landscapes of varying size. Patch density equals the number of patches in the landscape, divided by total landscape area ($m^2$) and multiplied by 10,000 and 100 (to convert to 100 ha).

(iii) *Mean patch size:* The average patch size within a particular class, or at the landscape level, the average size of all classes. Mean patch size can serve as a habitat fragmentation index.

(iv) *The largest patch index:* It is a simple measure of dominance quantifying the percentage of landscape area occupied by the largest patch of a class.

(v) *Fractal dimension index (FDI):* The double-logged fractal index is used to describe the complexity of a patch boundary, and is more complex than the metrics mentioned above[26]. For surfaces, the value ranges between 2 (completely smooth) and 3 (infinitely crumpled). Fractals were useful for assessing land-cover categories according to how well they fit the landscape.

$$\text{FDI} = 2\ln(0.25 * \text{perimeter of forest})/\ln(\text{area of forest}).$$

National-level grid of 5 km × 5 km (each 25 sq. km) was generated for time-series assessment and to analyse the trends in spatio-temporal distribution of forest cover. On each spatial database, the area covered by forest was calculated and the change from year to year (1930–1960, 1960–1975, 1975–1985, 1985–1995, 1995–2011) was evaluated. Change (negative and positive) was quantified in the four size classes, i.e. <1, 1–5, 5–10 and >10 sq. km, for each grid cell.

For a more detailed verification of the results, the ground reference data were compared with the classified maps and the accuracy was quantitatively assessed based on overall accuracy and Kappa statistics.

The results provide quantitative account of spatial distribution of forest cover, rates of deforestation and trend of forest fragmentation in AP. The forest cover change analysis was based on the spatial database generated for six time periods, viz. 1930–1960, 1960–1975, 1975–1985, 1985–1995, 1995–2005 and 2005–2011. An assessment of the statistics on changed area indicates the

**Table 2.** State-level and regional-level distribution of forest cover in Andhra Pradesh (AP) (area in sq. km)

| Period | Telangana | % of TGA | Coastal Andhra | % of TGA | Rayalaseema | % of TGA | AP | % of TGA |
|---|---|---|---|---|---|---|---|---|
| 1930 | 43,403 | 37.8 | 24,877 | 26.8 | 17,112 | 25.4 | 85,392 | 31.0 |
| 1960 | 31,438 | 27.4 | 21,423 | 23.1 | 15,202 | 22.6 | 68,063 | 24.7 |
| 1975 | 20,553 | 17.9 | 16,385 | 17.6 | 10,002 | 14.9 | 46,940 | 17.1 |
| 1985 | 20,205 | 17.6 | 15,562 | 16.8 | 9,752 | 14.5 | 45,520 | 16.6 |
| 1995 | 19,825 | 17.3 | 15,129 | 16.3 | 9,456 | 14.1 | 44,409 | 16.1 |
| 2005 | 19,347 | 16.8 | 14,781 | 15.9 | 9,449 | 14.0 | 43,577 | 15.8 |
| 2011 | 19,304 | 16.8 | 14,776 | 15.9 | 9,443 | 14.0 | 43,523 | 15.8 |

TGA, Total geographical area.

**Table 3.** Trend of annual net rate of deforestation in AP

| *T*1 | *T*2 | Telangana | Coastal Andhra | Rayalaseema | AP |
|---|---|---|---|---|---|
| 1930 | 1960 | –1.08 | –0.50 | –0.39 | –0.76 |
| 1960 | 1975 | –2.83 | –1.79 | –2.79 | –2.48 |
| 1975 | 1985 | –0.17 | –0.52 | –0.26 | –0.31 |
| 1985 | 1995 | –0.19 | –0.28 | –0.31 | –0.25 |
| 1995 | 2005 | –0.24 | –0.23 | –0.01 | –0.19 |
| 2005 | 2011 | –0.04 | –0.01 | –0.01 | –0.02 |
| 1930 | 2011 | –1.00 | –0.64 | –0.73 | –0.83 |
| 1960 | 2011 | –0.96 | –0.73 | –0.93 | –0.88 |
| 1975 | 2011 | –0.17 | –0.29 | –0.16 | –0.21 |
| 1985 | 2011 | –0.18 | –0.20 | –0.12 | –0.17 |
| 1995 | 2011 | –0.17 | –0.15 | –0.01 | –0.13 |

significant change during 1930–2011 (Table 2). The progression of deforestation was witnessed by the proportion of existing forest cover, with reference to geographical area of the state. We calculated the total forest area to be 85,392 sq. km (31%) in 1930. As elsewhere in the forested states in India, in AP, deforestation started mainly after the development of infrastructure, dam construction and intense population growth after India's independence[16]. The remote sensing image interpretation-based forest area analyses the forest cover and percentage of total geographical area (in parenthesis) for 1960, 1975, 1985, 1995, 2005 and 2011 to be 68,063 sq. km (24.7%), 46,940 sq. km (17.1%), 45,520 sq. km (16.6%), 44,409 sq. km (16.1%), 43,577 sq. km (15.8%) and 43,523 sq. km (15.8%) respectively.

According to the State Forest Reports of FSI, the total forest cover of AP was 49,573 sq. km in 1987, which decreased to 47,112 sq. km by 1995 with net negative change of 2461 sq. km (ref. 15). While forest cover reported as 44,372 sq. km in 2005 has shown an increase to 46,389 sq. km in 2011 with net positive change of 2017 sq. km (ref. 15). In the present study based on natural definition of forest cover, the loss was 832 and 54 sq. km during 1995–2005 and 2005–2011 respectively.

Within a period of eight decades (1930–2011), the net forest cover decline in AP was 41,869 sq. km (49% of the total forest area). Between 1930 and 1975, there was a severe reduction in the forest cover, which was reported as 38,452 sq. km (45% of the forest area). The forest cover loss during 1975–1985 was 1420 sq. km, followed by 1111 sq. km during 1985–1995 and 832 sq. km during 1995–2005. The forest loss was 578 sq. km year$^{-1}$ during 1930–1960, 1408 sq. km year$^{-1}$ during 1960–1975, 142 sq. km year$^{-1}$ during 1975–1985, 111 sq. km year$^{-1}$ during 1985–1995, 83 sq. km year$^{-1}$ during 1995–2005 and 9 sq. km year$^{-1}$ during 2005–2011.

Region-wise analysis showed that the forests throughout the state faced various degrees of deforestation. Among the three regions (1930–2011), historical deforestation was very high in Telangana with forest cover loss of 55.5% of area, followed by 44.8% in Rayalaseema and 40.6% in Coastal Andhra. Of the total 23 districts in AP, 14 districts, viz. Nalgonda, Rangareddy, Medak, Anantapur, Krishna, Nizamabad, Mahabubnagar, Adilabad, Guntur, Karimnagar, Kurnool, Khammam, Visakhapatnam and Warangal have shown >30% forest area loss during 1930–2011. In these districts, the major cause of forest conversion is primarily ascribed to expansion of agriculture and plantations, transition to scrub due to logging, change to water bodies due to construction of dams and shifting cultivation. Out of the total deforested area (3417 sq. km) during 1975–2011, highest forest cover loss of >10% was recorded in three districts, i.e. Visakhapatnam, Khammam and Adilabad.

The rate of deforestation was high during 1960–1975. Annual net rate of deforestation for the period 1930–1960 was 0.76, while it was 2.48 for 1960–1975 and 0.13 for 1995–2011. There has been an apparent decline in the rate of annual deforestation since 1995. During 1995–2005, the net rate of deforestation was 0.19. More importantly, the net deforestation rate was low (0.02) during the recent period (2005–2011) indicating good forest protection measures undertaken by the Andhra Pradesh Forest Department (Table 3).

Spatial patterns of forest cover change have been identified across grid cell size of 5 km × 5 km. In Figure 1, the spatial data for 1930, 1960, 1975, 1985, 1995 and 2011 are displayed along with grid-wise representation of forest cover. A total of 11,341 grids were identified in AP. Of these, 11,003 are full grids and 308 are partial grids. The number of forest grids varies across the periods ranging from 7189 in 1930, 6651 in 1960, 5441 in

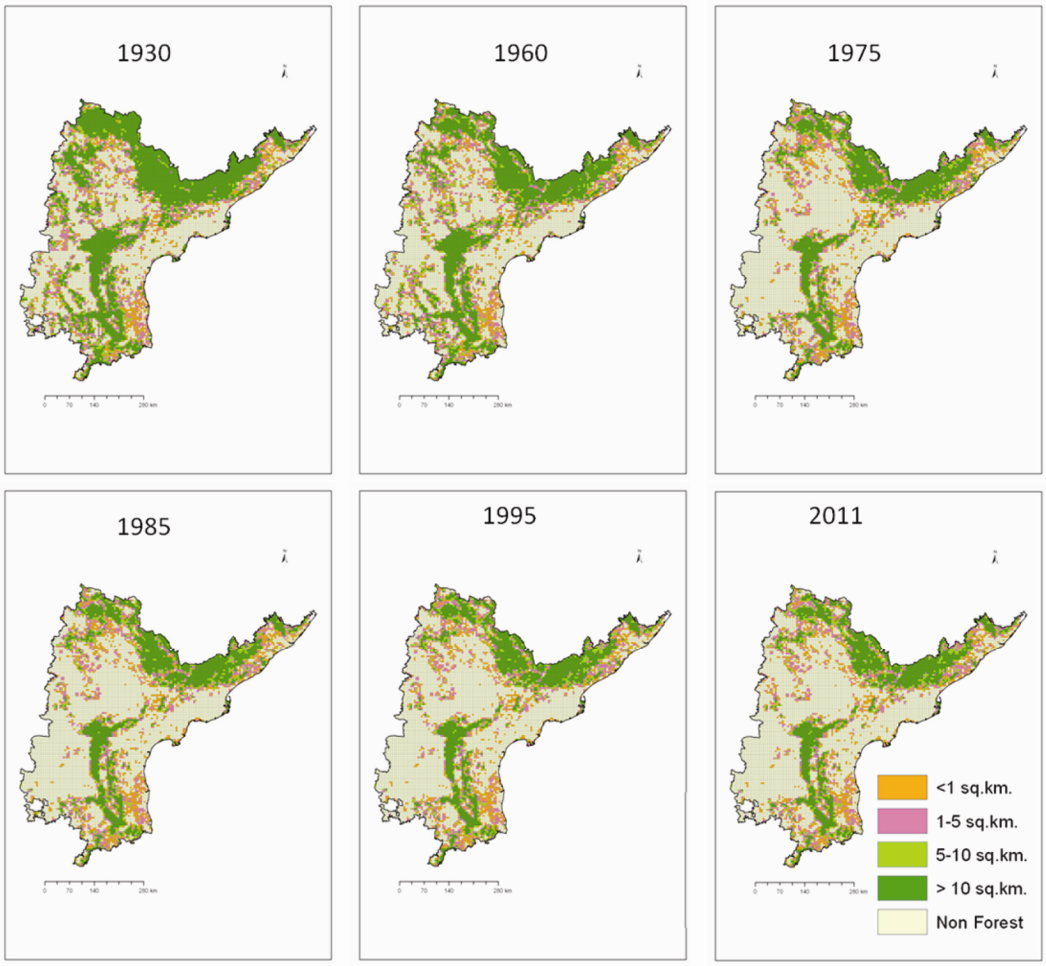


**Figure 1.** Spatial distribution of forest cover: 1930–2011.

**Table 4.** Analysis of grid-wise negative changes in AP

| Size class (sq. km) | 1930–1960 | 1960–1975 | 1975–1985 | 1985–1995 | 1995–2011 |
|---|---|---|---|---|---|
| <1 | 1,110 | 1,397 | 331 | 2,423 | 831 |
| 1–5 | 1,660 | 1,967 | 314 | 317 | 245 |
| 5–10 | 682 | 854 | 66 | 39 | 49 |
| >10 | 507 | 479 | 14 | 7 | 7 |
| Total | 3,959 | 4,697 | 725 | 2,786 | 1,132 |

No. of 5 km × 5 km cells affected by negative changes has been given.

1975, 5432 in 1985, 5347 in 1995 to 5317 in 2011. The number of forest grids representing more than >10 sq. km has shown significant variation due to large-scale deforestation.

Grid-wise analysis clearly shows that the highest number of grids has undergone negative changes during 1930–1975, 1985–1995 and 1995–2005 (Figure 2 *a*, Table 4). Forest cover change maps of 1930–1960, 1960–1975 and 1975–2011 are presented in Figure 2 *a*–*c*. The construction of Nagarjuna Sagar dam during 1960 was responsible for submergence of forest cover in parts of central AP. There are a total of 1132 grids that have shown loss of forest cover during 1995–2011. Fifty-three grids have shown positive changes in forest cover during 1995–2011. This is an indication of afforestation/reforestation progammes taken up by the Andhra Pradesh Forest Department contributing towards the increase in forest cover. There are 775 grids showing afforestation/reforestation during 1960–2011 (Figure 3).

The overall classification accuracy of the forest cover maps of 1975, 1985, 1995, 2011 was estimated as 88.2%, 89.1%, 90.4% and 91.8% respectively, while kappa value

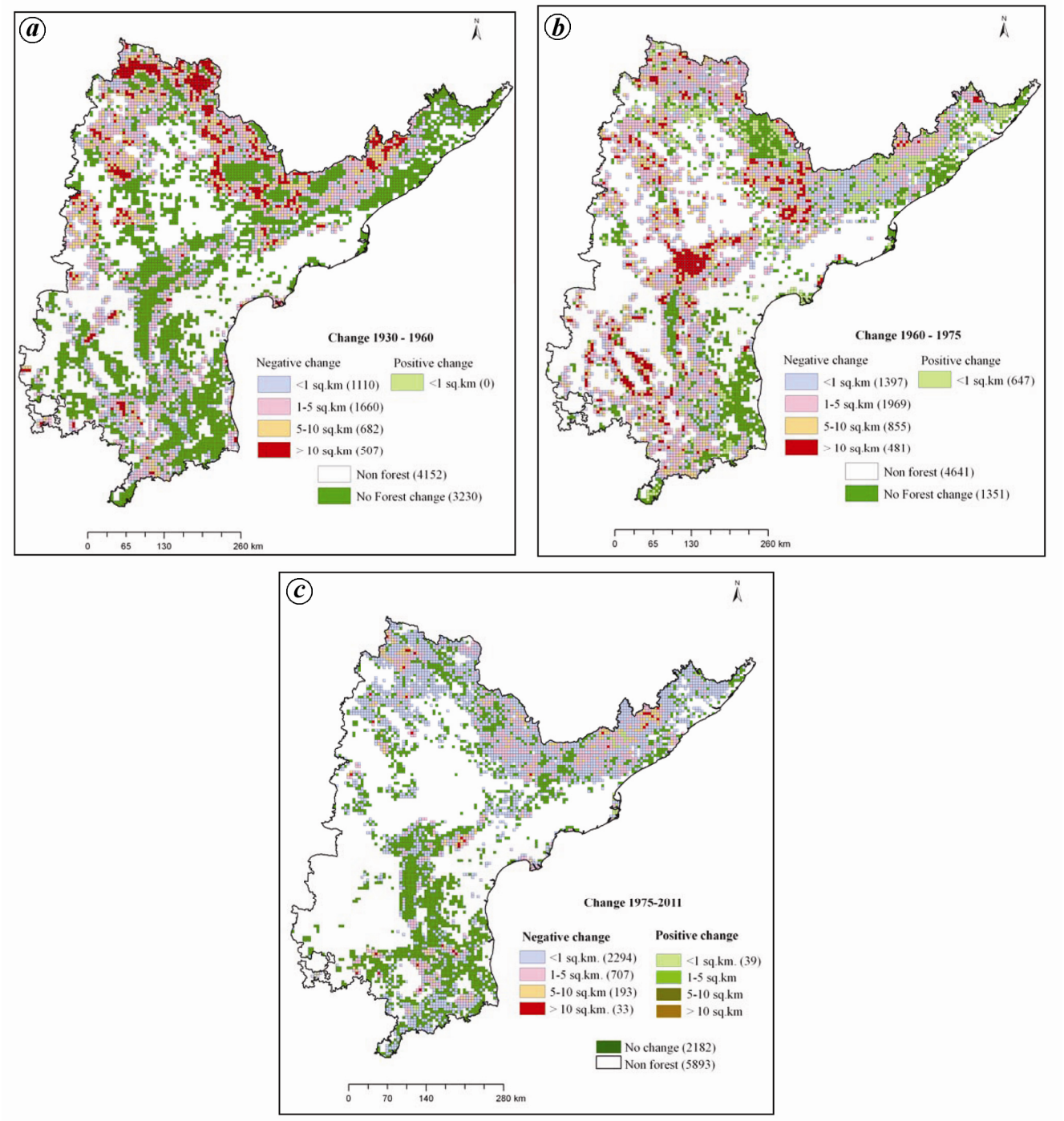


**Figure 2.** Grid-wise forest cover changes in AP: ***a***, 1930–1960; ***b***, 1960–1975; ***c***, 1975–2011.

**Table 5.** Areal extent of forest types in AP (1975–2011; area in sq. km)

| Forest type | 1975 | Percentage | 1985 | Percentage | 1995 | Percentage | 2011 | Percentage |
|---|---|---|---|---|---|---|---|---|
| Semi-evergreen | 1,989 | 4.2 | 1,786 | 3.9 | 1,716 | 3.9 | 1,701 | 3.9 |
| Moist deciduous | 6,974 | 14.9 | 6,929 | 15.2 | 6,778 | 15.3 | 6,757 | 15.5 |
| Dry deciduous | 35,396 | 75.4 | 34,262 | 75.3 | 33,547 | 75.5 | 32,795 | 75.4 |
| Dry evergreen | 199 | 0.4 | 200 | 0.4 | 194 | 0.4 | 194 | 0.4 |
| Teak mixed | 500 | 1.1 | 498 | 1.1 | 472 | 1.1 | 380 | 0.9 |
| Thorn | 1,532 | 3.2 | 1,528 | 3.4 | 1,416 | 3.2 | 1,413 | 3.2 |
| Mangrove | 348 | 0.7 | 317 | 0.7 | 285 | 0.6 | 283 | 0.6 |
| Total | 46,940 | 100.0 | 45,520 | 100.0 | 44,409 | 100.0 | 43,523 | 100.0 |

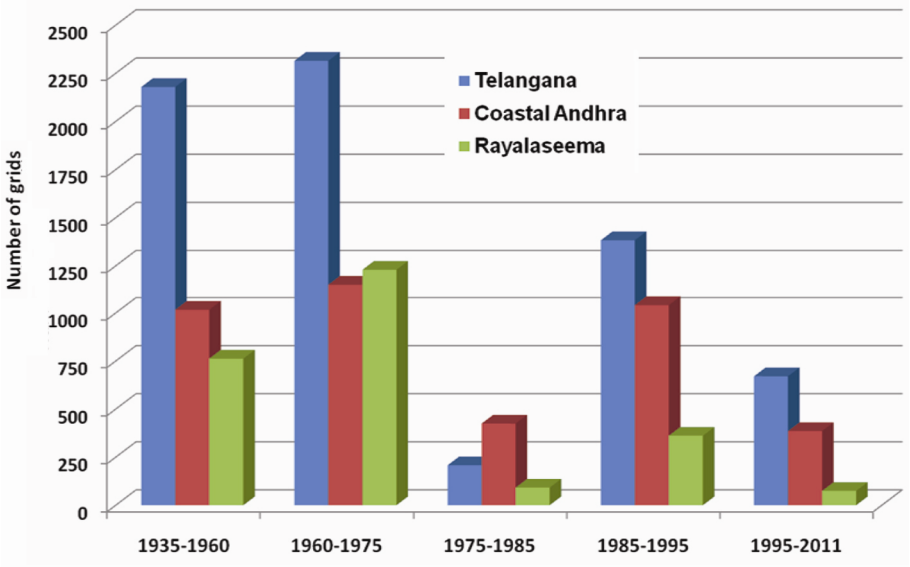


**Figure 3.** Region-wise distribution of the number of grids showing deforestation.

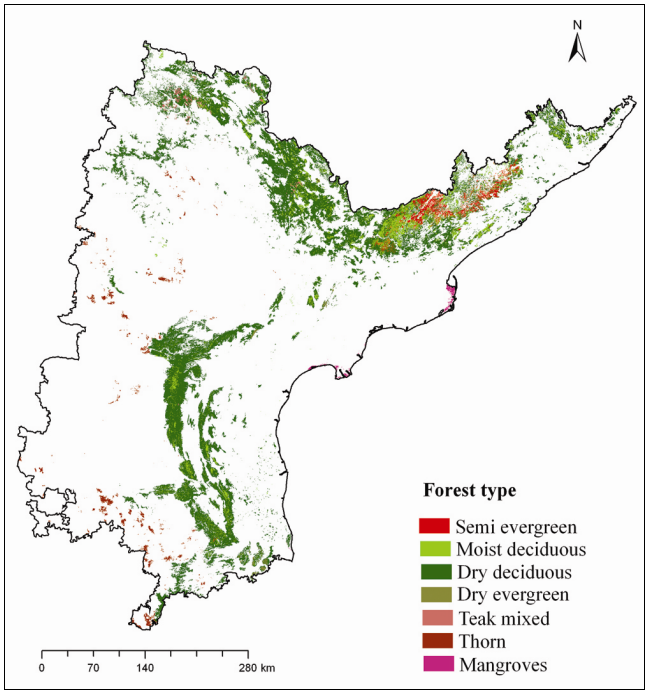


**Figure 4.** Forest type map of AP: 2011.

was >0.87. Vegetation type map of 1 : 50,000 scale (2004) prepared as part of national project on biodiversity characterization at landscape level was consulted for validation of forest cover maps of 1975 to 2005 (ref. 27).

Seven major forest types, i.e. semi-evergreen forests, moist deciduous forests, dry deciduous forests, dry evergreen forests, teak mixed forests, thorn forests and mangroves were delineated (Table 5).

The forest type distribution for 2011 is shown in Figure 4. In AP, dry deciduous forests occupy more than three-fourths of the forest cover, while in Odisha, these occupy only 21% of forest cover[16]. A comparative evaluation based on spatial extent revealed that significant changes occurred during 36 years in all the forest types. Ecologically unique forest types, i.e. mangroves, semi-evergreen forests and dry evergreen forests showed reduction in area of 18.7%, 14.5% and 2.6% respectively. About 7.3% of dry deciduous forests and 3.1% of moist deciduous forests have declined during the 36-year period.

Due to high economic potential, teak mixed forests have undergone large-scale deforestation and accounted for loss of 24% of the area during 1975–2011. Annual rate of deforestation of teak mixed forests was high (0.76%), followed by mangroves (0.58%), semi-evergreen forests (0.43%), dry deciduous forests (0.21%), moist deciduous forests (0.09%) and dry evergreen forests (0.07%). A net rate of deforestation of –0.16 was accounted for the mangroves of Godavari delta during 1977–2005 (ref. 28). The loss of mangroves was due to encroachment by agriculture, aquaculture and coastal erosion. Forest cover change analysis in dry deciduous forests of Pranahita Wildlife Sanctuary in AP from 1993 to 2004 showed deforestation rate as –0.28 (ref. 29). A study from 1988 to 2006 showed a deforestation rate of –0.81 in R.V. Nagar range, Visakhapatnam, AP[30].

In order to estimate the forest patches and level of isolation of fragmentation, the forest patches were categorized under seven classes, i.e. <1, 1–5, 5–10, 10–20, 20–50, 50–100 and >100 sq. km (Table 6). Then the number of forest patches falling under each class was quantified and analysed across spatial data of forest cover. Of the total 3981 forest patches, 2809 (70.6%) belonged to <1 sq. km patch size category in 1930. The number of <1 sq. km patches was 4356 in 1960, 7724 in 1975, 8337 in 1985, 8562 in 1995 and 9499 in 2011.

**Table 6.** Size class distribution of forest patches in AP

| Patch class (sq. km) | 1930 | | 1960 | | 1975 | | 1985 | | 1995 | | 2011 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Count | Percentage | Count | Percentage | Count | Percentage | Count | Percentage | Count | Percentage | Count | Percentage |
| <1 | 2,809 | 70.6 | 4,356 | 78.4 | 7,724 | 88.2 | 8,337 | 88.6 | 8,562 | 88.7 | 9,499 | 89.6 |
| 1–5 | 601 | 15.1 | 576 | 10.4 | 660 | 7.5 | 699 | 7.4 | 716 | 7.4 | 726 | 6.9 |
| 5–10 | 205 | 5.1 | 227 | 4.1 | 137 | 1.6 | 137 | 1.5 | 135 | 1.4 | 141 | 1.3 |
| 10–20 | 155 | 3.9 | 181 | 3.3 | 96 | 1.1 | 91 | 1.0 | 92 | 1.0 | 83 | 0.8 |
| 20–50 | 122 | 3.1 | 115 | 2.1 | 75 | 0.9 | 79 | 0.8 | 75 | 0.8 | 80 | 0.8 |
| 50–100 | 45 | 1.1 | 49 | 0.9 | 27 | 0.3 | 27 | 0.3 | 27 | 0.3 | 27 | 0.3 |
| >100 | 44 | 1.1 | 49 | 0.9 | 41 | 0.5 | 42 | 0.4 | 41 | 0.4 | 41 | 0.4 |
| Total | 3,981 | 100 | 5,553 | 100 | 8,760 | 100 | 9,412 | 100 | 9,648 | 100 | 10,597 | 100 |

**Table 7.** Areal extent of forest patches in AP (area in sq. km)

| Patch class (sq. km) | 1930 | | 1960 | | 1975 | | 1985 | | 1995 | | 2011 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Area | Percentage | Area | Percentage | Area | Percentage | Area | Percentage | Area | Percentage | Area | Percentage |
| <1 | 569 | 0.7 | 739 | 1.1 | 1,453 | 3.1 | 1,569 | 3.4 | 1,379 | 3.1 | 1,455 | 3.3 |
| 1–5 | 1,440 | 1.7 | 1,411 | 2.1 | 1,495 | 3.2 | 1,562 | 3.4 | 1,598 | 3.6 | 1,617 | 3.7 |
| 5–10 | 1,490 | 1.7 | 1,638 | 2.4 | 964 | 2.1 | 962 | 2.1 | 952 | 2.1 | 987 | 2.3 |
| 10–20 | 2,235 | 2.6 | 2,556 | 3.8 | 1,362 | 2.9 | 1,286 | 2.8 | 1,314 | 3.0 | 1,182 | 2.7 |
| 20–50 | 3,927 | 4.6 | 3,554 | 5.2 | 2,372 | 5.1 | 2,506 | 5.5 | 2,345 | 5.3 | 2,467 | 5.7 |
| 50–100 | 3,187 | 3.7 | 3,506 | 5.2 | 1,937 | 4.1 | 1,918 | 4.2 | 1,868 | 4.2 | 1,980 | 4.5 |
| >100 | 72,544 | 85.0 | 54,659 | 80.3 | 37,357 | 79.6 | 35,717 | 78.5 | 34,953 | 78.7 | 33,835 | 77.7 |
| Total | 85,392 | 100 | 68,063 | 100 | 46,940 | 100 | 45,520 | 100 | 44,409 | 100 | 43,523 | 100 |

**Table 8.** Change in spatial pattern of forest in 1930, 1960, 1975, 1985, 1995 and 2011

| Landscape metrics | 1930 | 1960 | 1975 | 1985 | 1995 | 2011 |
|---|---|---|---|---|---|---|
| Number of forest patches | 3,981 | 5,553 | 8,760 | 9,412 | 9,646 | 10,597 |
| Patch density index (per 100 ha) | 1.4 | 2.0 | 3.2 | 3.4 | 3.5 | 3.9 |
| Mean patch size (sq. km) | 21.5 | 12.3 | 5.7 | 5.1 | 4.8 | 4.3 |
| Largest patch index (%) | 44.9 | 15.2 | 15.9 | 15.0 | 15.0 | 14.9 |
| Fractal dimension index | 2.2 | 2.2 | 2.3 | 2.3 | 2.3 | 2.3 |

Patches of >100 sq. km contributed to highest forest area of 72,544 sq. km in 1930, while it was 33,835 sq. km in 2011 (Table 7). It is evident that there has been extensive decline in the size of the largest forest patches due to deforestation.

Large-scale deforestation in AP has led to a decline in forest patch area and increase in the number of patches. The total number of forest patches increased from 3981 in 1930 to 10,597 in 2011 (Table 6). Mean patch size of forest varied across time periods. The mean patch size showed severe reduction in area of 21.5 sq. km in 1930 to 12.3 sq. km in 1960, 5.7 sq. km in 1975, 4.8 sq. km in 1995 and reached to 4.3 sq. km by 2011. Largest patch index of forest landscape in 1930 was estimated at 44.9, whereas 14.9% of the forest area was concentrated in a single large patch in 2011. Patch density index (per 100 ha) increased from 1.4 to 3.9 during 1930–2011. Fractal dimension index varied unpredictably with forest cover changes (Table 8). The landscape analysis using different landscape metrics in geo-spatial domain indicates ongoing biotic pressure in the forests of AP.

The long-term forest change analysis based on the earliest and authentic spatial documentation has brought out clearly the magnitude of deforestation in AP. This analysis also highlights the second-order impact of deforestation in terms of forest fragmentation. Comprehensive spatial analysis about the status of forests is useful in formulating the policies related to sustainable use and biodiversity conservation.

1. Murali, K. S. and Hedge, R., Patterns of tropical deforestation. *J. Trop. For. Sci*., 1997, **9**(4), 465–476.
2. Myers, N., Mittermeier, R. A. and Mittermeier, C. G., Biodiversity hotspots for conservation priorities. *Nature*, 2000, **403**, 853–858.
3. Shukla, J., Nobre, C. and Sellers, P., Amazon deforestation and climate change. *Science*, 1990, **247**, 1322–1325.

4. Bishop, R., Economic efficiency, sustainability and biodiversity. *Ambio*, 1993, **22**, 69–73.
5. FAO, Assessing forest degradation – towards the development of globally applicable guidelines. Forest Resources Assessment Working Paper 177, Food and Agriculture Organization, Rome, 2011.
6. Gustafson, E. J., Quantifying spatial landscape pattern: what is the state of art? *Ecosystems*, 1998, **1**, 143–156.
7. Furby, S., Land cover change: specification for remote sensing analysis. National Carbon Accounting System Technical Report No. 9. Australian Greenhouse Office, Canberra, Australia, 2002.
8. Potapov, P. V. *et al.*, Quantifying forest cover loss in Democratic Republic of the Congo, 2000–2010, with Landsat ETM+ data. *Remote Sensing Environ*., 2012, **122**, 106–116.
9. Wilcove, D. S., McLellan, C. H. and Dobson, A. P., Habitat fragmentation in the temperate zone. In *Conservation Biology* (ed. Soul´e, M. E.), Sinauer, Sunderland, MA, 1986, pp. 237–256.
10. McGarigal, K., Cushman, S. A., Neel, M. C. and Ene, E., FRAGSTATS: spatial pattern analysis program for categorical maps, 2002; www.umass.edu/landeco/research/fragstats/fragstats.html (accessed on 17 August 2009).
11. Riitters, K., Wickham, J. and Coulston, J., A preliminary assessment of Montreal process indicators of forest fragmentation for the United States. *Environ. Monit. Assess*., 2004, **91**, 257–276.
12. Dewan, A. M., Yamaguchi, Y. and Rahman, M. Z., Dynamics of land use/cover changes and the analysis of landscape fragmentation in Dhaka Metropolitan, Bangladesh. *GeoJournal*, 2012, **77**, 315–330; doi:10.1007/s10708-010-9399-x.
13. Reddy, C. S., Sreelekshmi, S., Jha, C. S. and Dadhwal, V. K., National Assessment of Forest Fragmentation in India: landscape indices as measures of the effects of fragmentation and forest cover change. *Ecol. Eng*., 2013, **60**, 453–464.
14. Kharuk, V. I., Im, S. T., Ranson, K. J. and Naurzbaev, M. M., Temporal dynamics of larch forest in the forest–tundra ecotone. *Doklady Earth Sci*., 2004, **398**, 1020–1023.
15. FSI, India State of Forest Reports, Forest Survey of India, Dehra Dun, 1987–2011.
16. 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.
17. Reddy, C. S., Dutta, K. and Jha, C. S., Analysing the gross and net deforestation rates in India. *Curr. Sci*., 2013, **105**(11), 1492–1500.
18. Reddy, C. S., Hari Krishna, P., Anitha, K. and Joseph, S., Mapping and inventory of forest fires in Andhra Pradesh, India: current status and conservation needs. *ISRN For.*, 2013; DOI:10.5402/2012/380412.
19. Romijn, E., Ainembabazi, J. H., Wijaya, A., Herold, M., Angelsen, A., Verchot, L. and Murdiyarso, D., Exploring different forest definitions and their impact on developing REDD+ reference emission levels: a case study for Indonesia. *Environ. Sci. Policy*, 2013, **33**, 246–259.
20. Ravindranath, N. H., Murthy, I. K., Priya, J., Upgupta, S., Mehra, S. and Nalin, S., Forest area estimation and reporting: implications for conservation, management and REDD+. *Curr. Sci.*, 2014, **106**(9), 1201–1206.
21. Champion, H. G. and Seth, S. K., *A Revised Survey of the Forest Types of India*, Manager of Publications, Delhi, 1968.
22. Census, 2011; http://censusindia.gov.in/2011-prov-esults/prov_data_products_andhra.html/ (accessed 13 November 2013).
23. http://sunsite/berkeley.edu/EART/India/250k/ (accessed on 8 February 2011).
24. http://glcfapp.umiacs.umd.edu:8080/esdi (accessed on 14 November 2012).
25. Puyravaud, J. P., Standardizing the calculation of the annual rate of deforestation. *For. Ecol. Manage.*, 2003, **177**, 593–596.
26. Li, X., He, H. S., Bu, R., Wen, Q., Chang, Y., Hu, Y. and Li, Y., The adequacy of different landscape metrics for various landscape patterns. *Pattern Recogn*., 2005, **38**, 2626–2638.
27. NRSA, *Biodiversity Characterization at Landscape Level in Eastern Ghats and East Coast using Remote Sensing and Geographic Information System*, National Remote Sensing Agency, Hyderabad, 2007; ISBN-978-81-7525-878-5.
28. 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.
29. 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**(2), 73–79.
30. 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.

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# Mineralogy of kaolin clays in different forest ecosystems of southern Western Ghats, India

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**Random X-ray powder diffraction (XRD) and scanning electron microscopy (SEM) were used to identify 1 : 1 clay minerals in soils of five different forest ecosystems such as moist deciduous forests, evergreen forests, shola forests, grasslands and scrub jungles in the southern Western Ghats, India. The study sites experience a humid tropical climate with intense leaching and weathering, except scrub jungle which lies in the rain shadow area of the Western Ghats. XRD analyses of air-dried samples, confirmatory tests using formamide intercalation and SEM could establish kaolinite–halloysite coexistence in clay fractions of three different ecosystems of the Western Ghats. Earlier studies on clay mineralogy in the region failed to establish such coexistence because of the relative metastable nature of halloysite with respect to kaolinite. The identification of soil systems with metastable minerals like halloysite presents interesting possibilities of further studies vis-à-vis soil genesis and management in the tropics.**

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