Research Article

Contrasting Fire Regimes in a Seasonally Dry Tropical Forest and a Savanna Ecosystem in the Western Ghats, India

Narendran Kodandapani

Asian Nature Conservation Foundation
III Floor Biological Sciences Building
Center for Ecological Sciences
Indian Institute of Science
CV Raman Avenue, Bangalore 560012, India

Tel.: 91-80-23315490; e-mail: naren@ces.iisc.ernet.in

ABSTRACT

Tropical dry forests and savannas constitute more than half of all tropical forests and grasslands, but little is known about forest fire regimes within these two extensive types of ecosystems. Forest fire regimes in a predominantly dry forest in India, the Nilgiri landscape, and a predominantly savanna ecosystem in the Sathyamangalam landscape, were examined. Remote sensing data were applied to delineate burned areas, determine fire size characteristics, and to estimate fire-rotation intervals. Belt transects (0.5 ha) were used to estimate forest structure, diversity, and fuel loads. Mean area burned, mean number of fires, and mean fire size per year were substantially higher in the Nilgiri landscape compared to the Sathyamangalam landscape. Mean fire-rotational interval was 7.1 yr in the Nilgiri landscape and 44.1 yr in the Sathyamangalam landscape. Tree (≥10 cm diameter at breast height) species diversity, tree density, and basal area were significantly higher in the Nilgiri landscape compared to the Sathyamangalam landscape. Total fuel loads were significantly higher in tropical dry and moist deciduous forests in the Nilgiri landscape, but total fuel loads were higher in the tropical dry thorn forests of the

RESUMEN

Los bosques tropicales secos y las sabanas constituyen más de la mitad de todos los bosques y pastizales tropicales; sin embargo, se conoce muy poco sobre los regímenes de fuego en esos extensos ecosistemas. En este trabajo, se examinaron los regímenes de fuego en un bosque tropical, el paisaje de Nilgiri, y en un ecosistema de sabana en el paisaje Sathyamangalam, ambos en la India. Se utilizaron datos de sensores remotos para delinear áreas quemadas, determinar las características del tamaño de los incendios y para estimar sus intervalos de rotación. Se usaron transectos en fajas (0.5 ha) para estimar la estructura forestal, la diversidad y la carga de combustibles. Las medias de área quemada, número de incendios y tamaño de los incendios por año fue substancialmente mayor en el paisaje de Nilgiri comparado con el de Sathyamangalam. El intervalo medio entre incendios fue de 7.1 años en el paisaje de Nilgiri y de 44.1 años en el de Sathyamangalam. La diversidad, densidad y área basal de los árboles (≥10 cm de diámetro normal) fueron significativamente mayores en el paisaje de Nilgiri que en el de Sathyamangalam. Las cargas totales de combustible fueron significativamente mayores en los bosques tropicales secos y húmedos en el paisaje de Nilgiri, aunque la carga total de combustibles fue mayor en el bosque tropical espinoso seco

Sathyamangalam landscape. Thus, the two landscapes revealed contrasting fire regimes and forest characteristics, with more and four-fold larger fires in the Nilgiri landscape. The dry forests and savannas could be maintained by a combination of factors, such as fire, grazing pressures, and herbivore populations. Understanding the factors maintaining these two ecosystems will be critical for their conservation.

en el paisaje de Sathyamangalam. Ambos paisajes revelaron características estructurales y regímenes de incendios diferentes, con más eventos de fuego de hasta cuatro veces más tamaño en el paisaje de Nilgiri. Los bosques secos y sabanas podrían mantenerse mediante una combinación de factores tales como el fuego, la presión de pastoreo y la población de herbívoros. El entendimiento de los factores que mantienen esos dos ecosistemas será crítico para su conservación.

Keywords: conservation, India, fire regimes, fire-rotation interval, fire size

Citation: Kodandapani, N. 2013. Contrasting fire regimes in a seasonally dry tropical forest and a savanna ecosystem in the Western Ghats, India. Fire Ecology 9(2): 102–115. doi: 10.4996/fireecology.0902102

INTRODUCTION

The Indian sub-continent is extremely diverse in terms of climate, vegetation type distribution, and flammability of vegetation types. Vegetation types range from alpine ecosystems to tropical rainforests (Ravindranath and Sukumar 1998). The rich biological diversity in the forests of India has resulted in four regions (Western Ghats, Himalayas, Indo Burma, and Sundaland) being designated as hotspots of biodiversity among 34 global hotspots (Mittermeier *et al.* 2005). Carbon dating of charcoal from the Western Ghats indicates forest burning as early as 5000 yr BP (Chandran 1997). Fire continues to be an annual feature of many landscapes and there are several causes for it (Kodandapani *et al.* 2008). Fires set in agricultural landscapes to clear land of crop residues escape into adjoining forest areas (Saha 2002). Shifting cultivation that slashes and burns vegetation to clear land is extensively practiced in parts of northeastern India, as well as in central parts of India (Ravindranath and Sukumar 1998). Fires enter forests through incendiarism and accidental fires (Kodandapani *et al.* 2008). Prescribed burning to create forage in grasslands and savannas for certain wildlife species also results in fire introduction within adjacent forests (Landsberg and Lehmkuhl 1995). Fires are also introduced into forests by various indigenous communities to aid in the collection of non-timber forest products (Narendran *et al.* 2001, Saha 2002).

Four Spatial Clusters of Fire in Indian Ecosystems

Variation in fire ecology within India is best described by four geographic clusters. The first cluster is in northwest India, where fires occur in the coniferous forests of species such as fir, spruce, and pine in the Himalayan region. Here fire is applied by local communities to clear needles and grass and to enhance regeneration within the forest (Joshi 1991, Bahuguna and Upadhyay 2002). The second spatial cluster occurs in northeast India, where fires are predominantly due to slash and burn agriculture, also known as *jhum*, in the tropical evergreen forests, montane forests, subtropical forests, and moist deciduous forests. Close to 50% of all forest fires in India occurs in this cluster (Bahuguna and Upadhyay 2002). Between 1989 and 1995, 1000 km^2 of forests were brought under shifting cultivation in the seven northeastern states of India (Raman 2007). In recent years, the increasing human population is forcing a reduction in the time between fires (*jhum* cycle) from 20 yr to 30 yr, to 5 yr (Puri *et al*. 2011). The third spatial cluster occurs in central parts of India, and these fires are mainly due to slash and burn agriculture, as well as to the use of fire for the collection of non-timber forest products, such as *Madhuca indica* J.F. Gmel. and *Diospyros melanoxylon* Roxb., by indigenous communities (Saha 2002). Fires in this cluster are extensive within the tropical moist deciduous forests. The fourth spatial cluster occurs in southern India, in the Western and Eastern Ghats, and these fires are predominantly due to accidents, fires set for forest management purposes, incendiarism, and slash and burn in parts of the Eastern Ghats (Kodandapani *et al*. 2004, 2008; Vadrevu *et al*. 2006; Bhadarinath *et al*. 2011; Renard *et al*. 2012). In this cluster, fires are predominantly in tropical dry deciduous forests, tropical dry thorn forests, tropical moist deciduous forests, and, to a smaller extent, in the tropical evergreen forests.

Seasonally dry tropical forests (hereafter dry forests) are extensive and widespread globally and also within India. These forests constitute >40% of the tropical forests of the world (Furley 2007). Dry forests have both a grass layer and a tree layer. In contrast, savannas are predominantly a grassy layer with a discontinuous tree layer. These savannas constitute ~20% of the vegetated land surface in the tropics (Bond and Parr 2010). Although fire has been documented as a regular part of these dry forests and savannas, there is uncertainty regarding the magnitude of various components of the fire regime (Higgins *et al.* 2007). Further, at local scales, the processes contributing to their distribution are unknown (van Wilgen *et al*. 2004). While successional concepts have been put forward to explain the distribution of dry forests and savannas in the Western Ghats (WG) (Pascal 1986), little attention has been given to the effect of processes like fire on successional states (Warman and Moles 2009).

The objectives of this study were to: (1) estimate the magnitude of the various components of the fire regime in two landscapes of dry forest and savanna; and (2) examine forest characteristics and fuel load composition in the two landscapes.

STUDY AREAS

The study areas were located in the WG biodiversity hotspot (Figure 1), one of 34 global hotspots of biodiversity (Mittermeier *et al.* 2005), and the one with the highest human density (Cincotta *et al.* 2000). The WG covers only 5% of India's total land area, but contain more than 4000, or 27%, of the country's total

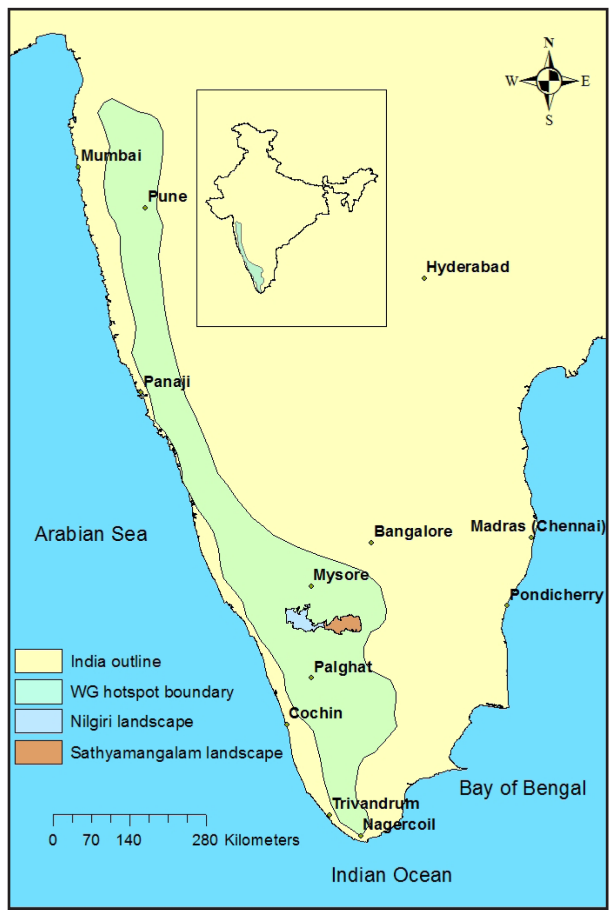

Figure 1. Location of the Nilgiri and Sathyamangalam landscapes in the Western Ghats of India.

plant species. The WG hotspot boundary extends for 160 000 km^2 that stretch for 1600 km along the west coast of southern peninsular India, on average 40 km inland from the shore line, from 21° N to 8° N. The Nilgiri landscape, a dry forest ecosystem, (latitude 11° 32' N to 11° 59' N, longitude 76° 12' E to 76° 52' E), and the Sathyamangalam landscape, a savanna ecosystem (latitude 11° 29' N to 11° 49' N, longitude 76° 50' E to 77° 28' E) were chosen for the study (Figure 1). Each landscape covers ~1500 km^2. Elevation of the Sathyamangalam landscape varies from 233 m to 1727 m. The elevation of the Nilgiri landscape varies from 0 m to 1450 m. Mean annual precipitation (MAP) in the Nilgiri landscape ranges from 600 mm to about 2000 mm. In the arid Sathyamangalam landscape, MAP ranges from 600 mm to 1100 mm, exceeding 1000 mm only at higher elevations. Sathyamangalam was a forest reserve before conversion to a wildlife sanctuary in 2008 (Reddy *et al*. 2012).

Forest Types in the Nilgiri Landscape

Tropical dry deciduous forests are by far the largest vegetation type in the Nilgiri landscape and constitute about 65 % of the area, with MAP ranging from 1000 mm to 1500 mm. The floristic composition includes overstory species such as *Tectona grandis* L.f., *Terminalia crenulata* Roth, *Ougeinia oojeinensis* (Roxb.) Hocher., *Diospyros montana* Roxb., and *Anogeissus latifolia* (Roxb. ex D.C.) Wall. ex Bedd. The canopy cover ranges between 40 % and 60 %. The understory includes several shrubs and forbs 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). Shrubs include *Indigofera pulchella* Roxb., *Helicteres isora* L. and *Grewia hirsuta* Vahl. (Prasad 2012). In addition, *Lantana camara* L. occurs across the landscape. 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 (Sundarapandian and Swamy 1999).

Tropical dry thorn forests constitute about 20 % of the area on the Nilgiri landscape. Climatically, this vegetation type receives MAP of about 800 mm. 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., and *Ziziphus xylopyrus* (Retz.) Willd. There are also several grass species including *Heteropogon contortus.* Shrubs such as *Ziziphus* spp., *Canthium* spp., and *Randia* spp. are distributed in these forests (Prasad 2012).

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., *Terminalia crenulata*, *Tectona grandis*, *Dalbergia latifolia* Roxb., *Lannea coromandelica* (Houtt.) Merrill, *Terminalia bellirica* (Gaertn.) Roxb., and *Elaeocarpus tuberculatus* Roxb. The canopy cover is between 60 % and 80 %. The understory consists of both forbs and grass species such as *Themeda cymbaria*, *Imperata cylindrica* (L.) P. Beauv., and *Cymbopogon flexuosus*. Exotic species such as *Lantana camara*, *Eupatorium odoratum* L., *Ageratum conyzoides* L., and *Parthenium hysterophorus* L. also occur in the landscape. This vegetation is restricted to the high rainfall regions of the landscape (generally above 1800 mm yr^{-1}).

Forest Types in the Sathyamangalam Landscape

In the Sathyamangalam savanna landscape, the three dominant forest types are the tropical dry thorn forests, the tropical dry deciduous forest, and the tropical moist deciduous forest.

The tropical dry thorn forests are the largest vegetation type in the Sathyamangalam landscape and constitute about 50 % of the area in the landscape. Its MAP is between 600 mm and 1000 mm. The canopy cover is between 30 % and 40 %. The floristic composition includes *Albizia amara* (Roxb.) Boiv., *Acacia* spp., *Erythroxylon monogynum* Roxb., and *Catunaregam dumetorum* (Lam.) Tirven.

The deciduous forests, both tropical moist deciduous and tropical dry deciduous, constitute 18 % and 24 % of the landscape, respectively, and are distributed at higher elevations, between 900 m and 1350 m. The MAP is >900 mm in these two forest types. Typical species include *Anogeissus latifolia*, *Tectona grandis*, and *Terminalia* spp. In addition, there are patches of tropical evergreen forests and high elevation grasslands (Reddy *et al*. 2012).

METHODS

Remote Sensing of Burned Areas

Fire maps for both the landscapes were developed from satellite data. For the Nilgiri landscape, remote sensing data from seven years between 1996 and 2005 were used to delineate annually the burned and unburned areas. Indian Remote Sensing (IRS) satellite imagery was used to classify the burned and unburned forest areas. The images were subjected to preliminary processing such as atmospheric and geometric corrections. The IRS-IB LISS I image acquired on 6 Mar 1996; the IRS-IC LISS III images acquired on 22 Mar 1997, 12 Mar 1999, 1 Mar 2001, and 24 Feb 2002; and the IRS-P6 LISS III images acquired on 9 Mar 2004 and 4 Mar 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 a 1:250 000 scanned Survey of India (SOI) topographic map. The root mean square (rms) error was ±9.21 m or <0.40 pixels. The other six images were georegistered to this reference image. The rms errors ranged from ±0.07 pixels to ±0.1 pixels.

For the Sathyamangalam landscape, 16 yr of remote sensing data were used to delineate the burned and unburned areas. The IRS-IC LISS III images acquired on 1 Mar 1997, 22 Mar 1998, and 21 Mar 1999; the IRS-ID LISS III images acquired on 24 Apr 2000, 15 Mar 2001, 28 Feb 2002, and 10 Mar 2003; and the IRS-P6 LISS III images acquired on 14 Mar 2004, 13 Feb 2005, 28 Mar 2006, 23 Mar 2007, 22 Feb 2008, 16 Feb 2009, 7 Mar 2010, 2 Mar 2011, and 25 Feb 2012 were used for this purpose. The 2012 image was georectified using a 1:250 000 scanned Survey of India (SOI) topographic map. The rms error was ±11 m or <0.50 pixels. The other 15 images were georegistered to this reference image, with rms errors ranging from ±0.05 pixels to ±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 (Kodandapani *et al*. 2008).

Estimating Mean Fire-Rotation Interval (mFRI) Maps

The fire-rotation 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, Agee 1993, Cochrane *et al*. 1999). Data for all years of the two landscapes were then combined to yield the number of times an average pixel burned over the 7 (Nilgiri) or 16 (Sathyamanglam) sampled periods. An overall mFRI was calculated by first calculating a weighted average of the number of fire occurrences per hectare (number of times pixels burned multiplied by the proportion of the whole landscape that was burned 0, 1, 2… times over the sample periods) and then calculating the inverse of this proportion. A pixel-level mFRI was calculated for each pixel by tallying the number of times a pixel burned, and dividing that by the number of sample periods.

Sampling Forest Characteristics

Transects. Data on woody plant species were collected from belt transects of 500 m × 10 m in the study areas. In the Sathyamanglam landscape, 16 transects were from the tropical dry deciduous forests, 10 from the tropical dry thorn forests, and 9 transects from the tropical moist deciduous forests. In the Nilgiri landscape, 17 transects were enumerated in the tropical dry deciduous forests, 10 transects from the tropical dry thorn forests, and 2 transects from the tropical moist deciduous forests. Methods were adapted from Cochrane and Schultz (1999).

Species composition. All individual trees ≥10 cm diameter at breast height (dbh) were enumerated along each transect and were identified to species.

Fuel composition and fuel load estimation. At intervals of 25 m along the transect, fuel load was estimated by applying the modified planar intercept method (Uhl and Kauffman 1990, Cochrane *et al*. 1999). Fuels data were collected in four size classes (0 cm to 0.6 cm, 0.6 cm to 2.5 cm, 2.5 cm to 7.6 cm, 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 hr, 10 hr, 100 hr, and 1000 hr time lags (Pyne *et al*. 1996). In the fuel size class >7.6 cm, both the number and diameter of logs that intercept the fuel line were recorded. Finally the condition of these fuels, in terms of whether they were sound or rotten, was recorded.

Statistical Analysis

Student's *t*-test was conducted to assess differences in the means of the forest characteristics in the different forest types. Comparisons among fire sizes were carried out using ANOVA. Linear regressions were carried out to assess significant trends in area burned in the two landscapes. All analysis was conducted in the statistical software R (R-Project 2006).

RESULTS

Fire Regimes

The Nilgiri and Sathyamangalam landscapes showed no trend in either the area burned per year ($P > 0.05$) or in the number of fires ($P > 0.05$) (Figure 2). Annual fire frequency in the Nilgiri landscape was 650 ±232,

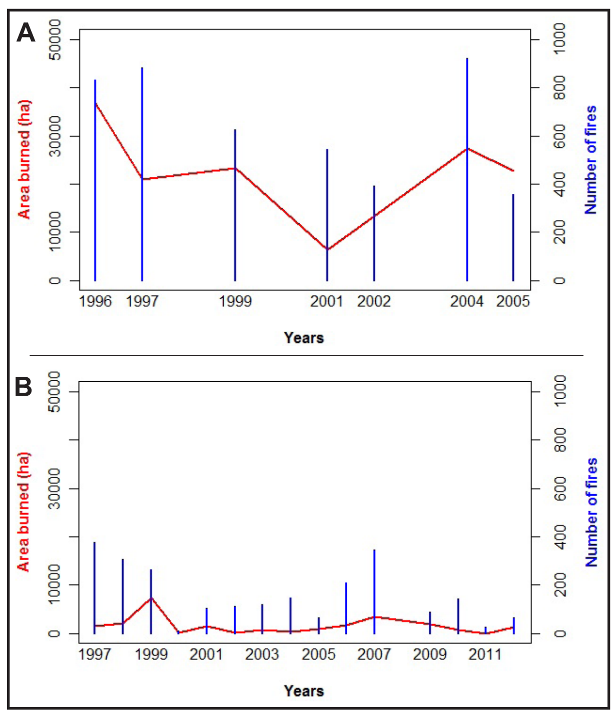

Figure 2. (A) Area burned (red line) and number of fires (blue bars) in the Nilgiri landscape (1996 to 2005). (B) Area burned (red line) and number of fires (blue bars) in the Sathyamangalam landscape (1997 to 2012).

compared to 159 ±115 for the Sathyamangalam landscape (Figure 2). Mean fire rotational intervals (mFRI), the time required to burn the equivalent of the total landscape area, was 7.1 yr for the Nilgiri landscape and 44.1 yr for the Sathyamangalam landscape.

There is substantial spatial heterogeneity in the pattern of fire across the two landscapes (Figure 3). When mean FRI is calculated on a pixel basis, some pixels in the Nilgiri landscape burned in all seven periods (mFRI = 1) while others did not burn at all during the study period (Table 1). Fire activity is scattered across the whole of the Nilgiri landscape, but

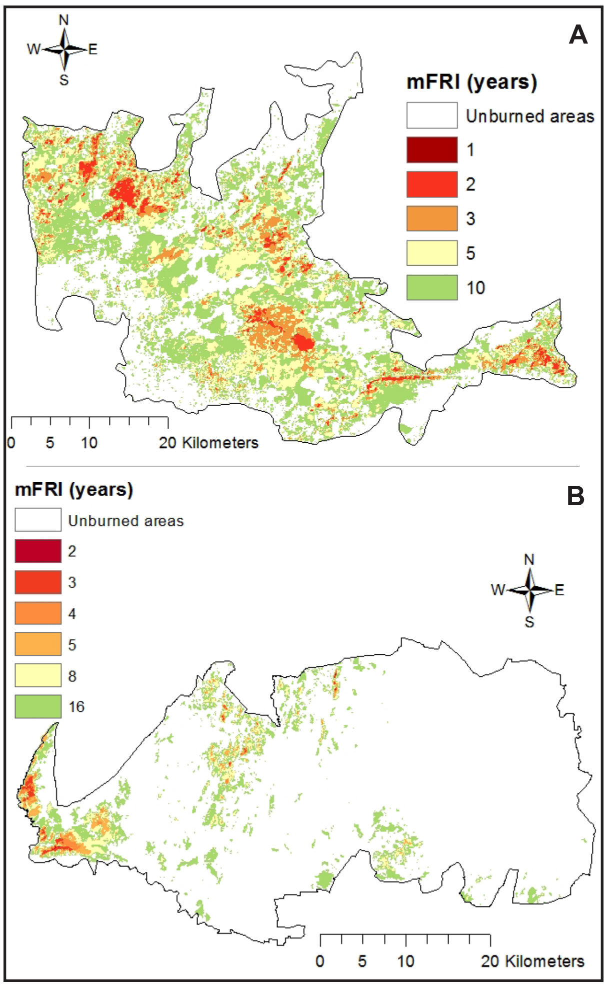

Figure 3. (A) Spatial pattern of mean FRI in the Nilgiri landscape (1996 to 2005). (B) Spatial pattern of mean FRI in the Sathyamangalam landscape (1997 to 2012).

Table 1. Area burned (ha) over the 7 sample periods for the Nilgiri landscape and 16 sample periods for the Sathyamangalam landscape. The Nilgiri and Sathyamangalam landscapes encompass 154 500 ha and 152 900 ha, respectively.

Times burned	Landscape area burned (ha)	
(*n*)	Nilgiri	Sathyamangalam
0	64 708	128 480
1	47 304	9 500
2	26 437	5 903
3	11 935	4 553
4	3 392	2 571
5	614	1 286
6	104	500
7	6	107

there is a clear east-west gradient visible in the Sathyamangalam landscape. About 84 % of the area in the Sathyamangalam landscape did not burn, whereas 42 % of the area did not burn in the Nilgiri landscape (Table 1).

A small percentage of fires in both landscapes account for the bulk of area burned. In the Nilgiri landscape, 10 % of the fires accounted for 90 % of the burned area, while in the Sathyamangalam landscape, 10 % of fires accounted for 86 % of the burned area. In both landscapes, small fires ≤10 ha are abundant (Figure 4). Mean fire size was significantly higher ($P = 0.002$) at 30 ha in the Nilgiri landscape compared to 10 ha in the Sathyamangalam landscape. At 9 921 ha, the largest fire size in the Nilgiri landscape was four-fold larger than the 2 425 ha for the largest fire in the Sathyamangalam landscape.

Analysis of Forest Characteristics in the Two Landscapes

Tree species diversity, density of trees, basal area, and fuel loads were higher in the Nilgiri landscape compared to the Sathyamangalam landscape (Table 2). Tree species richness in the analyses by individual vegetation type followed a similar pattern (Tables 3

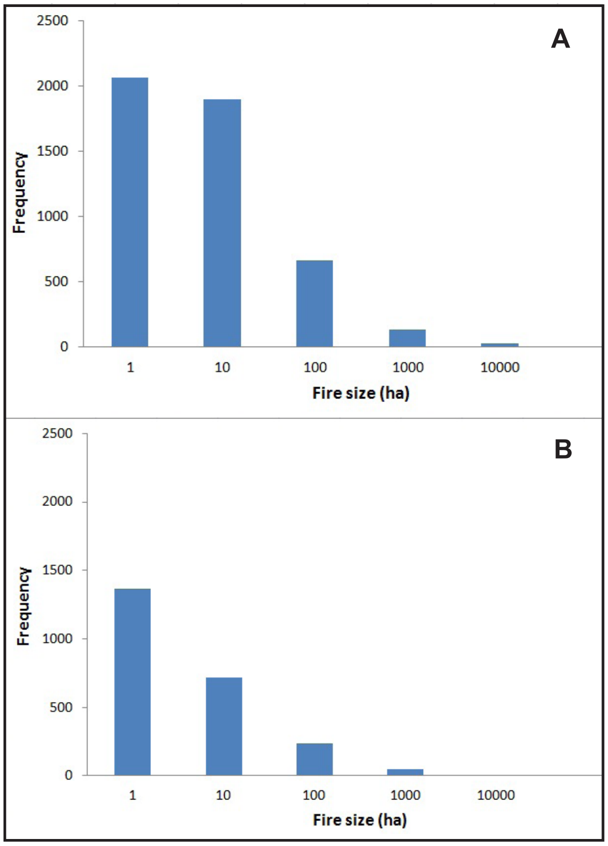

Figure 4. (A) Frequency distribution of fire size in the Nilgiri landscape (1996 to 2005). (B) Frequency distribution of fire size in the Sathyamangalam landscape (1997 to 2012).

Table 2. Weighted averages of forest characteristics and fuel loads in the Nilgiri (1996 to 2005) and Sathyamangalam (1997 to 2012) landscapes.

	Landscape	
	Nilgiri	Sathyamangalam
Tree species richness (no. per 0.5 ha)	18.4	13.6
Trees ≥10 cm dbh (ha^{-1})	280.0	147.0
Basal area (m^2 ha^{-1})	19.0	8.5
1 hr fuels (Mg ha^{-1})	1.3	0.7
10 hr fuels (Mg ha^{-1})	1.0	1.9
100 hr fuels (Mg ha^{-1})	2.9	8.6
1000 hr fuels (Mg ha^{-1})	12.5	5.2
Total fuels (Mg ha^{-1})	17.7	16.3

through 5). The weighted mean of tree density in the Nilgiri landscape was higher than in the Sathyamangalam landscape (Table 2). The individual vegetation types showed a similar trend (Tables 3 and 4). However, tree density in the tropical moist deciduous forests in the two landscapes was similar (Table 5).

The weighted mean of basal area in the Nilgiri landscape was higher than in the Sathyamangalam landscape (Table 2). The individual vegetation types showed a similar trend (Tables 3 through 5).

The weighted mean of 1 hr forest fuels in the Nilgiri landscape was double that in the Sathyamangalam landscape (Table 1). The 1 hr forest fuels were higher in the tropical dry deciduous forest and the tropical moist deciduous forests in the Nilgiri landscape compared

Table 3. Forest characteristics and fuel loads in tropical dry deciduous forests in the Nilgiri (1996 to 2005) and Sathyamangalam (1997 to 2012) landscapes. Means are presented with standard deviations, utilizing Welch's *t* test.

	Landscape	
	Nilgiri	Sathyamangalam
Tree species richness (no. per 0.5 ha)	17.1 ±8.4*	12.3 ±4.9
Trees ≥10 cm dbh (ha^{-1})	343 ±167***	122 ±66
Basal area (m^2 ha^{-1})	23.8 ±8.8***	5.5 ±3.3
1 hr fuels (Mg ha^{-1})	1.44 ±0.65***	0.68 ±0.3
10 hr fuels (Mg ha^{-1})	1.1 ±0.6**	1.7 ±0.78
100 hr fuels (Mg ha^{-1})	3.4 ±4*	7.8 ±6
1000 hr fuels (Mg ha^{-1})	15.3 ±15**	2.0 ±2.8
Total fuels (Mg ha^{-1})	21.3 ±17*	12.3 ±8

* = 0.05
** = 0.01
*** = 0.001

Table 4. Forest characteristics and fuel loads in tropical dry thorn forests in the Nilgiri (1996 to 2005) and Sathyamangalam (1997 to 2012) landscapes. Means are presented with standard deviations, utilizing Welch's *t* test.

	Landscape	
	Nilgiri	Sathyamangalam
Tree species richness (no. per 0.5 ha)	19.2 ±6.8**	11.3 ±4.4
Trees ≥10 cm dbh (ha^{-1})	148 ±45**	93 ±49
Basal area (m^2 ha^{-1})	8.7 ±2.3***	3.0 ±2
1 hr fuels (Mg ha^{-1})	0.7 ±0.3ns	0.5 ±0.2
10 hr fuels (Mg ha^{-1})	0.6 ±0.4	1.6 ±0.7***
100 hr fuels (Mg ha^{-1})	1.2 ±1.3	7.4 ±8**
1000 hr fuels (Mg ha^{-1})	2.5 ±1.7ns	4.5 ±7
Total fuels (Mg ha-1)	5.1 ±2.5	14.0 ±15*

* = 0.05
** = 0.01
*** = 0.001
ns = not significant

Table 5. Forest characteristics and fuel loads in tropical moist deciduous forests in the Nilgiri (1996 to 2005) and Sathyamangalam (1997 to 2012) landscapes. Means are presented with standard deviations, utilizing Welch's *t* test.

	Landscape	
	Nilgiri	Sathyamangalam
Tree species richness (no. per 0.5 ha)	25 ±1.4**	18.6 ±4
Trees ≥ 10 cm dbh (ha^{-1})	398 ±139	248 ±133
Basal area (m^2 ha^{-1})	30 ±2.8*	19.7 ±13.2
1 hr fuels (Mg ha^{-1})	2.95 ±0.1***	1 ±0.5
10 hr fuels (Mg ha^{-1})	2.1 ±0.1ns	2.3 ±1.4
100 hr fuels (Mg ha^{-1})	7.1 ±6.9ns	11.2 ±10.8
1000 hr fuels (Mg ha^{-1})	38.3 ±12.3ns	11.5 ±16.1
Total fuels (Mg ha^{-1})	50.4 ±5.5**	24.2 ±23.6

* = 0.05
** = 0.01
*** = 0.001
ns = not significant

to the Sathyamangalam landscape (Tables 3 and 5). In the tropical dry thorn forests, 1 hr fuels did not significantly differ between the two landscapes (Table 4). The weighted mean of 10 hr and 100 hr forest fuels in the Nilgiri landscape was less than for the Sathyamangalam landscape (Table 2). The masses of both size classes of fuel were higher in the tropical dry deciduous forests and the tropical dry thorn forests of the Sathyamangalam landscape compared to the Nilgiri landscape (Tables 3 and 4), but there were no differences for the tropical moist deciduous forests of the two landscapes (Table 5).

The weighted mean mass of 1000 hr forest fuels in the Nilgiri landscape was higher than in the Sathyamangalam landscape (Table 2). The 1000 hr fuels were significantly higher in the tropical dry deciduous forests in the Nilgiri landscape compared to the Sathyamangalam landscape, but were not significantly different in the tropical dry thorn forests and tropical moist deciduous forests in the two landscape (Tables 3 through 5).

The weighted mean mass of the total fuel loads was higher in the Nilgiri landscape than in the Sathyamangalam landscape. Total fuels were significantly higher in the tropical dry deciduous forests and the tropical moist deciduous forests in the Nilgiri landscape compared to the Sathyamangalam landscape (Tables 3 and 5). The total fuel load was substantially higher in the tropical dry thorn forests in the Sathyamangalam landscape compared to the Nilgiri landscape (Table 4).

DISCUSSION

Forest fires are annual disturbance events in the two landscapes dominated by dry forests and savannas in the WG (Kodandapani *et al*. 2004). Contrasting fire metrics occurred across the two landscapes, especially with reference to the mFRI, the mean fire size, and the largest fire size in the two landscapes. The fire size distribution was similar in both of the landscapes, in the sense that small fires (≤10 ha) are abundant. Although the two landscapes are different in terms of their protected area histories, this alone may not be the chief reason for the large differences in the magnitude of the forest fire regimes. A combination of climate, fuels, and topography, as well as ignition sources, could be driving these patterns of wildland fires in the two landscapes (Renard *et al*. 2012).

Productivity is higher in the Nilgiri landscape, whereas the low rainfall in the Sathyamangalam landscape has resulted in the domination of tropical dry thorn forests. The higher fuel loads in the tropical deciduous forests in the Nilgiri landscape could be driving the frequent fires in the Nilgiri landscape, as the mean fire-return interval is seven times more frequent than for the Sathyamangalam landscape. In the Sathyamangalam landscape, most fires occur in the tropical deciduous forests that are found at medium elevations, which receive higher rainfall. A few high elevation grassland patches (Sukumar *et al*. 1995) are also distributed in the Sathyamangalam landscape. The higher dead fuel loads in the tropical dry thorn forests in the Sathyamangalam landscape could be due to the higher biotic pressures in the forests (Reddy *et al*. 2012).

The two adjacent landscapes provide contrasting spatial patterns of fire. Although MAP declines considerably as one moves east into the Sathyamangalam landscape, several tree species are common to both landscapes. While certain studies (Bond and Parr 2010) tend to classify similar sparsely treed landscapes as savannas, the present classification into dry forests in the Nilgiri landscape and savanna in the Sathyamangalam landscape is important, and reflects local variations in fire regimes. While it is true that both landscapes have been subjected to logging activities in the past, there are significant differences in the structure and diversity of forests in the two landscapes (Sukumar *et al*. 2005; Kodandapani *et al.* 2008).

Anthropogenic ignitions are common in tropical ecosystems. Both in the Nilgiri and the Sathyamangalam landscapes, this is the dominant ignition source. An important reason for the distinct spatial patterns of fire activity in the two landscapes could be the road network in the two landscapes. In the Nilgiri landscape, ~50% of the forest area is within 1 km of the road network, whereas in the Sathyamangalam landscape, ~30% of the landscape is within 1 km of the road network. Earlier studies have demonstrated that the presence of roads increases human pressures on wildlands and, therefore, possible causes of ignitions by accident and negligence (Renard *et al.* 2012). The large fires in the Nilgiri landscape can be attributed to the fine (grass and litter) fuel loads; they constitute about one-quarter of the total fuel loads in the landscape (Kodandapani *et al.* 2008). The road connectivity and the fine fuel continuity in the Nilgiri landscape could be driving these spatial patterns of fire in the Nilgiri landscape (Kodandapani *et al.* 2008). Fire suppression is less developed in Indian forest ecosystems, as the only methods for fire suppression are through forest fuelbreaks and early detection using forest watch towers, and resources are meagre for these activities. Besides, almost all fire management efforts occurs post-fire in Indian ecosystems. Hence, fire suppression may not be an important factor in driving these distinct spatial patterns of fire activity in the two landscapes.

From a conservation perspective, sustaining these dry forests and savannas is important as they harbour high biodiversity of not only plant species, but are also a preferred habitat for several endangered animals such as the Asian elephant (*Elephas maximus*) and the tiger (*Panthera tigris*). Further, these two landscapes form a crucial connecting link for species migrations between the Western and Eastern Ghats (Reddy *et al.* 2012). Compared to tropical rainforests, where several studies have been conducted on biodiversity, these dry forests have not been studied extensively and require new studies. While it is true that several dry forests in India and elsewhere in the tropics are a result of human transformations (Gadgil 1993), dry forests and savannas are natural ecosystems that evolved several millennia ago (Cerling *et al.* 1997). C4 grasses that are commonly found distributed in dry forests and savannas evolved under low CO_2 concentrations, wherein this photosynthetic pathway had an advantage. However, under increasing CO_2 concentrations, as projected by several General Circulation Models, these ecosystems could be under threat as a result of CO_2 fertilization and consequent replacement of grassy biomes by forests (IPCC 2007, Bond and Parr 2010).

The management of fire and vegetation in the forests of the WG has a long history (Kodandapani *et al*. 2008). While fuelbreaks are the common method of fire suppression in several forests in the WG, different views have been put forth regarding the management of fire in Indian ecosystems. Some research indicates that fire has been part of Indian ecosystems for several millennia, and that fire prevention has lead to the proliferation of invasive species, which ironically has increased the frequency of fires in ecosystems (Sundaram and Hiremath 2005). However, other studies show that increased fire frequency in the Nilgiri landscape did not have an impact on the abundance of *Lantana camara* (Prasad 2012). Despite these views, it is clear that there is a need for more scientific research on fire regimes and forest characteristics at various scales to strengthen our understanding of ecological processes. Developing similar maps of fire-rotation intervals for Indian forests would provide valuable information on the mixed fire regimes, similar to the research conducted in the Pacific Northwest forests (Agee 1993).

ACKNOWLEDGEMENTS

I would like to thank the forest departments of Karnataka, Tamil Nadu, and Kerala for permission to conduct this research. I would like to acknowledge the support received from Mr. N. Satheesh and Mr. A.S. Singhar of the Tamil Nadu forest department for research in the Sathyamangalam landscape. Mr. B. Vinoth provided research assistance in Sathyamangalam. I would also like to thank Prof. R. Sukumar and Dr. C. Arivazhagan for their support. I thank Dr. J. Lehmkuhl and two anonymous reviewers for comments and helpful suggestions on earlier versions of this manuscript.

LITERATURE CITED

Agee, J.K. 1993. Fire ecology of Pacific Northwest forests. Island Press, Washington, D.C., USA.

Badarinath, K. V.S., A.R. Sharma, and S.K. Kharol. 2011. Forest fire monitoring and burnt area mapping using satellite data: a study over the forest region of Kerala State, India. International Journal of Remote Sensing 32: 85−102. doi: 10.1080/01431160903439890

Bahuguna, V.K., and A. Upadhyay. 2002. Forest fires in India: policy initiatives for community participation. International Forestry Review 4: 122−127. doi: 10.1505/IFOR.4.2.122.17446

Bond, W.J., and C.L. Parr. 2010. Beyond the forest edge: ecology, diversity and conservation of grassy biomes. Biological Conservation (Special Issue) 143: 2395–2404. doi: 10.1016/j.biocon.2009.12.012

Cerling, T.E., J.M. Harris, B.J. MacFadden, M.G. Leakey, J. Quade, V. Elsenmann, and J.R. Ehlerlinger. 1997. Global vegetation change through the Miocene/Pliocene boundary. Nature 389: 153–158. doi: 10.1038/38229

Chandran, M.D.S. 1997. On the ecological history of the Western Ghats. Current Science 73: 146–155.

Cincotta, R.P., J. Wisnewski, and R. Engelman. 2000. Human population in the biodiversity hotspots. Nature 404: 990–992. doi: 10.1038/35010105

Cochrane, M.A., and M.D. Schulze. 1999. Fire as a recurrent event in tropical forests of the eastern Amazon: effects on forest structure, biomass, and species composition. Biotropica 31: 2–16.

Cochrane, M.A., A. Alencar, M.D. Schulze, C.M. Souza Jr., D.C. Nepstad, P. Lefebvre, and E.A. Davidson. 1999. Positive feedbacks in the fire dynamics of closed canopy tropical forests. Science 284: 1832–1835. doi: 10.1126/science.284.5421.1832

Furley, P.A. 2007. Tropical savannas and associated forests: vegetation and plant ecology. Progress in Physical Geography 31: 203–211. doi: 10.1177/0309133307076107

Gadgil, M. 1993. Restoring the productivity of Indian savannas. Pages 221–235 in: M.D. Young and O.T. Solbrig, editors. World's savannas: economic driving forces, ecological constraints and policy options for sustainable land use. Man and the biosphere series, volume 12. UNESCO, Paris, France.

Higgins, S.I., W.J. Bond, E.C. February, A. Bronn, D.I.W. Euston-Brown, B. Enslin, N. Govender, L. Rademan, S. O'Regan, A.L.F. Potgieter, S. Scheiter, R. Sowry, L. Trollope, and W. S.W. Trollope. 2007. Effects of four decades of fire manipulation on woody vegetation structure in savanna. Ecology 88: 1119–1125. doi: 10.1890/06-1664

Hiremath, A.J., and B. Sundaram. 2005. The fire-lantana cycle hypothesis in Indian forests. Conservation and Society 3: 26–42.

IPCC [Intergovernmental Panel on Climate Change]. 2007. The physical science basis. Contribution of Working Group I to the fourth assessment report of the IPCC. Cambridge University Press, United Kingdom.

Joshi, V. 1991. Biomass burning in India. Pages 185–193 in: J.S. Levine, editor. Global biomass burning: atmospheric, climatic, and biospheric implications. The MIT Press, Cambridge, Massachusetts.

Kodandapani, N., M.A. Cochrane, and R. Sukumar. 2004. Conservation threat of increasing fire frequencies in the Western Ghats, India. Conservation Biology 18: 1553–1561. doi: 10.1111/j.1523-1739.2004.00433.x

Kodandapani, N., M.A. Cochrane, and R. Sukumar. 2008 A comparative analysis of spatial, temporal, and ecological characteristics of forest fires in a seasonally dry tropical ecosystem in the Western Ghats, India. Forest Ecology and Management 256: 607–617. doi: 10.1016/j.foreco.2008.05.006

Landsberg, J.D., and J.F. Lehmkuhl. 1995. Tigers, rhinos and fire management in India. Pages 101–107 in: J.M. Greenlee, editor. Proceedings on fire effects on rare and endangered species and habitats. International Association for Wildland Fire, Moscow, Idaho, USA.

Mittermeier, R.A., P.R. Gil, M. Hoffman, J. Pilgrim, T. Brooks, C.G. Mittermeier, J. Lamoreux, and G.A.B. Da Fonseca. 2005. Hotspots revisited: earth's biologically richest and most endangered terrestrial ecoregions. University of Chicago Press, Illinois, USA.

Narendran, K., I.K. Murthy, H.S. Suresh, H.S. Dattaraja, N.H. Ravindranath, and R. Sukumar. 2001. Nontimber forest product extraction, utilization and valuation: a case study from the Nilgiri Biosphere Reserve, southern India. Economic Botany 55: 528–538. doi: 10.1007/BF02871715

Norton-Griffiths, M. 1979. The influence of grazing, browsing, and fire on the vegetation dynamics of the Serengeti. Pages 310–352 in: A.R.E. Sinclair and M. Norton-Griffiths, editors. Serengeti: dynamics of an ecosystem. The University of Chicago Press, Illinois, USA.

Pascal, J.P. 1986. Explanatory booklet on the forest map of south India. French Institute, Pondicherry, India.

Pinard, M.A., and J. Huffman. 1997. Fire resistance and bark properties of trees in a seasonally dry forest in eastern Bolivia. Journal of Tropical Ecology 13: 727–740. doi: 10.1017/S0266467400010890

Prasad, A.E. 2012. Landscape scale relationships between the exotic invasive shrub *Lantana camara* and native plants in a tropical deciduous forest in southern India. Journal of Tropical Ecology 28: 55–64. doi: 10.1017/S0266467411000563

Puri, K., G. Areendran, K. Raj, S. Mazumdar, and P. Joshi. 2011. Forest fire risk assessment in parts of northeast India using geospatial tools. Journal of Forestry Research 22: 641–647. doi: 10.1007/s11676-011-0206-4

R-Project 2006. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Raman, T.R.S. 2007. On fire. Wildlife Conservation May/June: 46-51.

Ravindranath, N.H., and R. Sukumar. 1998. Climate change and tropical forests in India. Climatic Change 39: 563–581. doi: 10.1023/A:1005394505216

Reddy, P.A., A. Kumaraguru, J. Bhagavatula, D.S. Gour, M. Bhavanishankar, M.S. Sarkar, K. Harika, S.M. Hussain, and S. Shivaji. 2012. Tiger presence in a hitherto unsurveyed jungle of India—the Sathyamangalam forests. Conservation Genetics 13: 779–787. doi: 10.1007/s10592-012-0326-1

Renard, Q., R. Pélissier, B.R. Ramesh, and N. Kodandapani. 2012. Environmental susceptibility model for predicting forest fire occurrence in the Western Ghats of India. International Journal of Wildland Fire 21(4): 368–379. doi: 10.1071/WF10109

Saha, S. 2002. Anthropogenic fire regime in a central India deciduous forest. Current Science 82: 1144-1147.

Sukumar, R., H.S. Suresh, and R. Ramesh. 1995. Climate change and its impact on tropical montane ecosystems in southern India. Journal of Biogeography. 22: 533–536. doi: 10.2307/2845951

Sukumar, R., H.S. Suresh, H.S. Dattaraja, S. Srinidhi, and C. Nath. 2005. The dynamics of a tropical dry forest in India: climate, fire, elephants and the evolution of life-history strategies. Pages 510–529 in: D.F.R.P. Burslem, M.A. Pinard, and S.E. Hartley, editors. Biotic interactions in the tropics: their role in the maintenance of species diversity. Cambridge University Press, United Kingdom.

Suresh, H.S., H.S. Dattaraja, and R. Sukumar. 1996. The flora of Mudumalai wildlife sanctuary, Tamil Nadu, southern India. Indian Forester 122: 507–519.

Sundarapandian, S.M., and P.S. Swamy. 1999. Litter production and leaf-litter decomposition of selected tree species in tropical forests at Kodayar in the Western Ghats, India. Forest Ecology and Management 123: 231–244. doi: 10.1016/S0378-1127(99)00062-6

Uhl, C., and J.B. Kauffman. 1990. Deforestation fire susceptibility and potential tree responses to fire in the eastern Amazon. Ecology 71: 437–449. doi: 10.2307/1940299

Vadrevu, K.P., A. Eaturu, and K.V.S. Badarinath. 2006. Spatial distribution of forest fires and controlling factors in Andhra Pradesh, India using SPOT satellite datasets. Environmental Monitoring Assessment 123: 75–96. doi: 10.1007/s10661-005-9122-4

Van Wagner, C.E. 1978. Age-class distribution and the forest fire cycle. Canadian Journal of Forest Research 8: 220–227. doi: 10.1139/x78-034

van Wilgen, B.W., N. Govender, H.C. Biggs, D. Ntsala, and X.N. Funda. 2004. Responses of savanna fire regimes to changing fire-management policies in a large African national park. Conservation Biology 18: 1533–1540. doi: 10.1111/j.1523-1739.2004.00362.x

Warman, L., and A.T. Moles. 2009. Alternative stable states in Australia's wet tropics: a theoretical framework for the field data and a field-case for the theory. Journal of Landscape Ecology 24: 1–13. doi: 10.1007/s10980-008-9285-9