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A comparative analysis of spatial, temporal, and ecological characteristics of forest fires in seasonally dry tropical ecosystems in the Western Ghats, India

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ABSTRACT

The Western Ghats in India is one of the 25 global hotspots of biodiversity, and it is the hotspot with the highest human density. This study considers variations in the regional fire regime that are related to vegetation type and past human disturbances in a landscape. Using a combination of remote sensing data and GIS techniques, burnt areas were delineated in three different vegetation types and various metrics of fire size were estimated. Belt transects were enumerated to assess the vegetation characteristics and fire effects in the landscape. Temporal trends suggest increasingly short fire-return intervals in the landscape. In the tropical dry deciduous forest, the mean fire-return interval is 6 years, in the tropical dry thorn forest mean fire-return interval is 10 years, and in the tropical moist deciduous forest mean fire-return interval is 20 years. Tropical dry deciduous forests burned more frequently and had the largest number of fires in any given year as well as the single largest fire (9900 ha). Seventy percent, 56%, and 30% of the tropical moist deciduous forests, tropical dry thorn forests, and tropical dry deciduous forests, respectively have not burned during the 7-year period of study. The model of fire-return interval as a function of distance from park boundary explained 63% of the spatial variation of fire-return interval in the landscape. Forest fires had significant impacts on species diversity and regeneration in the tropical dry deciduous forests. Species diversity declined by 50% and 60% in the moderate and high frequency classes, respectively compared to the low fire frequency class. Sapling density declined by ca. 30% in both moderate and high frequency classes compared to low frequency class. In tropical moist deciduous ecosystems, there were substantial declines in species diversity, tree density, seedling and sapling densities in burned forests compared to the unburned forests. In contrast forest fires in tropical dry thorn forests had a marginal positive effect on ecosystem diversity, structure, and regeneration.

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1. Introduction

The Western Ghats in India is one of the 25 global hotspots of biodiversity. It is also the hotspot with the highest human density and hence vulnerable to anthropogenic disturbances in the form of grazing, logging, and annual forest fires (Sukumar et al., 2005; Kodandapani et al., 2004). While the process of deforestation has been contained over the years, pressures leading to erosion of forest biomass and local extinctions of species continue (Daniels et al., 1995). Tropical dry forests constitute 40% of all tropical forests, however very few studies have examined the factors that influence the dynamics of these ecosystems (Sukumar et al., 2005). A number of factors including variability in climate, herbivory both by mammals, livestock, and forest fires are some of the important factors responsible for vegetation dynamics in these ecosystems (Goldammer, 1993; Norton-Griffiths, 1979; Silori and Mishra, 2001). The large-scale destruction and transformation of forests into degraded formations through logging and forest fragmentation (Menon and Bawa, 1998); and existing biotic pressures on forests in the form of logging, grazing, and collection of non-timber forest products (Narendran et al., 2001) have rendered forests vulnerable to forest fires. The current distribution of vegetation types in the Western Ghats is a result of gradients in physical site conditions such the elevation, slope-aspect, climate, substrate, and past human disturbances (Pascal, 1986; Chandran, 1993). Many of these physical and environmental characteristics of the landscape in turn affect vegetation flammability and the behavior of fire in the forest (Stott, 2000).

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Over centuries, India's rural communities have created extensive savannas bordering their farmlands through extraction of woody biomass, grazing by livestock and annual dry season fires (Gadgil, 1993; Goldammer, 1988). Fire regimes in terms of the size, frequency, intensity, timing, number of fires, ignition pattern, ecological effects, and behavior are defined within a spatial scale and this provides information in assessing differences in fire regimes (Agee, 1993; Souza, 1984; Wells et al., 2004). Currently, only a mention of forest fires is made in forest working plans, and area burnt in a given year is recorded within these plans (Kodandapani et al., 2004). However, information on the spatial variation of fires in a landscape, the temporal pattern of fires including the fire-return interval, and differences in vegetation characteristics and ecological effects between vegetation types has not been assessed in the Western Ghats, in India. However there are few studies in the Indian subcontinent on some of these aspects of forest fires (Goldammer, 1990; Puyravaud et al., 1995; Saha, 2002; Hiremath and Sundaram, 2005; Sukumar et al., 2005; Sankaran, 2005).

2. Link between fire regimes and field studies

Although various systems have been adopted to study fire regimes (Agee, 1993), for the purpose of this paper we have defined fire regimes by considering differences in disturbance characteristics across forest types. The three forest types found in the study area exhibit differences in species composition, structure, biomass, and forest fuel characteristics. These forest types also constitute about 69% of the forest area in the Western Ghats (Olson and Dinerstein, 2002). Information on various components of the fire regime such as fire frequency, fire size, obtained from satellite data, and fire effects obtained from field studies, have been summarized by forest type. Field studies were conducted to assess this relationship between fire regime and forest type, as defined by differences in fuel composition, fuel loads, and ecosystem effects as defined by forest structure, forest floristics, and regeneration patterns, in each of the three forest types. We hypothesis that spatial and temporal characteristics of current fire regimes in the Nilgiri landscape have lead to a decline in various components of forest biodiversity resulting in impoverished ecosystems. Specifically the objectives of the study are 1. Determine spatial and temporal characteristics of forest fires in three forest types in the Nilgiri landscape. 2. Quantify forest vegetation characteristics in the three forest types in the Nilgiri landscape. 3. Assess the effects of forest fires on woody plant species richness, composition, regeneration, structure, and biomass in the three forest types in the Nilgiri landscape.

3. Humans and fire in the Western Ghats

The causes of forest fires in the landscape are manifold. As in other parts of the World, several factors have contributed to the growing incidence of fire in the forests of the Western Ghats.

3.1. Indigenous communities and fires

Conflicts arise due to resource access and in many instances over the character of a particular resource, whether rangeland or forest. A number of indigenous tribes have lived within forests for many hundreds of years, these tribes collect a number of non-timber forest products (NTFP) from these forests and it is their main source of income (Narendran et al., 2001). However with the control of forests vested in the hand of the states, these communities have been alienated and laws preventing their entry into forests have curtailed their livelihood. Incendiarism has been used as a method to protest against loss of their forest rights.

3.2. Agricultural fires in the Western Ghats

Rural communities collect fuelwood, fodder, NTFP, and graze cattle within forests, the probability of fire introduction into forests is thus very high. Fires are set to destroy crop residues on agricultural fields, this is a fertilizing process and is practiced just before the onset of the southwest monsoon during the months of April and May. About 20% of the annual rainfall is received during these 2 months (Sukumar et al., 2004). The probability of spread of fire from agricultural lands into forest lands has increased with the fragmentation of the landscape and the altered land-use land-cover spatial configuration in the Western Ghats (Kodandapani et al., 2004).

3.3. Fire and forestry

Past forest fire policies that excluded fire from the forest, had their origins in the European forestry model. Two important consequences of this fire policy were immediately apparent. One, the lack of fire lead to the accumulation of fuels within forests and two, opportunities for regeneration of certain timber species especially Sal (*Shorea robusta* Gaertner f.) and teak (*Tectona grandis* L.f.) declined. Thus by 1926 the cycle of fire practices had come full circle. A new policy made provisions for early burning the general practice and to extend complete protection only for special temporary sites. Fire plays an important role in the maintenance and alteration of forest stand composition, regeneration of seedlings within certain dominant forest types. In natural forests, the annual forest fires scorch the seeds of trees such as *T. grandis* and facilitate germination by removing a portion of the seed coat (Seth and Kaul, 1978).

4. Background

4.1. Spatial parameters of fire regimes

The study was located in the Nilgiri Biosphere Reserve (NBR), in the Western Ghats, a region known for high levels of endemism among various taxa (Myers et al., 2000). The contiguous forest area is home to three wildlife sanctuaries, the Mudumali wildlife sanctuary (MWLS), the Bandipur wildlife sanctuary and the Wynaad wildlife sanctuary (Fig. 1) hereafter referred to as Nilgiri landscape. The area of the NBR is 5520 km^2 of which the Nilgiri landscape constitutes 1545 km^2. Human presence within the Nilgiri landscape is almost negligible, as it is a protected area; however it is surrounded by human settlements. The landscape thus offers a unique opportunity to assess the incidence of forest fires as a function of distance from the edge of park boundary. It is unique because of the contiguity of the forests as well as the close juxtaposition with human settlements along most of the park boundary. However, the situation is made possible only when one combines the three wildlife sanctuaries into a single legal unit. Individually, these wildlife sanctuaries have at least one of their boundaries at a significant distance away from human settlements. Another unique attribute associated with the landscape is that these three wildlife sanctuaries are spread across three different states in southern India, namely Karnataka, Tamil Nadu, and Kerala (Nair et al., 1977). The landscape is also extremely diverse in terms of the rainfall pattern, altitude, topography, and edaphic factors, which is reflected in vegetation types, including the tropical moist deciduous forest ecosystems, tropical dry deciduous forest ecosystems, and the tropical dry thorn forest ecosystems.

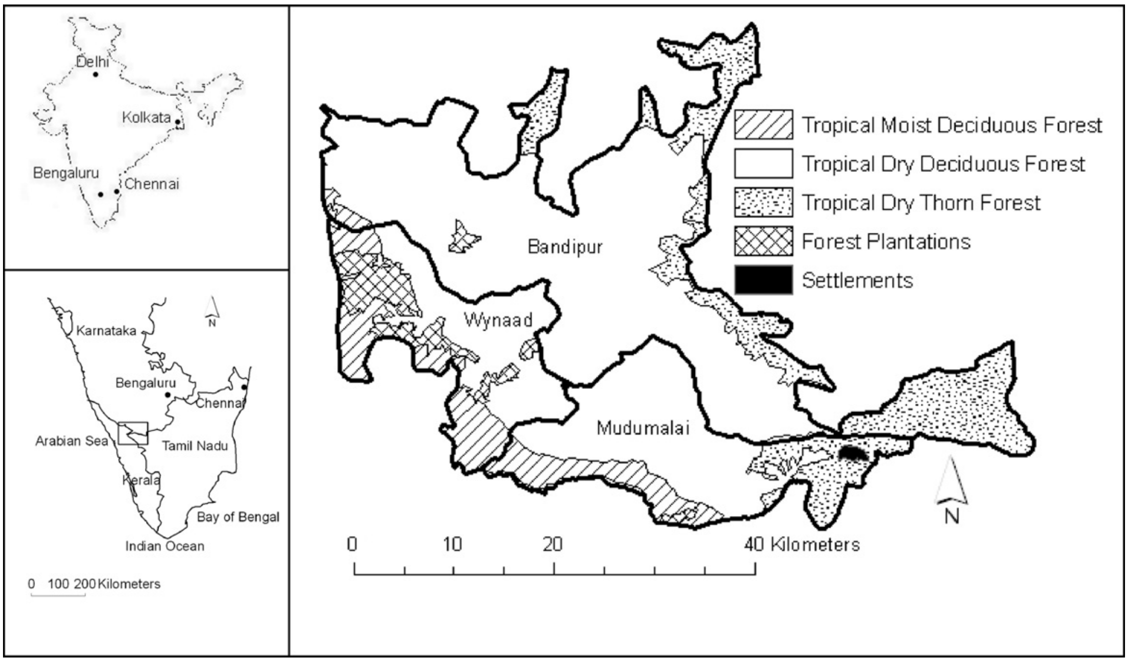

Fig. 1. Map showing the Nilgiri landscape and its location in the Western Ghats, India.

4.2. Vegetation types and forest fires in the Nilgiri landscape

Forest fires in the Nilgiri landscape are mainly surface fires and very rarely canopy fires (Kodandapani et al., 2004). Surface fuels such as the grass fuel loads and the leaf litter are extremely important for the flammability and spread of fires in the ecosystem. The canopy cover, the floristic composition of tree species, and past disturbances in the landscape, influence fuel continuity and determine how easily vegetation may be ignited and the intensity at which it will burn once ignited. The grass fuels are the dominant fuels in the landscape. A brief description of the three vegetation types is provided below.

The tropical dry deciduous forests are by far the largest vegetation type in the Nilgiri landscape, they constitute about 65% of the area in the Nilgiri landscape and rainfall ranges from 1000 to 1500 mm year^{-1}. The floristic composition includes overstorey species such as *T. grandis* (L.f.), *Terminalia crenulata* (Roth.) *Ougeinia oojeinensis* (Roxb.) Hocher., *Diospyros montana* (Roxb.), and *Anogeissus latifolia* (Roxb. ex D.C.) Wall. ex Bedd., the understorey includes several shrubs, herbs as well as grass species such *Themeda cymbaria* (Hack.), *T. triandra* (Forssk.), *Cymbopogon flexuosus* (Nees) Wats., and *Heteropogon contortus* (L.) Beauv. (Suresh et al., 1996). The canopy cover is between 40% and 60%. Due to the marked seasonality in this forest type, trees shed their leaves and are normally dormant between January and May, depending on the onset of the monsoon rains (Murphy and Lugo, 1986; Sundarapandian and Swamy, 1999).

The tropical dry thorn forests constitute about 20% of the area on the Nilgiri landscape. Climatically, this vegetation type receives less rainfall, about 800 mm year^{-1}. The physiognomy of this forest type is short with several species of *Acacia*, including *Acacia chundra* (Willd.) and *A. leucophloea* (Roxb.) Willd. Other species include *Ziziphus mauritiana* (Lam.), *Ziziphus rugosa* (Lam.), *Ziziphus xylopyrus* (Retz.) Willd. There are also several grass species including *H. contortus* (L.) Beauv.

Finally, the tropical moist deciduous forests constitute about 10% of the Nilgiri landscape area. Floristically, this vegetation type is composed of both deciduous and evergreen species. The floristic composition includes *Lagerstroemia microcarpa* (Wt.), *T. crenulata* (Roth.), *T. grandis* (L.f.), *Dalbergia latifolia* (Roxb.), *Lannea coromandelica* (Houtt.) Merrill, *Terminalia bellirica* (Gaertner) Roxb. and *Elaeocarpus tuberculatus* (Roxb.). The canopy cover is between 60% and 80%. The understorey consists of both herbs and grass species such as *T. cymbaria* (Hack.), *Imperata cylindrica* (L.) Beauv., and *C. flexuosus* (Nees) Wats. This vegetation is restricted to the high rainfall regions of the landscape (generally above 1800 mm year^{-1}).

5. Methods

A map of vegetation types in the Nilgiri landscape and maps of fire were overlaid to enable extraction of information on the spatial and temporal characteristics of forest fires across the three vegetation types. All GIS analyses were carried out using ArcInfo (ESRI, 2002) techniques. Vegetation structure, composition, and species diversity of woody plant species were related to the fire history data in 29 belt transects of 500 m $\times$ 10 m in the three vegetation types.

5.1. Vegetation map

The vegetation map obtained from Pascal (1982) is an appropriate level of generalization for the vegetation distribution in the landscape. The scale of the map is 1:250,000. The spatial distribution of vegetation types was digitized from the Mercara-Mysore sheet of the forest map of South India. More detailed descriptions of the methods and data are available elsewhere (Pascal, 1986). Physiognomy or gross morphology, floristic composition, and climate have been incorporated in deriving the map and all these variables are to a large extent responsible for the current fire regime in the landscape (Pascal, 1986). The vegetation classification also reflects the characteristics of fuels in the landscape. Fairly large contiguous areas are also useful in assessing the broad spatial and temporal trends associated with fire occurrence and spread in the landscape. Thus the classification into the tropical dry deciduous forests, the tropical dry thorn forests, and the tropical moist deciduous forests is useful and relevant.

5.2. Delineating forest fires in the Nilgiri landscape

Fire maps for the Nilgiri landscape have been developed from satellite data. Indian Remote Sensing (IRS) satellite imagery was used to classify the burnt and unburnt forest areas. The images were subjected to preliminary processing such as atmospheric and geometric corrections. The IRS-IB LISS I image acquired on 6 March 1996, IRS-IC LISS III image acquired on 22 March 1997, IRS-IC LISS III image acquired on 12 March 1999, IRS-ID LISS III image acquired on 1 March 2001, IRS-IC LISS III image acquired on 24 February 2002, IRS-P6 LISS III image acquired on 9 March 2004, and IRS-P6 LISS III image acquired on 4 March 2005 were used for this purpose. The spatial resolution for these images was 23 m except for the image acquired in 1996, which was 72 m. The 2005 image was georectified using one 1:250,000 scanned Survey of India (SOI) topographic map. The rms error was $\pm$9.21 m or $<$0.40 pixels. The other six images were georegistered to this reference image. The rms errors ranged from $\pm$0.07 to $\pm$0.1 pixels. The cloud cover for each of the scenes was less than 10%. The images were subjected to atmospheric corrections by applying the dark-object subtraction (DOS) method.

A methodology specific to the study area was developed by performing supervised classification by generating training sites from burned areas that we identified on the images. Through an interactive process, we identified spectral signatures of burnt areas in each of the three broad forest types. The advantage of this method over using only a single forest type has been the ability to capture the variability in the spectral signature of burned areas due to differences in the structure, phenology, and exposure to soil fractions in these ecosystems. We delineated fire maps by combining burned areas from each of the three forest types. The fire maps were assessed for their accuracy from field surveyed fire maps of the Mudumalai wildlife sanctuary. The Mudumalai wildlife sanctuary is a long-term ecological research (LTER) site and field surveyed annual fire maps have been maintained since 1989, fire maps were validated with this dataset (Sukumar et al., 1992; Kodandapani et al., 2004).

5.3. Spatial analysis of fire pattern in the Nilgiri landscape

We assessed the spatial pattern of FRI as a function of distance from the Nilgiri landscape boundary. The fire-return interval is the average number of years required to burn an area under consideration, with the understanding that some areas may not burn while other areas may burn more than once during a cycle (Van Wagner, 1978; Cochrane et al., 1999). Buffers of 1 km from the boundary, up to a distance of 11 km, were generated by applying methods of buffer creation in ArcInfo (ESRI, 2002). The area of forest in each buffer distance class (e.g. 0–1, 1–2, 2–3 km, etc.) was then calculated by applying ArcInfo commands (ESRI, 2002). Using the supervised classification method described above, the spatial distribution of surface fires were mapped and the area burnt in each buffer distance class was calculated. Data for all years of the study area were then combined to yield an average burned area for each buffer distance class. The proportion of average burned area in each buffer distance class was estimated. The FRI was obtained for each buffer distance class by calculating the inverse of this proportion and plotted as a function of distance from the Nilgiri boundary.

5.4. Forest structure, diversity, fuel loads, and fire frequency

5.4.1. Transects

Data on woody plant species was collected from belt transects of 500 m $\times$ 10 m in the study areas. Twenty-nine transects were randomly selected in the study area, of which 17 were from the tropical dry deciduous forests, 10 from tropical dry thorn forests, and 2 transects from tropical moist deciduous forests. Methods were adapted from Cochrane and Schulze (1999).

5.4.2. Canopy cover

Along each transect, canopy cover was estimated by collecting canopy pictures using a fish eye lens. Pictures were taken at intervals of 25 m along each transect. The images were later downloaded and analyzed for the canopy cover using gap analysis software (Ter Steege, 1996).

5.4.3. Regeneration of woody plant species

At intervals of 25 m on transects, regeneration of woody plant species was estimated in quadrats of 10 m $\times$ 10 m. There were 20 quadrats in each transect. Data was collected in two size classes 0–5 and 5–10 cm dbh in four sub-quadrats of 25 m^2 each. Mortality of individuals in these two size classes was also recorded along transects.

5.4.4. Species composition

All individuals $\geq$10 cm dbh were enumerated along each transect and identified to species. Species that could not be identified in the field were sampled and pressed for collection and these have been deposited in the herbarium of the field station of the Center for Ecological Sciences, Indian Institute of Science, Masinagudi, India. These specimens were later identified with the help of botanists at the institute.

5.4.5. Fuel composition and fuel load estimation

Fuel load was estimated by applying the modified planar intercept method (Cochrane et al., 1999; Uhl and Kauffman, 1990) at intervals of 25 m along the transect. Fuels data was collected in four size classes 0–0.6, 0.6–2.5, 2.5–7.6, and $>$7.6 cm along a 10.5 m line laid randomly at intervals of 25 m along the transect. These fuel classes correspond to 1, 10, 100, and 1000 h time lags (Pyne et al., 1996). In the fuel size class $>$7.6 cm, apart from recording the number of these logs that intercept the fuel line, diameter measurements of the fuels were also collected. Finally the condition of these fuels, in terms of whether they were sound or rotten, was recorded.

5.4.6. Estimating grass and leaf litter

In the different forest types, we collected grass and leaf litter in 1 m $\times$ 1 m quadrats. The grass and leaf litter were weighed in the field using a balance, they were next packed and transported to the field station where they were first allowed to dry in the open before oven drying at 100 °C for 24 h and weighed again. Leaf fall and curing of fine fuels stretches from January to early March.

5.4.7. Fire history of transects

From information obtained from local forest records, remote sensing data and also the fire mapping exercise, we obtained the fire frequency of each of the 29 transects in the Nilgiri landscape over the period 1989–2005. Twenty-six of the 29 transects were located in the Mudumalai wildlife sanctuary, where spatial information on fire occurrence is available from 1989 to 2005. We classified forest transects under three classes of fire frequency. Transects that burned only once under the category low, transects with frequencies 2, 3, 4, and 5 under moderate fire frequency class, and greater than 5 in high fire frequency class. The fire frequency data corresponds to a 16-year time period. Since, the tropical moist deciduous forests burned rarely, transects were only classified as either burned or unburned.

5.4.8. Statistical tests

Comparison of spatial, temporal, and ecological characteristics were conducted using one-way analysis of variance (ANOVA) followed by Tukey's multiple comparison tests using SPSS (2001).

6. Results

6.1. Spatial and temporal characteristics of fires in the Nilgiri landscape

The fire maps of the Nilgiri landscape provided information on the spatial characteristics of fires as well as inter-annual variability in fire occurrence among the three forest types. The overall accuracy of the fire maps ranged from 85% to 95% of the burnt areas for the 7-year time period.

The temporal pattern of areas burned for each of the three forest types is plotted with the primary *Y*-axis (bar) showing the total area burned (Fig. 2a–c). The mean area burnt in the tropical moist deciduous forest is 770 ± 930 ha, with a mean FRI of 20 years; the mean area burnt in the tropical dry thorn forest is 3200 ± 3180 ha, with a mean FRI of 10 years; the mean area burnt in the tropical dry deciduous forest is 17,000 ± 8700 ha, with a mean FRI of 6 years. The mean area burnt for the entire Nilgiri landscape is 21,600 ± 9700 ha, this translates into a mean FRI of 7 years for the Nilgiri landscape. In the tropical dry deciduous and tropical dry thorn forests at least one out of the 7 years has witnessed >30% of the forest type under fire. However, in the tropical moist deciduous forests, fires seldom burn large areas with only 19% of the forest type under fire in one out of the 7 years.

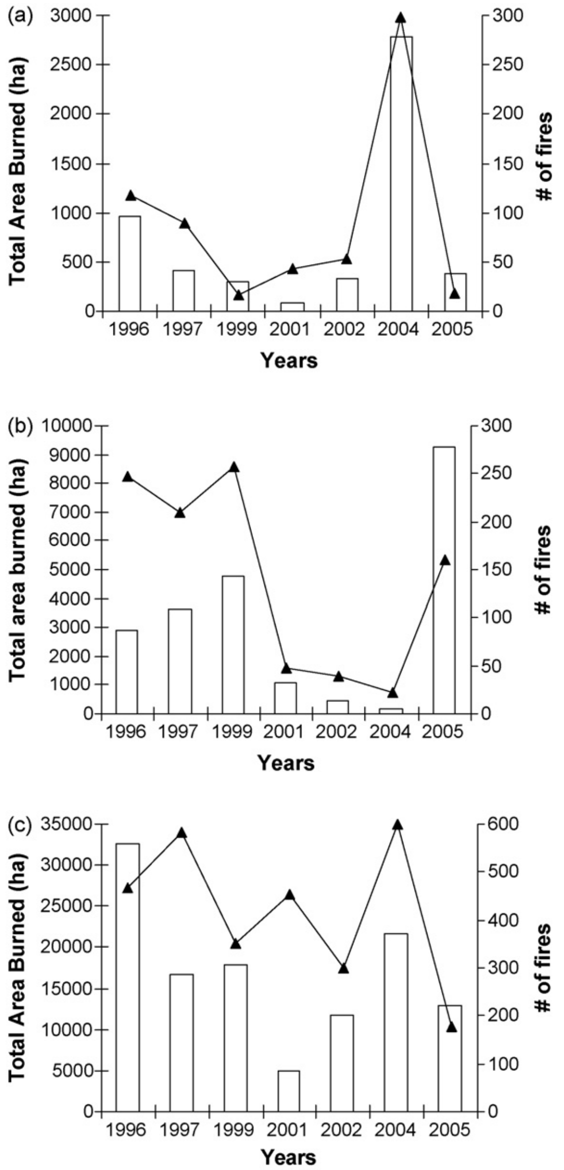

Fig. 2. Spatial and temporal characteristics of forest fires in the Nilgiri landscape. (a) Tropical moist deciduous forests, (b) tropical dry thorn forests and (c) tropical dry deciduous forests.

There is considerable variation in the spatial characteristics of fires in the landscape. Fifty percent or more of the fire polygons in a given year tend to occur in the tropical dry deciduous forests. The mean fire size in the tropical moist deciduous forest was 10 ha, it was two and four times larger in the tropical dry thorn and tropical dry deciduous forests, respectively compared to the tropical moist deciduous forests. The spatial pattern of burnt areas is plotted on the secondary *Y*-axis (line) showing the total number of fires in each of the three forest types (Fig. 2a–c). However, the largest fires (9900 ha in 1996) occurred in the tropical dry deciduous forests followed by the tropical dry thorn forests (3700 ha in 2005) and the tropical moist deciduous forests (1500 ha in 2005). The total area burnt, mean fire size, and maximum fire size were significantly larger in the tropical dry deciduous forests compared to the tropical dry thorn and tropical moist deciduous forests (ANOVA with Tukey's multiple comparisons, $p < 0.01$)

6.2. Fire frequency and forest type

In this analysis the term fire frequency describes the number of times the respective fire polygons have burned during the 7-year period. Fire frequency information was assessed by forest type, the bars show the proportion of area under different fire frequency classes (Fig. 3a–c). About 70% of the tropical moist deciduous forests and 56% of the tropical dry thorn forests have not burnt even once, whereas only 33% of the tropical deciduous forests have not burnt even once. Similarly, tropical dry deciduous forests (34%) and tropical dry thorn forests (18%) have the largest amount of area that has burned more than once and support the highest fire frequencies of seven and five times, respectively, although these high frequencies have very small areas in the landscape.

6.3. Modeling FRI as a function of distance from park boundary

The fire-return interval is long (>10 years) up to a distance of 5 km from the Nilgiri boundary. The negative exponential model provided a function of FRI with increasing distance from the Nilgiri boundary (Fig. 4a), with $F_{1,11} = 15.67$, $r^2 = 0.63$, $p = 0.003$. The area in the buffers ranged from 33,600 to 1600 ha. In the first buffer class, the tropical dry thorn forest constitutes ca. 50% of the buffer area and the tropical moist deciduous forest constitutes ca. 25% of the buffer area and the remaining area is under the tropical dry deciduous forests. In the second buffer class, the tropical dry thorn and the tropical dry deciduous forests each, constitute ca. 40% of the buffer area and the remaining area is under the tropical moist deciduous forests. In buffer classes 3–5 the tropical dry thorn forests and the tropical moist deciduous forests constitute <20% of the buffer area and are absent from buffer class 6. The tropical dry deciduous forest constitutes >50% of the buffer area for buffer classes 3–11 (Fig. 4b). The mean burnt area, as a proportion of buffer area is <5% in all buffer classes, for both the tropical dry thorn and tropical moist deciduous forests. In the tropical dry deciduous forests the proportion of burnt area varies between 2% and 25% for all buffer classes (Fig. 4c).

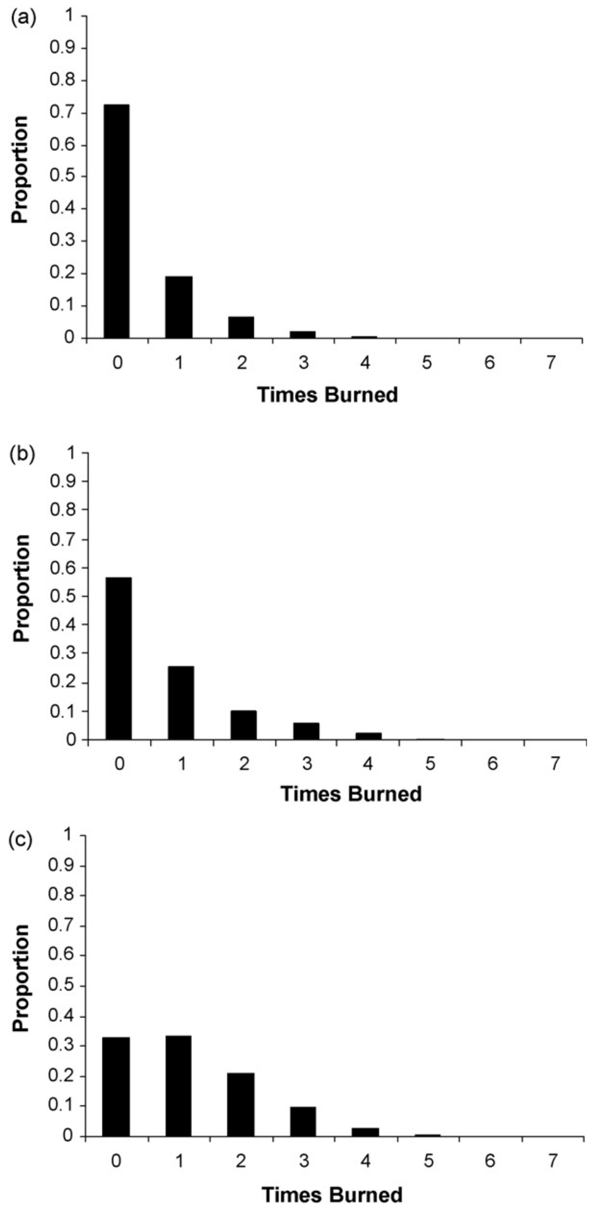

Fig. 3. Fire frequency distributions in the Nilgiri landscape. (a) Tropical moist deciduous forests, (b) tropical dry thorn forests and (c) tropical dry deciduous forests.

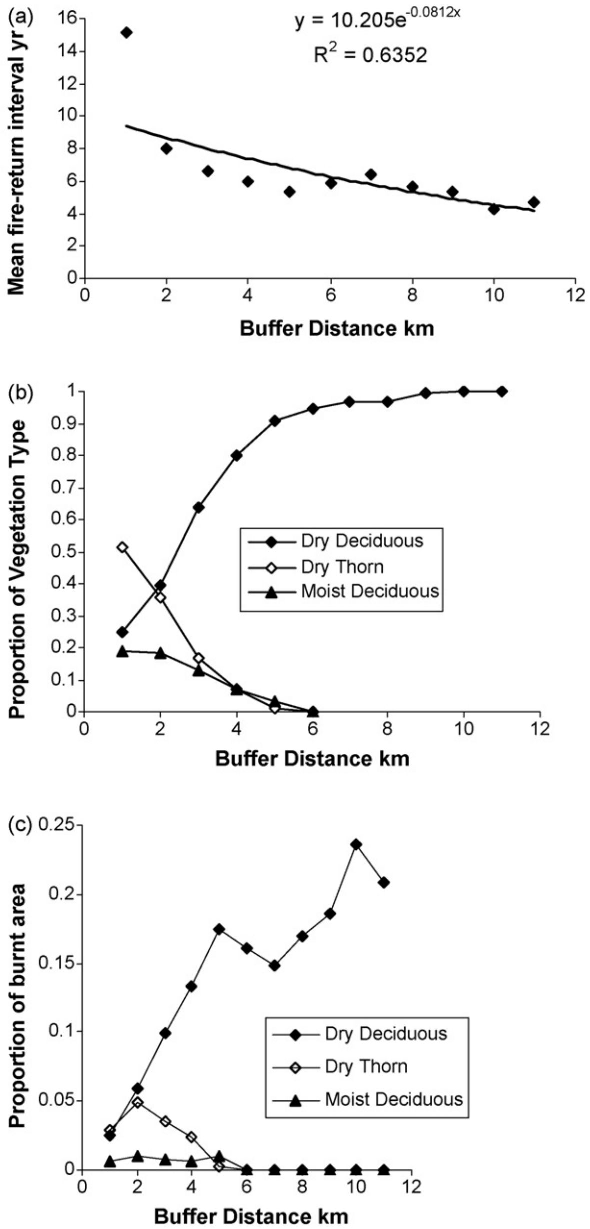

Fig. 4. (a) Fire-return interval as a function of distance from park boundary in the Nilgiri landscape. (b) Proportion of vegetation type in the buffer classes in the Nilgiri landscape. (c) Mean burnt area as a proportion of vegetation type in each buffer class in the Nilgiri landscape.

6.4. Fuel and vegetation characteristics of forests in the Nilgiri landscape

The occurrence and ecological effects of forest fires depend on climate, topography, and fuel loads in the three vegetation types. The vegetation characteristics such as the number of trees, the basal area, the density of seedlings and saplings and fuel composition show interesting differences in the three vegetation types.

6.4.1. Tropical dry deciduous forests

Table 1 summarizes the characteristics of forests in the tropical dry deciduous forests. The number of tree species represented by stems $\geq$10 cm dbh declined by ca. 50% in the moderate fire frequency class and by 60% in the high fire frequency class compared with the low fire frequency stands. Decreases in the number of tree species were followed by declines of ca. 26% decreases in tree density in moderate and high fire frequency classes. The density of seedlings (0–5 cm) dbh of forest species also decreased with increasing fire frequency. Seedling density declined by ca. 30% in both moderate and high fire frequency classes compared to low fire frequency class. The density of saplings (5–10 cm) dbh of forest species also decreased significantly with increasing fire frequency.

Estimated total fuel load ranged from 16 t ha^{-1} for moderate fire frequency class to 23.4 t ha^{-1} for the high fire frequency class. The grass fuel load constitutes 14% of the total fuel load and the litter fuel constitutes 8% of the total fuel load. Although difference in live basal area were not consistent across the three fire frequency classes, total dead basal area, on the other hand increased with increasing fire frequency.

Table 1
Comparison of forest structure and composition among fire classes in tropical dry deciduous forests of Western Ghats, India[a]

	Low fire frequency (n = 3)	Moderate fire frequency (n = 5)	High fire frequency (n = 9)
Tree species (0.5 ha)	33 (2)a	16 (4)b	13 (4)bc
Trees ≥ 10 cm dbh (No. ha^{-1})	441 (58)a	320 (229)a	324 (157)a
Dead standing trees ≥ 10 cm dbh (No. ha^{-1})	44 (9)a	39 (18)a	31 (17)a
Seedlings (No. ha^{-1})	1596 (346)a	1101 (696)a	1120 (526)a
Saplings (No. ha^{-1})	110 (51)a	20 (19)b	26 (23)bc
Fuel load			
1 h fuels (Mg ha^{-1})	1.2 (0.15)a	1.4 (0.8)a	1.5 (0.7)a
10 h fuels (Mg ha^{-1})	0.8 (0.5)a	1.2 (0.7)a	1.2 (0.5)a
100 h fuels (Mg ha^{-1})	3.8 (2.2)a	3.3 (5.5)a	3.2 (3.8)a
1000 h fuels (Mg ha^{-1})	17.5 (5.5)a	16 (20.7)a	14.3 (16)a
Total fuel load (Mg ha^{-1})	23.4 (6.3)a	16 (21)a	20.2 (18.5)a
Basal area (m^2 ha^{-1})	17 (0.5)a	27 (6.3)a	24 (11)a
Basal area dead (m^2 ha^{-1})	1.4 (0.7)a	2.7 (2.7)a	1.7 (1.5)a
Canopy cover (%)	56 (3)a	67 (5)b	66 (6)bc

[a] Means presented with S.D. noted parenthetically. Different letters denote significant differences among stand classes at $p < 0.05$ utilizing Tukey test.

Table 2
Comparison of forest structure and composition among fire classes in tropical dry thorn forests of Western Ghats, India[a]

	Low fire frequency (n = 3)	Moderate fire frequency (n = 4)	High fire frequency (n = 3)
Tree species (0.5 ha)	16 (5)a	19 (3)a	22 (12)a
Trees ≥ 10 cm dbh (No. ha^{-1})	133 (30)a	167 (58)a	137 (44)a
Dead standing trees ≥ 10 cm dbh (No. ha^{-1})	6 (7)a	12 (3)a	11 (11)a
Seedlings (No. ha^{-1})	262 (187)a	478 (236)a	355 (157)a
Saplings (No. ha^{-1})	62 (33)a	80 (40)a	81 (86)a
Fuel load			
1 h fuels (Mg ha^{-1})	0.9 (0.5)a	0.7 (0.1)a	0.5 (0.1)a
10 h fuels (Mg ha^{-1})	0.6 (0.5)a	0.6 (0.5)a	0.5 (0.3)a
100 h fuels (Mg ha^{-1})	0.3 (0.5)a	1.9 (1.7)a	1 (0.9)a
1000 h fuels (Mg ha^{-1})	1.7 (1.7)a	2.8 (2.4)a	2.9 (1.3)a
Total fuel load (Mg ha^{-1})	3.6 (2.1)a	6.3 (3.3)a	4.9 (0.8)a
Basal area (m^2 ha^{-1})	7 (0.5)a	9 (3)a	10 (2)a
Basal area dead (m^2 ha^{-1})	0.3 (0.3)a	0.5 (0.3)a	0.4 (0.5)a
Canopy cover (%)	33 (6)a	40 (9)a	34 (4)a

[a] Means presented with S.D. noted parenthetically. Different letters denote significant differences among stand classes at $p < 0.05$ utilizing Tukey test.

6.4.2. Tropical dry thorn forests

Table 2 summarizes the characteristics of forests in the tropical dry thorn forests. The number of tree species represented by stems ≥10 cm dbh increased by ca. 20% in the moderate fire frequency class and by ca. 40% in the high fire frequency class compared with low fire frequency stands. Increases in the number of tree species were followed by increases in tree density of ca. 26% in moderate and 3% in high fire frequency classes. The density of seedlings (0–5 cm) dbh of forest species also increased with increasing fire frequency. Seedling density increased by ca. 82% and 47% in both moderate and high fire frequency classes, respectively compared with low fire frequency class. The density of saplings (5–10 cm) dbh of forest species also increased by ca. 30% in both moderate and high frequency classes compared with the low frequency class.

Estimated total fuel loads ranged from 3.6 t ha^{-1} in the low fire frequency class to 6.3 t ha^{-1} in the moderate frequency class. The grass fuel constitutes 7% of the total fuel load, and the litter fuel constitutes 4% of the total fuel load. Both live and dead basal area increased with increasing fire frequency. Live total basal area increased by ca. 28% and 42% in the moderate and high frequency classes, respectively compared with low fire frequency class. Dead basal area also increased by 66% and 33% in the moderate and high frequency classes, respectively compared with the low fire frequency class.

6.4.3. Tropical moist deciduous forests

Table 3 summarizes the characteristics of forests in the tropical moist deciduous forests. The number of tree species represented by stems ≥10 cm dbh declined by 8% in the burnt forests compared with unburnt stands. Decreases in the number of tree species were followed by declines of ca. 40% in tree density in burnt forests. The density of seedlings (0–5 cm) dbh of forest species also decreased in burnt forests compared with unburnt forests. Seedling density declined by ca. 63% in burnt forests compared with unburnt forests. The density of saplings (5–10 cm) dbh of forest species also decreased by 66% compared with unburnt forests.

Estimated total fuel load was 54.3 t ha^{-1} in the unburnt forests and 46.5 t ha^{-1} in the burnt forests. Less than 1% of the total fuel load in the unburnt tropical moist deciduous forest is composed of

Table 3
Comparison of forest structure and composition among fire classes in tropical moist deciduous forests of Western Ghats, India

	Unburnt forests (n = 1)	Burnt forests (n = 1)
Tree species (0.5 ha)	26	24
Trees ≥ 10 cm dbh (No. ha^{-1})	496	300
Dead standing trees ≥ 10 cm dbh (No. ha^{-1})	10	10
Seedlings (No. ha^{-1})	6270	2484
Saplings (No. ha^{-1})	528	178
Fuel load		
1 h fuels (Mg ha^{-1})	2.9	3
10 h fuels (Mg ha^{-1})	2.2	2
100 h fuels (Mg ha^{-1})	2.2	12
1000 h fuels (Mg ha^{-1})	47	29.6
Total fuel load (Mg ha^{-1})	54.3	46.5
Basal area (m^2 ha^{-1})	28	32
Basal area dead (m^2 ha^{-1})	0.5	0.5
Canopy cover (%)	78	44

grass fuel, whereas 9% of the total fuel load is composed of leaf litter. In the burnt forests the grass fuel load constitutes 6% of the total fuel load and the leaf litter also constitutes 5.5% of the total fuel load. Although live basal area increased by ca. 14% in the burnt forests, there were no differences in the dead basal areas.

Fifty-three of the 107 tree species studied occur in more than one forest type. Ten species occur in all three forest types, 19 species occur in both tropical moist deciduous forests and tropical dry deciduous forests, 8 species occur in both tropical moist deciduous forests and tropical dry thorn forests, 16 species are common to both tropical dry deciduous and tropical dry thorn forests (Appendix A).

7. Discussion

Although humans had introduced fire in the forests of the Western Ghats at least 3500 years ago (Gadgil and Chandran, 1988), increased fragmentation of forests and continued demand on forest resources has contributed to detrimental changes in the spatial and temporal characteristics of the present fire regime (Kodandapani et al., 2004). An increase in the magnitude of various components of the fire regime has been accompanied by large-scale changes in structure, composition, and regeneration within the forests of the Western Ghats.

The spatial pattern of FRI from the park boundary points to the importance of vegetation characteristics in governing fire occurrence in the landscape. In addition, the periphery of the Nilgiri park boundary, which is spatially proximal to human settlements is vulnerable to the erosion of forest biomass, due to human usage of forest resources. Human disturbances such as logging, grazing, and harvesting of NTFP could be responsible for altering forest fuel characteristics and maintaining these spatial patterns in FRI (Goldammer, 1988). Further, climate in terms of higher mean annual rainfall in the moist deciduous forests, and lower mean annual rainfall in the tropical dry thorn forests is partly responsible for driving these spatial patterns in FRI in the landscape (Holdridge, 1947).

The large number as well as the size of fires in the dry deciduous forests can be explained due to the fuel characteristics especially grass fuels with compact arrangement of fuel particles in the fuelbed (Agee, 2000; D'Antonio and Vitousek, 1992), continuity in fuels (Miller and Urban, 2000), increased mean maximum daily temperature, and enhanced drying solar radiation during the fire season (Stott, 2000). Forest fires in the tropical dry deciduous forests have drastically altered the species diversity, structure, and regeneration within these forests. These results are consistent with findings of fire effects in other forests across the globe. Studies in the Amazon have shown that canopy cover, living biomass, and living adult tree densities declined with increasing fire frequency/intensity and were as low as 10–30% compared with unburned forests (Cochrane and Schulze, 1999; Gerwing, 2002). Recent studies in a 50 ha plot in the study area, have revealed the pronounced effects of fire especially on the lower size classes (1–10 cm dbh) in the forest (John et al., 2002). One estimate of mortality rates between 1988 and 1996 in the 50 ha plot showed disproportionate high mortality rates for stems 1–10 cm dbh of −79%, compared with −13.1% for stems >10 cm dbh; fire was the leading cause of mortality, accounting for as much as 15% of the annual mortality for the 1–10 cm dbh stems (Sukumar et al., 2005). The recurrent fires could result in increased dominance in these and similar forests in the Western Ghats, trees with either thick barks or resprouting mechanisms would proliferate (Hegde et al., 1998; Holdsworth and Uhl, 1997; Pinard and Huffman, 1997). Again in the 50 ha plot, >99% of recruitment has been through vegetative means (Sukumar et al., 2005).

Forest fires are rare in undisturbed moist deciduous forests, however past disturbance histories such as logging have now rendered the disturbed moist deciduous susceptible to fires (Woods, 1989). Once disturbed, the understorey of these forests are invaded by grass species, rendering the forests vulnerable to forest fires (Suresh et al., 1996; Freifelder et al., 1998). Despite, the altered fuel composition, the magnitude of various components of the fire regime is small compared with tropical dry deciduous forests. However, anomalies in climate could render these forests extremely vulnerable to fire events leading to large fires as seen in the year 2005 (Barlow and Peres, 2004; Siegert et al., 2001). A recent study of the Indian summer monsoon, has indicated a declining trend in both early and late monsoon rainfall and number of rainy days, this would increase the vulnerability of these forests to forest fires (Ramesh and Goswami, 2007). The severe decline in canopy cover, adult tree density, seedling, and sapling density in burnt forests are consistent with studies in other moist forests. For example fire in the wet forests of Malaysia resulted in declines of density of saplings (2.5–10.0 cm dbh) by >80%, fire induced significant loss to canopy cover, species richness, and increased colonization by pioneer species (Woods, 1989). Due to the disturbances such as forest fires and logging in this ecosystem the species composition has been altered and species predominantly found in the dry deciduous forests such as *Casia fistula* (L.), *A. latifolia*, *Xeromphis spinosa* (Thunb.) Keay are now found in this vegetation type (Daniels et al., 1995; Hegde et al., 1998).

In contrast to fires regimes in the tropical moist and dry deciduous forests, forest fires in tropical dry thorn forests are characterized by intermediate magnitude in various components of the fire regime. In addition forest fires could actually be having a net beneficial effect on the species diversity, composition, structure, and regeneration. The low fuel loads and also the low productivity (Mishra, 1983) in these ecosystems could result in patchy, low intensity fires (Oesterheld et al., 1999). These fires could actually be recycling nutrients back into the soil, mitigating invasive species, reducing flammability of vegetation, and promoting regeneration of seedlings and saplings (Goldammer, 1988). The conversion of these forests through their usage by humans for many millennia could have resulted in a significant influence on selection of fire tolerant species (Goldammer, 1988; Hegde et al., 1998). Studies in the Western Ghats have shown that bark thickness and occurrence of gum and resins contribute to the better survival or reproduction of tree species found in tropical dry thorn forests (Hegde et al., 1998). Similar effects of fire on species richness and regeneration have been reported in other ecosystems (Marozas et al., 2007).

7.1. Fire and forest management

The management of fire and vegetation in the forests of the Western Ghats has a long history. While fuelbreaks are the common method of fire management in several forests in the Western Ghats, prescribed burning can also be applied to reduce the high fuel loads and high intensity wildfires. The short FRI in the tropical dry deciduous forests has resulted in poor regeneration among several species, reducing the flammability of vegetation through prescribed burning or through the establishment of fuelbreak systems could result in improved fire management in these ecosystems (Goldammer, 1988). The fires in tropical dry deciduous forests are of high severity, wildfires are larger and of higher intensities because of higher total and dead fuel loads and greater horizontal fuel continuity. Prescribed burning especially under moist conditions could be pursued in the tropical dry deciduous forests to reduce fuel loads and create a spatial mosaic of fuel loads distribution, subsequent fires would maintain this mosaic. Fires in tropical moist deciduous forests are sporadic and patchy, fires can be managed in this ecosystem through natural or human created firebreaks. Prescribed burning in the tropical moist deciduous forests may not be an option because the period for adequate burning between moist and dry conditions could be narrow. Grazing by cattle is the tropical dry thorn forests is prevalent, the implications of grazing in reducing potential wildfire fuels and wildfire risk is unclear. Integrating information on FRI and spatial characteristics of fires in the three vegetation types along with their vegetation characteristics would reverse the deleterious effects of these fires on forest biodiversity in the Nilgiri landscape.

7.2. Forest fires and conservation

The current study provides a framework under which forest fires can be evaluated in human dominated Old World Tropics. It is important to characterize spatial and temporal variability of fires in the landscape and assess the response of biota to these changes. Quantifying the fire regime by vegetation type or some other representative ecological unit would provide insights into similarities and differences in fire regimes in a landscape. These fire regimes in themselves could be altering the composition of vegetation in these forests as well as promoting the invasion of species, such as *Lantana camara* (L.) and *Eupatorium odoratum* (L.) (Hiremath and Sundaram, 2005). Further in the Western Ghats in India, the human dimensions of fire use have to be integrated into forest fire studies. Indigenous communities and rural communities living at the edge of forests have used fire to alter vegetation characteristics for thousands of years (Gadgil and Chandran, 1988). About 35% of villages in India are classified as forest villages, where forest resources are important for the livelihoods of villagers. The results of this research suggest that all fire in a landscape need not have negative effects on the ecosystem. Remote sensing and GIS methods are very useful to assess spatial and temporal characteristics of fire regimes and must become an integral part of fire management. The current research suggests that fire management policies should take into account the variability in fire regimes, ecological characteristics of species, and past fire histories before fire management policies are outlined.

8. Conclusions

Forest fires are recurrent disturbance events in seasonally dry ecosystems of the Western Ghats. However the spatial and temporal characteristics of these forest fires exhibit considerable variation and are related to their vegetation characteristics, apart from variations in climate and topography. The spatial pattern of FRI in the study area emphasizes the differences in fire regimes across the three vegetation types. The short FRI in tropical dry deciduous ecosystems and increased susceptibility of tropical moist deciduous to forest fires have resulted in deleterious effects on composition, structure, and regeneration within these forests. Forest policies in the Western Ghats should recognize these inherent differences in fire regimes and ecological effects among vegetation types. Humans have used fires to alter vegetation characteristics for many thousands of years in the Western Ghats. Integrating human dimensions of fire use in the landscape would reduce the magnitude in spatial and temporal characteristics of fires, resulting in improved conservation of these forests.

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Appendix A. List of species found in the transects in the Nilgiri landscape

Code	Botanical name	Distribution
ACAC	*Acacia chundra*	c
ACAF	*Acacia ferruginea*	c
ACAL	*Acacia leucophloea*	c
ACTM	*Actinodaphne malabarica*	a
ALBA	*Albizia amara*	c
ANOL	*Anogeissus latifolia*	b, c
APHP	*Aphanamixis polystachya*	a
ATLW	*Atalantia wightii*	c
AZAI	*Azadirachta indica*	c
BAUR	*Bauhinia racemosa*	c
BAUS	*Bauhinia species*	b
BISJ	*Bischofia javanica*	b
BOMC	*Bombax ceiba*	b, c
BOMM	*Bombax malabaricum*	a, b
BRIR	*Bridelia retusa*	a, b, c
BUTM	*Butea monosperma*	b, c
CAND	*Canthium dicoccum*	c
CANP	*Canthium parviflorum*	c
CAPZ	*Capparis zeylanica*	c
CARA	*Careya arborea*	b
CASE	*Casearia esculenta*	b
CASF	*Cassia fistula*	a, b, c
CASO	*Casearia ovata*	a
CHLS	*Chloroxylon swietenia*	c
CINM	*Cinnamomum malabathrum*	a
CLES	*Clerodendrum serratum*	a
CORO	*Cordia obliqua*	a, b, c
CORW	*Cordia wallichii*	b, c
DALL	*Dalbergia latifolia*	a, b, c
DALL	*Dalbergia lanceolaria*	a, c
DICC	*Dichrostachys cinerea*	c
DILP	*Dillenia pentagyna*	a
DIOM	*Diospyros montana*	b, c
EHRC	*Ehretia canarensis*	c
ELAG	*Elaeodendron glaucum*	b, c
ELAT	*Elaeocarpus tuberculatus*	a, b
ERIQ	*Eriolaena quinquelocularis*	b
ERYI	*Erythrina indica*	b
ERYM	*Erythroxylum monogynum*	c
FICD	*Ficus drupacea*	a, b
FICH	*Ficus hispida*	c
FICT	*Ficus tsjahela*	a
FICR	*Ficus religiosa*	a, c
FLAI	*Flacourtia indica*	b, c
GARP	*Garuga pinnata*	a, b
GART	*Gardenia turgida*	b
GIVR	*Givotia rottleriformis*	b, c
GLOM	*Glochidion malabaricum*	a, b
GMEA	*Gmelina arborea*	b, c
GREO	*Grewia orbiculata*	b, c
GRET	*Grewia tiliifolia*	a, b
HALC	*Haldina cordifolia*	a
HARB	*Hardwickia binata*	c
HOPP	*Hopea parviflora*	a
HYMO	*Hymenodictyon orixense*	b
IXON	*Ixora nigricans*	a, c
KYDC	*Kydia calycina*	b
LAGL	*Lagerstroemia lanceolata*	a, b
LAGP	*Lagerstroemia parviflora*	a, b
MITP	*Mitragyna parvifolia*	a, c
MACP	*Macaranga peltata*	a

Appendix A (*Continued*)

Code	Botanical name	Distribution
MADI	*Madhuca indica*	b, c
MADL	*Madhuca longifolia*	b, c
MANI	*Mangifera indica*	a
MAYE	*Maytenus emarginata*	b, c
MELP	*Meliosma pinnata*	a
MORO	*Moringa oleifera*	c
NARC	*Naringi crenulata*	c
OUGO	*Ougeinia oojeinensis*	b
OLED	*Olea dioica*	a
OLEG	*Olea glandulifera*	a
PERM	*Persea macrantha*	a
PHYE	*Phyllanthus emblica*	a, b, c
PRET	*Premna tomentosa*	b, c
PTEM	*Pterocarpus marsupium*	a, b, c
RADX	*Radermachera xylocarpa*	a, b
RAND	*Randia dumetorum*	a, b
SANA	*Santalum album*	c
SAPE	*Sapindus emarginatus*	a, c
SCHO	*Schleichera oleosa*	a, b
SCHS	*Schrebera swietenioides*	a, b
SCOC	*Scolopia crenata*	a
SHOR	*Shorea roxburghii*	b
STEA	*Stereospermum atrovirens*	b, c
STEG	*Sterculia guttata*	a
STEP	*Stereospermum personatum*	a, b
STEU	*Sterculia urens*	a, b
STRP	*Strychnos potatorum*	a, c
SYZC	*Syzygium cumini*	a, b, c
TAMI	*Tamarindus indica*	c
TECG	*Tectona grandis*	a, b, c
TERB	*Terminalai bellirica*	a, b
TERC	*Terminalia crenulata*	a, b
TERCH	*Terminalia chebula*	a, b, c
TERP	*Terminalia paniculata*	a
TERT	*Terminalia tomentosa*	a, b
TODA	*Toddalia asiatica*	a
UNI1	*Unidentified species*	a, c
UNI2	*Unidentified species*	c
UNI3	*Unidentified species*	a
VIBP	*Viburnum punctatum*	a, b
VITA	*Vitex altissima*	a
WRIT	*Wrightia tinctoria*	a, c
XERS	*Xeromphis spinosa*	a, b
ZIZM	*Ziziphus mauritiana*	c
ZIZR	*Ziziphus rugosa*	b, c
ZIZX	*Ziziphus xylopyrus*	a, b, c

a, tropical moist deciduous; b, tropical dry deciduous; c, tropical dry thorn.

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