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Evaluating forest fragmentation and its tree community composition in the tropical rain forest of Southern Western Ghats (India) from 1973 to 2004

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Abstract A majority of the research on forest fragmentation is primarily focused on animal groups rather than on tree communities because of the complex structural and functional behavior of the latter. In this study, we show that forest fragmentation provokes surprisingly rapid and profound alterations in tropical tree community. We examine forest fragments in the tropical region using high-resolution satellite imagery taken between 1973 and 2004 in the Southern Western Ghats (India) in relation to landscape patterns and phytosociological datasets. We have distinguished fragmentation in six categories—interior, perforated, edge, transitional, patch, and undetermined—around each forested pixel. Furthermore, we have characterized each of the fragment class in the evergreen and semi-evergreen forest in terms of its species composition and richness, its species similarity and abundance, and its regeneration status. Different landscape metrics have been used to infer patterns of land-use changes. Contiguous patches of >1,000 ha covered 90% of evergreen forest in 1973 with less porosity and minimal plantation and anthropogenic pressures; whereas in 2004, the area had 67% forest coverage and a high level of porosity, possibly due to *Ochlandra* spread and increased plantations which resulted in the loss of such contiguous patches. Results highlight the importance of landscape metrics in monitoring land-cover change over time. Our main conclusion was to develop an approach, which combines information regarding land cover, degree of fragmentation, and phytosociological inputs, to conserve and prioritize tropical ecosystems.

Keywords Fragmentation · Kalakkad Mundanthurai tiger reserve · Tropical forests · Land-cover change · Landscape pattern · Remote sensing

Introduction

Forest fragmentation in tropical rain forests is considered as one of the greatest threats to global biodiversity because these forests are the most species-rich of terrestrial ecosystems (Myers 1986; Whitmore and Sayer 1992; Armenteras et al. 2003). The complex process of fragmentation and forest loss is a common phenomenon in tropical forests, and apart from forest degeneration, also brings about several physical and biological

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changes in the forest environment. (Skole and Tucker 1993; Serio-Silva and Rico-Gray 2002; Cordeiro and Howe 2003; Jha et al. 2005). These two processes may have negative effects on biodiversity, by increasing isolation of habitats (Debinski and Holt 2000), endangering species, modifying species' population dynamics (Watson et al. 2004), and expanding at the expense of interior habitat (Mace et al. 1998). Consequently, this is a leading cause for the decline and loss of species worldwide and has been a topic of considerable research and review (Noss 1996; Laurance et al. 1998a, b, 2002).

The effects of fragmentation on species richness tend to have sunk in the probability of successful dispersal and establishment (Gigord et al. 1999; Cordeiro and Howe 2003; Giriraj 2006) as well as reduced the capacity of a patch of habitat to sustain a resident population (Iida and Nakashizuka 1995). The ecological consequences of fragmentation may differ depending on the patterns of spatial configuration imposed on a landscape and how it varies both temporally and spatially (Ite and Adams 1998; Armenteras et al. 2003). Therefore, an understanding of the relationship between landscape patterns and the ecological processes influencing the distribution of species is required by resource managers to provide a basis for making land-use decisions (Turner et al. 2001).

Land use/land cover is a fundamental variable that impacts the forest fragmentation and isolation of habitats, which is being linked with human and physical environments. While the importance of human activities is widely recognized, the relative influence of human activities on environmental factors is less understood. However, land-cover maps indicate only the location and type of vegetation, and further processing is needed to quantify and map forest fragmentation (Turner and Gardner 1991; Gustafson 1998). Today, remote sensing is being considered an excellent tool for the analysis and effective monitoring of forest fragmentation. Several studies have used remote sensing to map patterns of forest fragmentation and to analyze the rates of forest-cover change in the tropics and elsewhere (Vogelmann 1995; Riitters et al. 2000, 2002; Wickham et al. 2000, 2007). Our objective is to map and compare patterns of forest fragmentation in temporal time by using a fragmentation model (Riitters et al. 2000, 2002; Wade et al. 2003) that distinguishes between the different levels of fragmentation. Our study also identifies areas of large interior forest and isolated patches for conservation priorities. Our study also helps to identify and prioritize regions using phytodiversity information from direct measurement of impacts.

Study area

The Kalakkad Mundanthurai Tiger Reserve (KMTR) is located at the southern end of the Western Ghats, Tamil Nadu, India (Fig. 1) and lies between 8°21′–8°52′ N latitude and 77°10′–77°33′ E longitude in the biogeographic provinces 4.14.4 (Deccan thorn forest) and 4.1.1 (Malabar rainforest) (Udvardy 1975). The area falls into two districts, namely, Tirunelveli and Kanya Kumari of Tamil Nadu and bounded in the west by the state of Kerala.

KMTR, the second largest protected area in the state of Tamil Nadu covers an area of 907 km^2 with hills towering to majestic heights ranging from 100 to 1,880 m (Agasthiar peak). Agasthyamalai hills, at the southern end of the Western Ghats, are known for high species diversity, harboring 2,000 flowering plant species with 7.5% endemism (Henry et al. 1984). The mid-elevation zone (700–1,400 m) is the tropical wet evergreen forest of the *Cullenia–Mesua–Palaquium* series (Pascal 1988). The topography is rugged with numerous perennial hill streams originating from the tropical rainforest areas in the upper slopes, and they confluence to form major rivers such as the Tambiraparani, Manimuthar, and Ramanadhi, which support the agricultural economy of millions in the adjoining plains. The forests of the reserve include the catchment area of the Manimuthar, Kodayar, Servalar, and Karaiar dams. The climate of the area is typically with a minimum rainfall of 1,200 mm to a maximum of 5,000 mm. Annual average temperature ranges from 13.5°C in the evergreen to 23°C in the deciduous forests. Dry period ranges from 3 to 5 months and number of rainy days is in the order of 89–92 days (Pascal 1982).

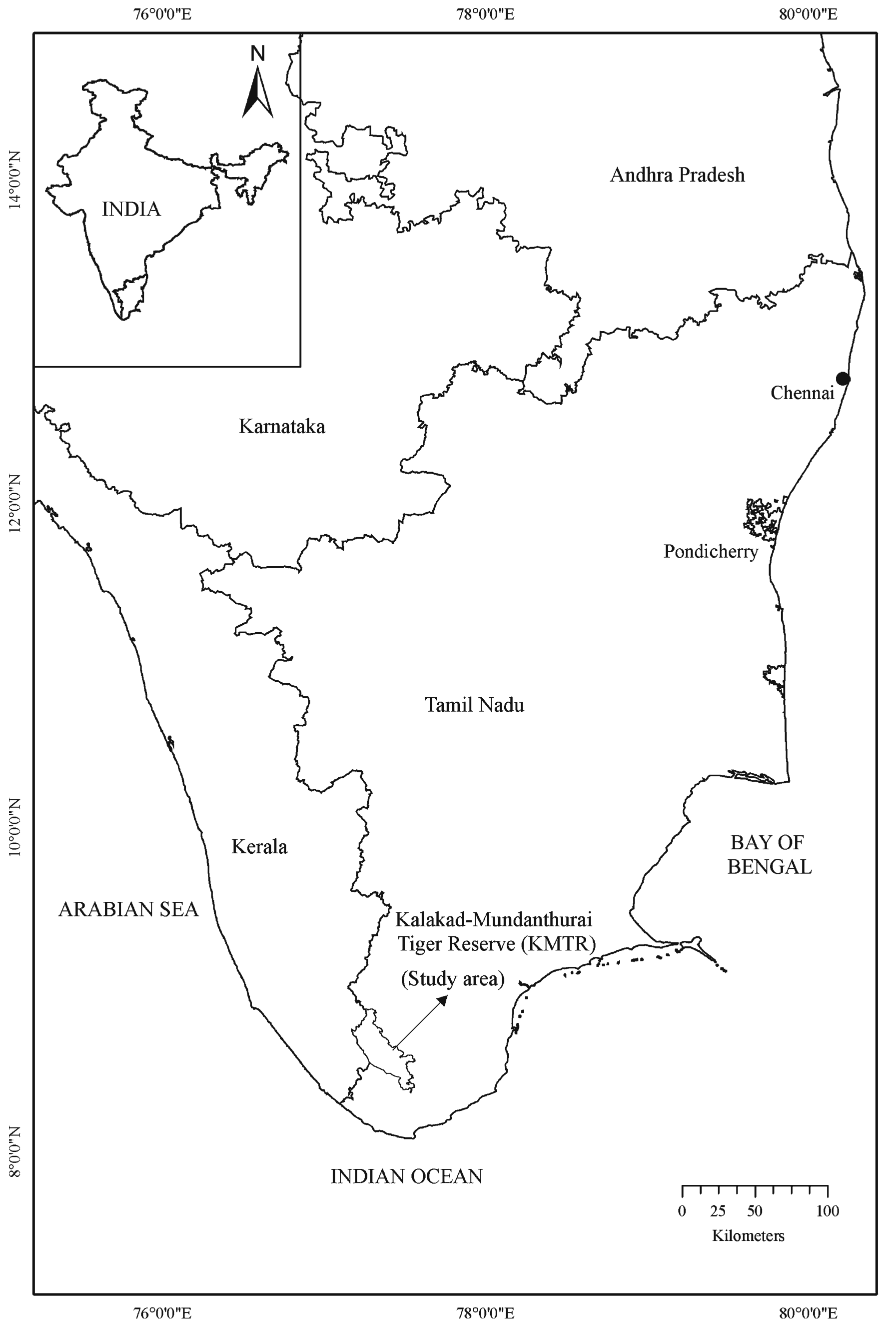

Fig. 1 Map showing the geographic position of KMTR, Southern Western Ghats, in Tirunelveli and Kanykumari district of Tamil Nadu state, south India

Forest types such as tropical evergreen, semi-evergreen, moist deciduous, dry deciduous, grasslands, and secondary succession exist in the study area. The dominant evergreen tree species are *Cullenia exarillata*, *Mesua ferrea*, *Palaquium elliptium*, *Myristica dactyloides*, and *Aglaia bourdillonii* and deciduous species includes *Anogeissus latifolia*, *Terminalia chebula*, and *Terminalia bellirica*. The major invasive species include *Lantana camara*, *Ageratum conyzoides*, and the *Eupatorium* species.

History of changes in KMTR

The evergreen forests of the KMTR have a long history of change in forest-cover and land-use type over the last 250 years (Caldwell 1989). Ramesh et al. (1997) quantified a significant loss of biologically rich areas between 1960 and 1990: 85.6 km^2 to plantations, 42 km^2 to encroachment, and 36.4 km^2 to reservoirs. A total of 28 enclaves have been identified within the KMTR (Ali and Pai 2001). A total of 189 eco-development villages are in the immediate vicinity of the park at the eastern perimeter in a 5-km broad strip. Ecological damages due to forest fire, invasion of reeds, and erosion are some of the major causes, which might have led to change in floristic composition, regeneration, and loss of endemics.

Materials and methods

Forest type classification using satellite data

Cloud-free satellite data of LANDSAT Multispectral Scanner (MSS) of March 1973 covering path and row 154/54 was obtained from the U.S. Geological Survey, USA, and IRS-1C Linear Imaging Self Scanner (LISS)-III satellite data of 19 March 2004 covering path and row 101/68 was obtained from the National Remote Sensing Agency, Hyderabad. LANDSAT-MSS data with a spatial resolution of 80 m and spectral bands (B1 0.5–0.6, B2 0.6–0.7, B3 0.7–0.8, and B4 0.8–1.1 μm), and IRS-P6 LISS-III data with a spatial resolution of 24 m and spectral bands (B2 0.52–0.59, B3 0.62–0.68, B4 0.77–0.86, and B5 1.55–1.70 μm) was analyzed in the present study.

Initially, evergreen and semi-evergreen forest patches of 2004 (LISS-III) was characterized using supervised classification technique based on the information of terrain, topography, and species database collected during landscape biodiversity characterization program for Western Ghats (Dutt et al. 2002). Based on the identified 2004 evergreen and semi-evergreen patches, an area of interest (AOI) was selected from the evergreen and semi-evergreen vegetation patch of 1973, assuming that these patches of 2004 had remained unchanged from 1973. Likewise, all the other land-cover classes were classified to generate vegetation and land-cover map of KMTR. After the completion of preclassification, misclassified areas were observed and reclassified using small AOI or through interactive editing for improved accuracy. The maximum likelihood algorithm (Lillesand and Kiefer 2000) was used to classify these patches. The classified vegetation and land-cover map were randomly checked in the field with Global Positioning System (GPS) points. The overall accuracy stands at 85% with a kappa statistics of 0.81. Finally, IRS LISS-III dataset were resampled to 80 m (equivalent to MSS) to facilitate comparison.

Landscape analysis

Landscape is defined as "an aggregation of heterogeneous elements, which interact with each other." Landscape has three intrinsic properties: structure, function, and change. These can be explained in terms of porosity, fragmentation, patch density, patchiness, interspersion, juxtaposition, contagion, etc. (Forman and Godron 1986). In the present study, the following landscape metrics have been studied to assess forest fragmentation patterns.

Fragmentation modeling

Land-cover map with a spatial resolution of 80 m was used to characterize the fragmentation levels around the evergreen and semi-evergreen forests pixel. To perform the fragmentation calculations, we used a "moving window" algorithm developed by Riitters et al. (2000). The model was designed to identify patterns of forest fragmentation using coarse- and fine-scale resolution land-use and land-cover information.

To implement the fragmentation model, the size of the analysis window had to be determined. After considering the resolution of data, delineation of the forest features, and practical assessment of the various window sizes, a 5 × 5 window was found to maintain an adequate representation of the proportion (Pf) of pixels in the window and also to represent the interior forest at an appropriate level. The window was centered on each land-cover pixel (forested or not), a fragmentation score was calculated for the window, and the result was assigned to the center pixel. Maps of four indices were produced for each forest classes to characterize forest fragmentation by

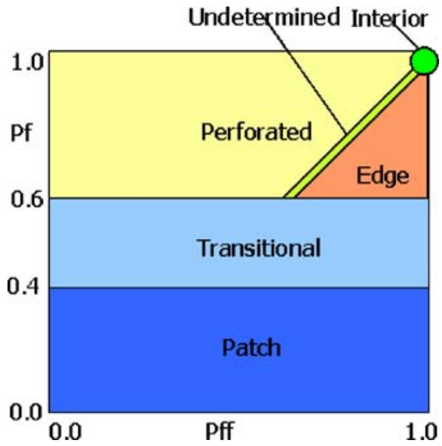

Fig. 2 Forest fragmentation categories from local measurements of Pf and Pff (adapted from Riitters et al. 2000)

anthropogenic pixels (Pfa), forest fragmentation by nonforest natural land-cover pixels (Pfn), overall forest connectivity (Pff), and forest area density (Pf). The computations are illustrated in detail in Riitters et al. (2000), as Pf was the proportion of the forests in the analysis window and Pff was the ratio of the number of adjacent (cardinal directions only) pixel pairs for which both pixels were forest, to the number of adjacent pixel pairs where either one or both pixels were forest. Figure 2 shows the classification model that identifies six fragmentation categories: (1) interior, for which Pf $= 1.0$; (2) patch, Pf < 0.4; (3) transitional, $0.4 <$ Pf < 0.6; (4) edge, Pf > 0.6 and Pf–Pff > 0; (5) perforated, Pf > 0.6 and Pf–Pff < 0, and (6) undetermined, Pf > 0.6 and Pf $=$ Pff.

Using the results from the forest fragmentation model, further research was conducted to produce maps, which identify the state of forest fragmentation of a specified region. The purpose for the forest fragmentation index was to provide a quick means to assess the extent of forest fragmentation within a region and to track trends in forest fragmentation to identify areas that would benefit from possible reforestation. Different indexes were used to generate forest fragmentation, e.g., total forest proportion (TFP), forest continuity (FC), and weighted forest area (WFA) (Vogelmann 1995; Wickham et al. 1999; Civco et al. 2002).

Patch metrics

Patch size, number, and shape Once the classified forest patches were prepared using satellite data, they were vectorized in geographic information system domain to characterize the patches. The information on patch size and number was extracted from the vectorized classified data. A minimum of 3×3 pixel window was set for patch analysis. A simple measure of patch shape is the perimeter-to-area (PA) ratio. This measure is often standardized so that the most compact possible form, either square or circle, is equal to 1. Higher perimeter value indicates increase of edge effect, an ecologically undesirable influence on most species population and communities.

Contagion index The contagion metric was first proposed by O'Neil et al. (1988) and later by several others (Graham et al. 1991; Gustafson and Parker 1992; Li and Reynolds 1993). It is a measure of clumping or aggregation of patches. It is also used as an indication of the degree of landscape fragmentation.

Fractal dimension Fractal dimension (FD) has been used for measurement, simulation, and as a spatial analytic tool in the mapping sciences (O'Neil et al. 1988; De Cola 1989). Changes in the FDs of the remote sensing images have implications on changes in the environmental conditions (Lam and Ouattrochi 1992). A number of studies have found that the FD of the landscape varies according to the type of land use (O'Neil et al. 1988; De Cola 1989).

Patch per unit Patch per unit (PPU) is low when the landscape is not fragmented. As the landscape becomes more fragmented, the PPU increases (Frohn 1998).

Landscape shape complexity As an alternative to the FD for quantifying patch shape complexity, patch shape complexity (SqP) has been introduced (Frohn 1998). The SqP considers the perimeter–area relationship for raster data structures and normalizes the ratio of perimeter to area to a value between 0 and 1.

Landscape shape index The landscape shape index (LSI) provides a standardized measure of total edge or edge density that adjusts for the size of the landscape. Because it is standardized, it has a direct interpretation in contrast to total edge. LSI is a measure of patch aggregation or disaggregations. LSI increase leads to an increase in disaggregation.

Floristic data analysis

A total of 95 sample points were chosen for phytosociological data collection. The samples points were randomly distributed covering different fragmented classes to understand their species richness, diversity, and dominance. While sampling, field inventory fragmented categories were combined as interior, patch, and other classes (transitional, edge, perforated, and undetermined). The geographic coordinates of the sample points were generated using the hand-held GPS; the locations for the field plots were reached. Plots (0.1 ha) were laid on the ground at the corresponding location. The field work was conducted from March 2004 to June 2004. Tree girths were measured at 1.3 m from the ground. Specimens identified were confirmed in the herbarium of the Botanical Society of India, Coimbatore and the Rapinat Herbarium, Tiruchirapalli. Of the total 95 plots, 68 plots were evergreen fragments (37, 19, and 12, respectively) and 27 plots were in the semi-evergreen fragment class (15, five, and seven, respectively).

Results

Vegetation types

Major phenological and land-cover types for the KMTR region between 1973 and 2004 are given in Table 1. The changes in vegetation cover based on digital classification shows a significant decrease of evergreen forest mostly to semi-evergreen forest types (Table 2). Of the total area covered by natural vegetation (857 km^2), the evergreen and semi-evergreen forest occupied around 60% of the area. In 1973, evergreen forest constituted 316 km^2, followed by semi-evergreen having 194 km^2. In 2004, the evergreen forest has degraded to 185 km^2 (i.e., it has lost almost 40% of land cover whereas semi-evergreen forest has increased by 36% to 268.1 km^2).

Table 1 Vegetation and land-cover distribution for the KMTR, Southern Western Ghats (India)

S. no.	Types	1973	2004
Phenelogical types			
1	Evergreen	316.72	185.49
2	Semi-evergreen	194.40	268.10
3	Moist deciduous	143.59	135.46
4	Dry deciduous	38.95	96.30
5	Dry evergreen	136.14	57.55
6	Grassland	27.36	75.14
Subtotal		857.16	818.04
Other land-cover types			
7	Shrubs	1.11	17.42
8	Ochlandra	13.56	23.82
9	Orchards	2.33	16.50
10	Fallow/barren	10.04	10.01
11	Water	15.22	21.67
12	Shadow	6.97	0.00
13	Cloud	1.07	0.00
Grand total		907.46	907.46

Landscape analysis

Forest fragmentation

The area under fragmentation in the evergreen forest type showed significant changes between 1973 and 2004 (Table 3). While the interior category decreased from 113.90 km^2 (36%) to 23.27 km^2 (12%) and perforated category decreased from 85.0 to 23.7 km^2, the other categories shows significant increase in fragmentation (patch category 14.82 to 25.3 km^2; edge category 66.8 to 80.15 km^2). There appear to be no significant change in the transitional category. In case of semi-evergreen, almost all categories except the perforated and transitional category showed significant increase (Table 3). Like evergreen forests, in these forests, also the transitional category did not show any significant change during 1973–2004. The perforated category showed a decrease from 60.4 to 31.7 km^2. The TFP of the evergreen forest has decreased by 40%, while the semi-evergreen patch showed an increase of TFP by 36%. A similar trend is also seen in the WFA values of

Table 2 Change matrix for the KMTR between 1973 and 2004, Southern Western Ghats (India)

1973 2004	Evergreen	Semi-evergreen	Others	Total
Evergreen	163.31	124.74	28.67	316.72
Semi-evergreen	21.02	119.19	54.20	194.40
Others	1.16	24.17	371.02	396.34
Total	185.49	268.10	453.88	907.46

evergreen and semi-evergreen forests. Evergreen FC decreased by 88.4%, while the semi-evergreen FC was seen to increase by 77% (Table 4).

Patch analysis

The patch size and distribution for the period of 1973–2004 shows a relative decrease in the number of smaller patches and an increase in the number of larger patches in the evergreen as well as the semi-evergreen type (Tables 5 and 6). In 1973, patches less than 50 ha constituted 7% (131 patches) while those in the 100–500 ha constituted 6.22% (nine patches) of the total evergreen area. Contrastingly, in 2004, the patches less than 50 ha constituted 9.77% (110 patches) and those in the 100–500 ha made up 12.53% (ten patches) of the evergreen forest area. Interestingly, 90% of the patches were greater than 1,000 ha in 1973 (three patches), compared to just 67% in 2004 (four patches). Similarly, in the semi-evergreen forest category, the 1973 data for patches greater than 1,000 ha showed 23% (three patches) while the 2004 data for large area showed 60% (three patches). The results revealed that the distribution of patches could be categorized into four different patterns, namely, large areas covered by lesser number of patches (evergreen forest of 1973), small areas covered by fewer number of patches (evergreen forest of 2004), small areas covered by a large number of patches (semi-evergreen forest of 1973), and small areas covered by the least number of patches (semi-evergreen forest of 2004) as seen in Tables 5 and 6.

Patches having a PA ratio of <0.015 in 1973 were 51% (i.e., 80 patches) compared to just 30% in 2004 (i.e., 42 patches), indicating the contiguity of large patches with lesser perimeter (Tables 5 and 6). In 2004, the tendency toward higher PA ratio (>0.025) was 37.41% (52 patches), compared to 10.83% (17 patches) in 1973. It is observed that complex shapes have increasingly higher PA ratios.

In the case of evergreen forests, FD increased from 1.32 to 1.35, while in case of semi-evergreen, it was constant at 1.37 (Tables 5 and 6). The PPU, which is an indication of clumping, showed an increase in the case of evergreen forest type

Table 3 Forest fragmentation categories for the evergreen and semi-evergreen (1973–2004) in KMTR of Southern Western Ghats (India), area in square kilometers

Sl		1973	2004
Evergreen forest			
1	Interior	113.9 (35.96)	23.27 (12.35)
2	Patch	14.78 (4.67)	25.33 (13.44)
3	Transitional	32.95 (10.40)	31.6 16.76)
4	Edge	66.88 (21.12)	80.15 (42.52)
5	Perforated	85.00 (26.84)	23.73 (12.59)
6	Undetermined	3.12 (1.01)	4.4 (2.33)
Total		316.72	188.49
Semi-evergreen forest			
1	Interior	10.47 (5.39)	29.35 (11.07)
2	Patch	29.56 (15.21)	35.24 (13.29)
3	Transitional	49.55 (25.49)	49.42 (18.64)
4	Edge	44.16 (22.72)	115.28 (43.49)
5	Perforated	60.41 (31.08)	31.69 (11.95)
6	Undetermined	0.25 (0.13)	4.12 (1.55)
Total		194.40	265.10

Values in parentheses indicate the percentage value for each fragment class

Table 4 Forest fragmentation conditions based on TFP and FC for evergreen and semi-evergreen (1973–2004) in KMTR of Southern Western Ghats (India)

	Evergreen		Semi-evergreen	
	1973	2004	1973	2004
TFP	0.355	0.212	0.218	0.298
WFA	274.38	147.06	150.28	207.19
FC	0.043	0.005	0.002	0.009

(1.18E - 07 to 2.17E - 07), while in case of semi-evergreen, the PPU showed a slight decrease from 2.44E - 07 to 2.31E - 07. The SqP in the case of evergreen forests showed an increase from 0.956 to 0.965, while for semi-evergreen it showed a marginal increase from 0.973 to 0.974. The degree of fragmentation indicated by the contagion matrix showed a slight decrease in the case of evergreen forest (0.452 to 0.450), while in case of semi-evergreen, there was an increase from 0.457 to 0.469.

Phytosociological analysis

Based on field data from 95 sample points of 0.1 ha, the tree species richness in evergreen and semi-evergreen showed a total of 339 species from 184 genera distributed in 62 families with a stand density of 560 stems ha^{-1} from 5,317 individuals (Table 7). Of the total 297 tree species observed in the evergreen forest, the interior fragment class had a tree species richness of 204 with a stand density of 705 stems ha^{-1} and 6.27H′ species diversity. While the patch class had 173 tree species with a stand density of 473 stems ha^{-1}, other fragment classes in total had only 126 tree species and a stand density of 435 stems ha^{-1} (Fig. 3). Contrastingly, the semi-evergreen forests of interior fragment class had 176 tree species with a stand density of 589 stems ha^{-1} and a high species diversity of 6.55. Patch and other fragment classes of the semi-evergreen class had a tree species richness of 61 and stand density of 392 and 297 stems ha^{-1} with varying diversity 5.30 and 5.22, respectively. Endemic evergreen tree species in the interior fragment class had high species richness (76) and high stand density (286 ha^{-1}) while, in contrast, the saplings of these systems had 160 individuals of 45 species.

Girth–class distribution for the different fragmented classes showed a uniform decrement with increase in forest fragmentation (Fig. 4). Evergreen forests of the interior category had uniform distribution in its frequency and abundance when compared to the fragmented category, which clearly explains the intactness and contiguity. The total number of plant families for the study site was 57. Euphorbiaceae, with 39 species, constitute an important family of canopy trees dominating the forest locally. Lauraceae (32), Rubiaceae (27), and Meliaceae (18) were the families represented next best, followed by Moraceae (18), Ebenaceae (17), and Myrtaceae (14).

A major dominance of *Cullenia exarillata* was observed in all the fragment categories of evergreen forests, while the interior class of the evergreen forests had a typical community structure

Table 5 Patch characteristics and other landscape metrics analyzed for the evergreen and semi-evergreen forests of KMTR, Southern Western Ghats (India)

Sl	Parameters	Evergreen		Semi-evergreen	
		1973	2004	1973	2004
1	Area (km^2)	290.25	150.14	193.45	229.89
2	Number of patches	157	139	361	199
3	Patch density	0.54	0.93	1.87	0.87
5	Patch size (ha)				
	<50	7.05 (131)	9.77 (110)	24.52 (292)	10.54 (171)
	50 to 100	3.18 (14)	6.58 (14)	10.37 (29)	2.81 (10)
	100 to 500	6.22 (9)	12.53 (10)	32.83 (34)	12.14 (11)
	500 to 1,000	0.00	3.33 (1)	8.87 (3)	13.90 (4)
	>1,000	90.60 (3)	67.79 (4)	23.41 (3)	60.61 (3)
6	Perimeter/area ratio				
	<0.015	50.96 (80)	30.22 (42)	48.75 (176)	14.57 (29)
	0.016–0.020	38.22 (60)	32.37 (45)	41.00 (148)	39.20 (78)
	>0.025	10.83 (17)	37.41 (52)	10.25 (37)	46.23 (92)

Numbers without parentheses indicate the percentage of evergreen forest, while numbers in parentheses indicate the number of patches

Table 6 Patch characteristics and other landscape metrics analyzed for the evergreen and semi-evergreen forests of KMTR, Southern Western Ghats (India)

Type	LSI	Patch cohesion	Contagion	D	PPU	SqP
Evergreen						
1973	16,997.04	99.9976	0.452	1.32	1.1764E - 07	0.965
1998	16,373.33	99.9952	0.450	1.36	2.1697E - 07	0.966
Semi-evergreen						
1973	16,997.04	99.9961	0.457	1.38	2.4433E - 07	0.973
1998	16,373.33	99.9967	0.460	1.38	2.3063E - 07	0.974

dominated by *Cullenia–Myristica–Mesua–Aglaia* and *Palaquium*. This dominance was not seen in the case of the highly fragmented systems. These classes were made up of both primary and secondary species like *Dimocarpus*, *Diospyros*, *Antidesma*, and *Mallotus*. On the other hand, *Mesua*, *Dimocarpus*, *Xanthophyllum*, and *Schleichera* species dominate semi-evergreen forests of the interior fragment. Other fragmented categories of the semi-evergreen forest include dominant species such as *Dimocarpus*, *Kingiodendron*, *Filicium*, *Hopea*, and *Scolopia* (Table 8).

Discussion and conclusions

The method presented in this paper can be easily extended to calculate fragmentation of any land-cover type for its quantification and impact assessment. It is also clearly independent of the scale and pixel size of analysis. Raster land-cover data of any resolution can be used directly. Different window sizes may also be used and may produce significantly different results (see Riitters et al. 1997, 2000, 2002). As such, it is important that decision makers apply the model at

Table 7 Consolidated phytosociological analysis for the evergreen and semi-evergreen forests in different fragment categories identified in the Southern Western Ghats (India)

Fragment class	Total plots	Species richness	No. of individuals	Species diversity	Endemics (species/individuals)		Stand density (ha^{-1})	Basal area (m^2/ha)
Evergreen forest								
Tree analysis								
Interior	37	204	2,609	6.27	76	1,057	705	64.1
Patch	19	173	898	6.53	61	283	473	39.7
Others	12	126	522	6.12	53	183	435	47.0
Total	68	297	4,029		106	1,523	593	54.3
Sapling analysis								
Interior	31	105	352	6.13	45	160	114	0.3
Patch	16	117	367	6.31	45	141	229	0.7
Others	10	78	208	5.87	37	79	208	0.6
Total	57	182	927		76	380	163	0.4
Semi-evergreen forest								
Tree analysis								
Interior	15	176	884	6.55	60	345	589	47.8
Patch	5	61	196	5.30	24	75	392	27.3
Others	7	61	208	5.22	16	68	297	30.3
Total	27	209	1,288		66	488	477	39.4
Sapling analysis								
Interior	15	95	206	6.11	35	85	137	0.4
Patch	5	50	107	5.37	20	45	214	0.6
Others	7	57	158	5.26	21	44	226	0.5
Total	27	137	471		50	174	174	0.5

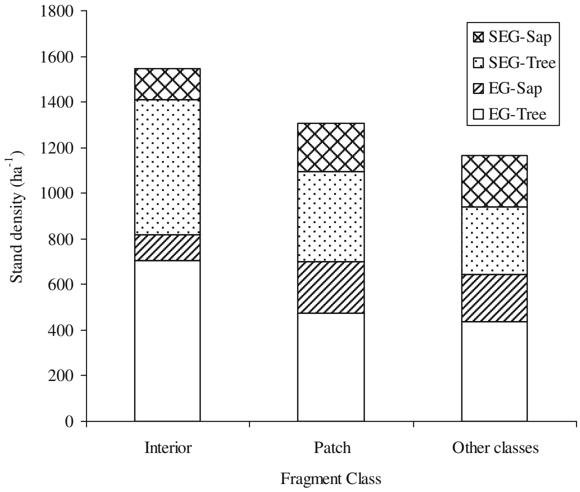

Fig. 3 Tree and sapling stand density based on the number of individuals and its fragment class for the evergreen and semi-evergreen forests in KMTR, Southern Western Ghats (India)

a scale appropriate to the policy under development. Reporting units of any size may be used to summarize fragmentation, which allows for multiscale assessments. Globally, researchers address the patterns of forests fragmentation using land-cover maps (Robinson et al. 1995; Riitters et al. 2000; Wickham et al. 2000, 2007; Southworth et al. 2002, 2004), and at the local scale, address the species loss due to forest fragments (Chittibabu and Parthasarathy 2000; Benitez-Malvido and Martinez-Ramos 2003; Zhu et al. 2004; Laurance et al. 2006; Laurance and Luizão 2007). Very few studies have been conducted in tropical forests to integrate process and function through a combination of land-cover maps derived from satellite image and phytosociological datasets (Jha et al. 2005; Roy et al. 2005; Giriraj 2006). Our study identified the needs of such approaches, which could be a useful tool to develop a combined strategy for protection, restoration, and management of forests—a strategy that includes opportunities for sustainable conservation of biological diversity.

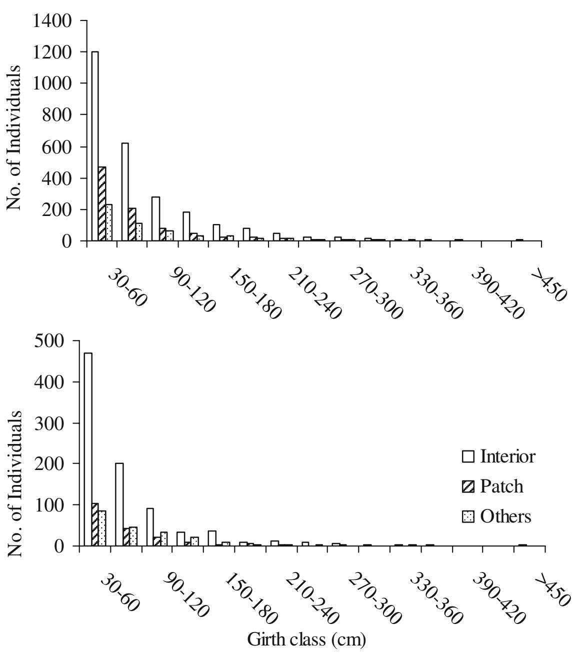

Fig. 4 Forest stand structure based on tree girth frequency in various size classes for the fragment category in KMTR, Southern Western Ghats (India)

Our findings from the fragmentation model in KMTR arise from a study of anthropogenic activities like encroachment, plantations, and selective felling or natural changes like invasion of reed brakes. We observed an increase in fragmentation over time, which might have led to an increase in the isolation of evergreen patches. Decreased patch size might have led to a reduction in the size of populations and to an increased extinction risk to the remaining populations. Furthermore, colonization rates may be reduced in isolated patches (Soons and Heil 2002; Joshi et al. 2006). Intuitively, forests fragmented by anthropogenic sources are at a higher risk of further fragmentation or removal than forests fragmented by natural causes. This isolation of forest patches leads to the negative impact on the stand regeneration and also adversely affects the survival of species, which require contiguous forest patches for their survival and regeneration (Niemi 1998; Laurance et al. 1998a, b, 2002). Most of the disturbance to the forest patches is as a result of indirect anthropogenic pressure rather than direct encroachment or clear felling. This is indicated by the significant increase in the FD, which is a representation of patch shape complexity (Krummel et al. 1987; Díaz-Delgado et al. 2004). Identifying man-made forest fragmentation may be a useful tool for policy and decision makers, allowing for improved risk assessments and better targeting of areas for

Table 8 Ten dominant IVI species in different fragment classes for the evergreen and semi-evergreen forest of Southern Western Ghats (India)

Interior		Patch		Others	
Evergreen forest					
*Cullenia exarillata**	28.20	*Cullenia exarillata**	21.93	*Cullenia exarillata**	31.22
Agrostistachys meeboldii	13.32	*Dimocarpus longan**	19.78	*Dimocarpus longan**	20.19
Syzygium gardneri	9.90	*Euodia lunu-ankenda**	7.87	*Meliosma pinnata*	7.62
*Myristica dactyloides**	9.72	*Acronychia pedunculata*	7.77	*Myristica dactyloides*	7.27
*Mesua ferrea**	9.58	*Diospyros foliolosa*	6.81	*Schleichera oleosa*	7.22
Hopea utilis	9.46	*Sageraea laurifolia*	6.63	*Pterospermum xylocarpum*	6.73
*Aglaia bourdillonii**	8.96	*Hopea parviflora**	6.61	*Mesua ferrea*	5.94
Calophyllum austroindicum	6.91	*Mesua ferrea**	6.32	*Calophyllum austroindicum**	5.36
Dimocarpus longan	6.77	*Mallotus philippensis*	5.86	*Antidesma menasu**	4.92
*Palaquium ellipticum**	5.63	*Hopea ponga*	5.32	*Tricalysia apiocarpa**	4.55
Semi-evergreen forest					
*Mesua ferrea**	15.51	*Dimocarpus longan**	28.96	*Hopea parviflora**	23.07
*Dimocarpus longan**	11.11	*Kingiodendron pinnatum**	22.01	*Syzygium mundagam**	15.77
Kingiodendron pinnatum	9.13	*Filicium decipens**	19.29	*Diospyros paniculata**	14.75
Canarium strictum	6.93	*Vitex altissima*	15.06	*Alstonia scholaris*	13.56
Scolopia crenata	6.24	*Phoebe wightii**	13.51	*Wrightia tinctoria*	12.65
*Xanthophyllum flavescens**	6.11	*Holigarna arnottiana**	10.33	*Eugenia thwaitesii**	11.97
*Myristica dactyloides**	6.05	*Acronychia pedunculata*	10.20	*Dimocarpus longan**	11.66
Syzygium gardneri	5.32	*Scolopia crenata*	9.84	*Garcinia gummi-gutta*	11.57
Symplocos macrocarpa	5.31	*Syzygium caryophyllatum*	8.88	*Acronychia pedunculata*	10.54
*Schleichera oleosa**	5.25	*Symplocos macrocarpa*	8.72	*Alangium salvifolium*	8.94

*Observed species dominant in the structure of the forest during field observation

protection or remediation. The method presented produces data that may be summarized and displayed in a myriad of ways, each of which may be useful to the decision process.

Patch characteristics of 1973 were significantly different in terms of size, proportion, shape, and context from those of 2004 because of type transition like evergreen to semi-evergreen, expansion of *Ochlandra* and orchards. The variation in the physical environment viz., climate, soil, topography, and other landform features might have led to heterogeneous spatial distribution of resources like water, nutrients, and light resulting in the formation of vegetation patches of different characters (Kolasa and Pickett 1991; Burnett et al. 1998; Nichols et al. 1998; Peters and Goslee 2001). In addition, naturally occurring and man-made disturbances also play a vital role in the patch formation and characteristics (Platt 1975; Fuller et al. 1998). Factors such as wildlife grazing, wildlife movement, fuel-wood extraction, fire, and collection of honey and nontimber forest products by local people are also prevalent in different degrees of biotic pressure. The extent of forest and commercial plantation activities and the protection and conservation measures followed in the area also vary in degree and kind.

Remarkably, the contiguous patches of >1,000 ha covered 90% of evergreen forest in 1973 and had less porosity where plantations and anthropogenic pressures are minimal when compared to the data of 2004 which showed a high level porosity of 67%, probably due to *Ochlandra* spread and increased plantations which resulted in the loss of such contiguous patches. The focused priority on conservation of these patches may be helpful to sustain biological diversity, as these patches of evergreen forests provide unique habitats for various endemic plant species and wildlife. These patches may be large enough to allow the natural disturbance regime to operate, maintain characteristic species composition, support mosaics of community formations, and sustain successional patterns and system functions (Pickett and Thompson 1978). The increase in the FD also point out to the fact that the KMTR is constantly under indirect pressure due to the surrounding biotic or climatic/edaphical conditions. Despite legal protection from major human activities, the region is subjected to various processes that ultimately prove detrimental to the sustenance of the native forest system. In this context, the moderate spatial and high spectral resolution data from wide field sensors can be used for the generation of extensive information regarding vegetation area, patch shape and size, fragmentation patterns, and porosity, which are the major indicators of the disturbance and land-use change in a region.

Patch analysis thus provides a simple framework for goal-oriented monitoring and management in a forest landscape that has experienced several degenerative trends, i.e., primary evergreen forests have been replaced by semi-evergreen forests and plantations; structurally complex forests of all ages have been replaced by simplified stands; large, well-connected patches have been replaced by smaller, more isolated patches; infrastructure has been developed in undisturbed landscapes; and natural fires have been suppressed. Several forests in Western Ghats and elsewhere in the tropics have experienced these kinds of changes with a concomitant loss of native biodiversity and ecological integrity (Dutt et al. 2002; Muthuramkumar et al. 2006). It is commonly accepted that species richness reduces with the fragmentation of tropical forests (Lovejoy et al. 1986; Bierregaard et al. 1992; Chittibabu and Parthasarathy 2000; Benitez-Malvido and Martinez-Ramos 2003; Laurance and Luizão 2007). The smaller the fragments are, the less species richness the fragments display (Newmark 1991; Leigh et al. 1993; Laurance 1994; Pither and Kellmann 2002). Research articles related to forest fragments that are published elsewhere mostly focus on various animal groups. Studies on plants related to tropical forest fragments are relatively fewer, although there have been some important ones (Leigh et al. 1993; Turner and Corlett 1996; Oliveira-Filho et al. 1997; Benitez-Malvido 1998; Laurance et al. 1998a, b; Cadotte et al. 2002; Benitez-Malvido and Martinez-Ramos 2003; Muthuramkumar et al. 2006; Laurance and Luizao 2007).

Temporal variation in species diversity can be strongly associated to external disturbances (Holt and Lawton 1994; Chesson et al. 2004). Disturbances like deforestation, fire, and harvest of selective species can strongly influence patterns of species diversity. A buffer of 100 m was analyzed on selected patches to understand the biotic pressure (e.g., orchards, secondary formations like reeds and semi-evergreens) and exchanges among patches, which determine the structure and function of the ecosystem. It reveals that 6.38% of evergreen and 5.13% of semi-evergreen forest have undergone several changes over the period between 1973 and 2004. Other similar attempts were carried out to understand the patch dynamics and biotic exchanges among patches and to determine the ecosystem structure and function (Lewin 1984; Nagendra 2001). High diversity relationships can be explained by the characteristics of the community, the habitat, the disturbance, and the sampling designs (Reice 1985; Noss 1996; Huston 1994; Mackey and Currie 2000, 2001; Giriraj 2006). In the present study, we have focused on the impact of strong local interactions and the increased importance of regional-scale processes of dispersal among the patches in controlling the number of species within a patch. Other similar case studies include those of Caswell and Cohen (1993), Mouquet et al. (2003), Mouquet and Loreau (2003), and He et al. (2005). In this connection, the spatial organization of the patches as identified in the study can form a baseline for continuous monitoring and assessment of the changes in habitat conditions.

Thus, the fragmentation index provides a useful tool for monitoring the changes in the species structure and pattern over time. High species richness and stand density was observed in the interior forest than in the patches and perforated systems (Table 7 and Fig. 3). Similarly, the species composition and abundance in the fragment class of the evergreen forest had made more changes in community structure than in the interior category leading to the replacement of habitat specialist species. The saplings in the evergreen forests of the interior category had lesser stand density than the fragment classes. This might be due to the prevalence of secondary and successional species like *Clerodendron*, *Macaranga*, and *Mallotus* and the creation of large gaps within the patches, which resulted in the formation of deciduous and other invasive species. Thus, ecology of the species groups changed conspicuously with the increase of forest fragments. The heliophilous or pioneer tree species increased and the shade-tolerant species reduced in the fragmented forests. The increased seedling ratio of edge individuals and the reduced level of endemics in the change areas indicate the probability of further transitions that may occur over the coming decades. The present study of forest fragments using remote sensing-based identification in temporal time, in combination with landscape metrics and phytosociological inputs, has helped in delineating areas of biodiversity conservation and prioritization.

Our recommended solution to prevent the loss of species is to establish a network of large protected areas throughout the tropics (Peres 1994). While this is an important goal, some tropical regions have lost so much of their forest cover that there are very few large forest patches remaining (Turner and Corlett 1996). Those large forested areas should remain priorities for conservation (Ghazoul 1996; Gascon et al. 2000), but it is also important to consider the potential role of the other, smaller forest patches which often constitute a large number of the remaining patches in disturbed tropical landscapes.

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