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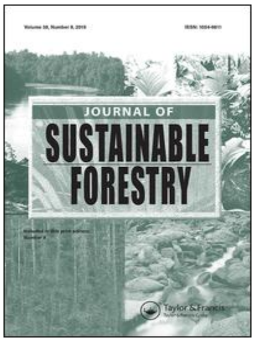

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ABSTRACT

The current study analyzes the tree diversity and regeneration status of species between repeated forest fires and unburned areas of the tropical dry deciduous forest of Panna Tiger Reserve (PTR), Madhya Pradesh, Central India. Fire frequency maps were prepared with the help of Landsat 5, 7, and 8 satellite images, and the study area was classified into seven fire frequency classes (B1 to B7) and one control class (B0). Five plots were laid in every fire class including the control. A total of 45 tree species belonging to 33 genera and 20 families were recorded during the study period and of these, 44, 26, and 25 species were recorded in the three-growth stages: trees, saplings, and seedlings, respectively. Of the 7873 individuals recorded, 2667, 1243, and 3963 were seedlings, saplings, and trees, respectively. Our results showed that tree species diversity was higher at moderate fire frequencies than controls, but decreased with increasing fire frequency classes. Regeneration of species was significantly different among all fire frequency classes. Certain fire-tolerant species were increasingly dominant with increasing fire frequency classes. With fires left to continue unabated, the dry deciduous forest of the Central Indian region could have lower tree diversity in the future.

KEYWORDS

Forest fire; fire frequency; diversity; regeneration; Central India

Introduction

Forest fires are a natural ecological disturbance agent creating a variety of effects on ecosystem composition, structure, and function at both the landscape and regional levels depending on the type of fire, fire intensity, fire frequency, and fire behavior (Keane et al., 2002; Whelan, 1995). Anthropogenic activities such as the collection of non-timber forest products and agricultural activities are the cause of most forest fires (Chaturvedi et al., 2017; Murthy et al., 2006), with these fires affecting species diversity, nutrient dynamics, regeneration potential, as well as emitting greenhouse gases that have negative consequences on the global climate (Amiro, 2001; Ray et al., 2019).

Forest fires are a major issue in the tropics during the dry season (Kodandapani et al., 2004), and tropical dry deciduous forests are especially fire-prone due to high total and dead

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fuel load, dry seedlings, and understorey litter (Verma & Jayakumar, 2015). These fires are a common phenomenon in tropical dry deciduous forests and long-term effects depend on both the frequency and seasonality of fire (Gill, 1975). Fires affect forests directly (killing of the stem of seedlings and saplings) as well as indirectly (changing the regeneration patterns of species, Balch et al., 2013; Kennard et al., 2002). In dry deciduous forests, the number of seedlings and saplings are greater in non-fire and low fire frequency zones compared to high fire frequency zones with lower numbers of seedlings and saplings (Jhariya et al., 2012). However, low-frequency fires can also reduce the density of seedlings and saplings of certain species (Hutchinson et al., 2012). Certain plant species have adapted to these fires by maintaining characteristics such as thick bark and altered timing of sprout germination for the post-fire reestablishment of forest ecosystems (Khan & Tripathi, 1989). The changes in vegetation structure and successional patterns could prompt an expansion of some fire-tolerant tree species, replace the normal regeneration of species (Syaufina & Ainuddin, 2011), as well as promote fire-tolerant grass species and shrubs (Furley et al., 2008; Ryan & Williams, 2011). There is a dearth of studies in the tropical dry deciduous forest of India on the post-fire regeneration of woody species (Kodandapani et al., 2008; Saha & Howe, 2003; Verma & Jayakumar, 2015). Hence, the present study aims to understand 1) the patterns of forest fire frequency using satellite imagery, 2) how tree species diversity responds to fire, and 3) how regeneration of woody species co-occurs with fire frequency classes in the tropical dry deciduous forests of Central India. Quantifying post-fire changes in regeneration and tree diversity in the Central Indian dry deciduous forests would be helpful for ecological assessment, sustainable forest management, and forest planning.

Materials and methods

Study site

The study was conducted in the Panna Tiger Reserve (PTR) (24° 29′ to 24° 45′ N and 79° 45′ to 80° 8′ E) and is located in the north-central region of Madhya Pradesh, Central India. It covers parts of Panna tehsil of Panna district and Bijawar and Chhatarpur tehsils of Chhatarpur district. It extends over an area of 543 km^2 along the Ken River, a tributary of the Yamuna, and the altitude varies from 208 to 495 m asl (Figure 1). Its topography is varied, with hills, plateaus, and river valleys. The PTR is a part of the Vindhyan hill range. The average annual rainfall in the area varies from 757–1885 mm, with the rainy season from early July to mid-September. Average annual temperatures range from 20.8°C to 27.6°C, with the lowest temperatures in the month of December and January and highest occurring during the month of May and June. The PTR is hot and dry for approximately seven months of the year. Champion and Seth (1968) have classified the forests of PTR into the following types: (1) Southern Tropical Dry Deciduous Forest, (2) Northern Tropical Dry Deciduous Mixed Forest, and (3) Dry Deciduous Scrub Forest. The dominant tree species are *Tectona grandis, Butea monosperma, Diospyros melanoxylon, Anogeissus pendula*, and *Lagerstroemia parviflora*.

Fire frequency mapping

Forest fire frequency maps were prepared using the Landsat 5, 7, and 8 images from 1997 to 2017 (20 years). Satellite images of PTR were extracted, geo-corrected, and classified into

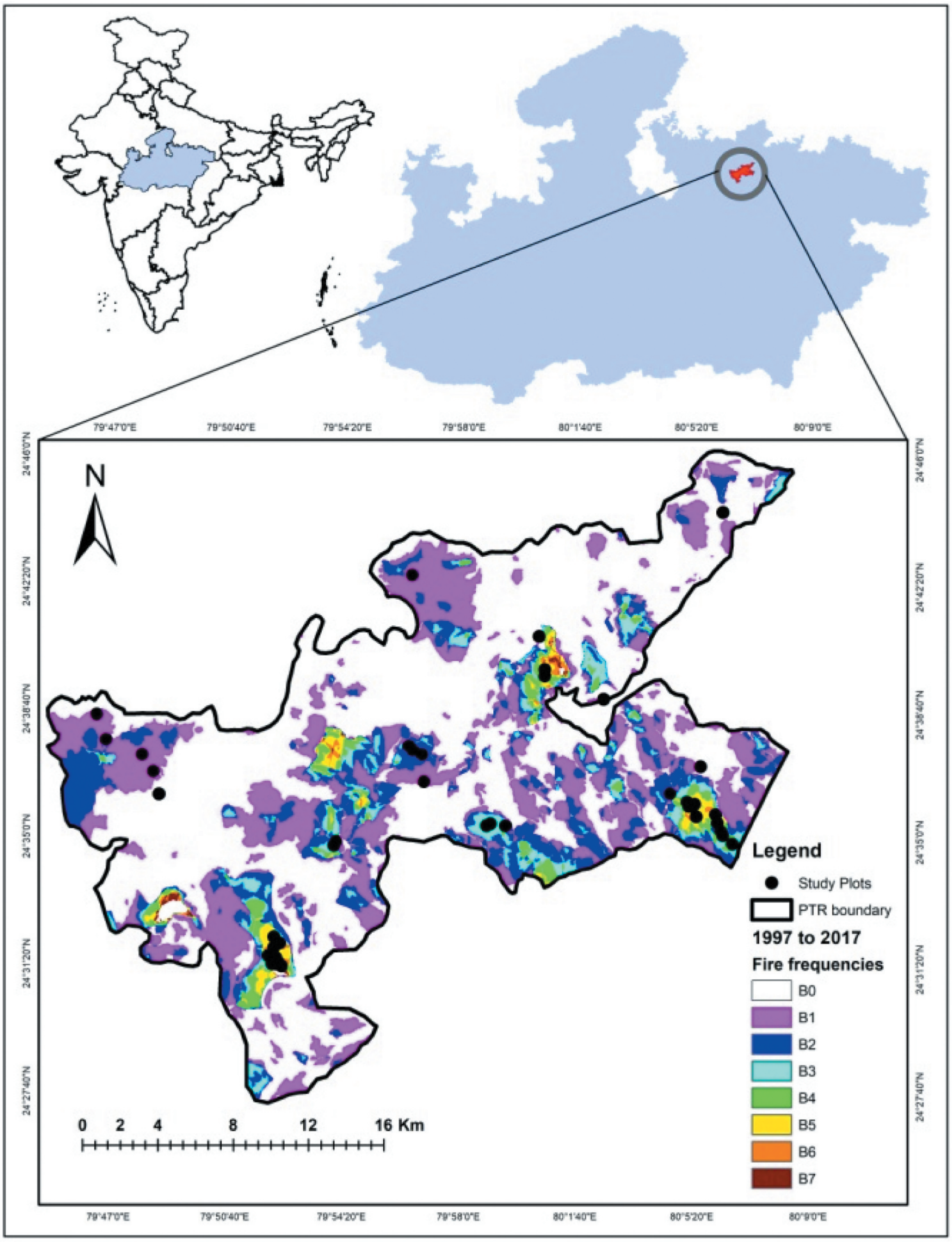

Figure 1. Location map of Panna Tiger Reserve, Madhya Pradesh, India.

unburned (control, B0) and burned (B1, i.e. burned once to B7, i.e. seven times burned) classes using supervised classification (Table 1). Supervised classification was performed based on the shortwave infrared (SWIR) composite image (band combination 7-4-3 in Landsat ETM+) to delineate burned areas. SWIR bands are especially suited for camouflage detection, change detection, disturbed soils, and vegetation stress (Verma et al., 2015). We used Earth Resource Development Assessment System (ERDAS) Imagine 2011 to analyze satellite images. All raster

Table 1. Description of fire frequency, burned area, species diversity, and stem density.

Class code	Fire frequency class	No. of plots	Area (%)	FRI (Year)	No of species			No. of stems
					Trees	Sapling	Seedling	
B0	Unburned (control)	5	53.51	0	20	9	11	1123
B1	Burned once	5	25.73	21	24	11	10	1068
B2	Burned twice	5	10.58	10.5	25	10	13	1027
B3	Burned thrice	5	4.93	7	19	11	13	1044
B4	Four-time burned	5	2.48	5.25	15	11	12	1013
B5	Five-time burned	5	1.67	4.2	18	16	11	942
B6	Six-time burned	5	0.52	3.5	17	8	13	852
B7	Seven-time burned	5	0.21	3	16	8	9	804

image data of the PTR were converted to vector form, assigning a unique identity value for all burned and unburned areas, and then again converted back to a raster file. All raster pictures were merged into a single fire frequency map utilizing the raster calculator tool in ArcGIS 10.

Field data sampling

Floristic data in the PTR were collected from 40 plots (0.25 ha each). Five 50 × 50 m^2 plots were randomly established in each fire frequency class (B1-B7) including the control (B0). Field vegetation data were gathered in the period of September and October 2018. Global Positioning System (GPS) was used for the identification of field sampling points. Measurements such as collar girth (CG) using a Vernier caliper, diameter at breast height (DBH) using a measuring tape, and height using laser range-finder (Nikon Forestry Pro) were recorded for all woody plants (>1 cm DBH) inside the plots. Additionally, 5 × 5 m^2 subplots were laid on four corners of the plot to enumerate seedlings and saplings. Seedlings were defined as plants with a height of less than 50 cm. Saplings were defined as plants with a height of 50–150 cm and neckline circumference in the range between 1 and 10 cm (Verma et al., 2017). Trees were defined as >10 cm DBH. All specimens were identified at the Department of Botany, Dr. Harisingh Gour Vishwavidyalaya Sagar, Madhya Pradesh, using checklists of PTR, flora of Madhya Pradesh, and available literature (Khanna, 2001; D. M. Verma et al., 1993).

Data analysis

The total number of species in all fire frequency and control classes were calculated in three growth forms (seedlings, saplings, and trees). For each growth form, stem density was calculated for each class and a one-way ANOVA was used to analyze any significant differences in these factors among the frequency classes. The diversity index of trees was evaluated using the Shannon–Wiener record (H′) (Shannon & Wiener, 1963). Dominance was calculated by Simpson’s index (1-D) (Simpson, 1949). Results were demonstrated in regards to stem density and the number of species for all growth forms per fire frequency class. Abundance was calculated for the 10 most dominant tree, seedling, and sapling species (Curtis & Mcintosh, 1950). Statistical analyses were performed using the IBM SPSS Statistics 20.

Results

Burned areas

The burned area showed a uniformly decreasing trend with increases in fire frequency. During the 20 years of the recorded burned area between 1997 and 2017, only 116.91 ha (0.22%) received fire seven times during the study period, 293.67 ha (0.54%) burned six times, 949.41 ha (1.70%) burned five times, 1413.81 ha (2.58%) burned four times, 2803.41 ha (4.93%) burned three times, 6021.27 ha (10.59%) burned two times, 14643.09 ha (25.83%) burned a single time, and 30454.83 ha (53.61%) never burned (Table 1). Fire return interval (FRI) for PTR varied from 20 years to 3 years and the average FRI was 15.36 years. Minimum time since last fire at sampling location was 1 year.

Species abundance and diversity

We recorded a total of 7873 stems belonging to 45 tree species, 33 genera, and 20 families. Of these, 44 species were recorded in the tree growth stage, whereas saplings and seedlings were represented by 26 and 25 species, respectively. Stem density in the tree growth stage was 391.9 ha^{-1}, whereas saplings and seedlings were 3107.5 and 6777.5 ha^{-1} respectively. The total numbers of species (including trees, saplings, and seedlings) present in each fire class were 22 (B0), 26 (B1 and B2 each), 20 (B3 and B5 each), 19 (B6), with the lowest numbers of species recorded being 17 (B4) and 16 (B7) (Figure 3d). The Shannon-Wiener (*H*') and Simpson's dominance index (1-D) values for the control plot were 3.13 and 0.84, respectively, and this value reached 3.47 and 0.86 in twice (B2) burned areas (Figure 2). Tree species richness showed a negative linear relationship (R^2 = 0.503) with fire frequency classes and decreased with increases in fire frequency class after B2 (Figure 3a), whereas the saplings and seedlings did not show any significant trend with fire frequency classes (Figure 3b,c). Total species richness (tree + seedlings + saplings) showed a negative linear relationship (R^2 = 0.554) with fire frequency classes (Figure 3d) and decreased with increasing fire frequencies. All fire frequency and control classes showed a greater differentiation in the distribution of stem diameter classes and showed a reverse J-shaped curve in all classes (Figure 4). The stems in lower DBH (1–10 cm) were higher across all fire frequency classes including the control compared to the higher DBH classes. With increases in fire frequency, the numbers of stems decreased across all fire frequency classes (Figure 4).

Tree species regeneration

The mean stem density of tree ($p = .05$) and seedling ($p = .023$) populations showed significant differences among the fire frequency classes, whereas the variation in saplings ($p = .118$) was not statistically significant. Tree populations showed a higher density in B3 and lower density in B6 (Figure 5a). With increases in fire frequency, the sapling population increased slowly until B4 before decreasing toward the B6 class and then increasing in the B7 class (Figure 5b). Seedling density did not change in classes B1, B5, and B7 whereas B4, B0, and B2 had lower seedling density values (Figure 5c). The abundance of *Tectona grandis* increased at tree stages with increases in fire frequency classes, whereas the other three species did not any show significant changes across fire frequency classes (Figure 6a). At the seedling stage, the abundance of

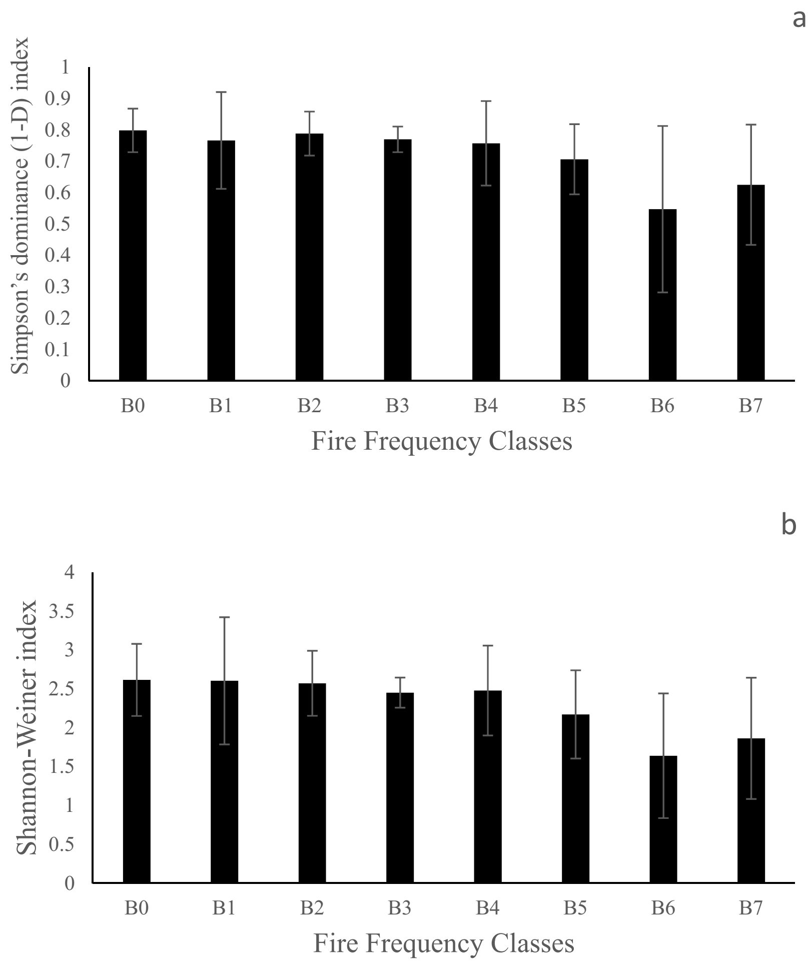

Figure 2. Diversity indices: (a) Simpson's dominance index and (b) Shannon-Weiner index for all fire frequency and control classes.

Tectona grandis did not show any significant difference at lower fire frequency classes but did increase in abundance with increases in fire frequency (Figure 6c). In the sapling stage, the abundance of *Tectona grandis* was higher in the B5 class whereas *Diospyros melanoxylon* linearly decreased with an increase in fire frequency classes (Figure 6b). The abundance of all species showed decreasing trends with increases in fire frequency in tree stages, whereas at the seedling and sapling stages the abundance did not show any uniform trend (Figure 6d). At the tree stage, the highest number of *Diospyros melanoxylon* was recorded in B3 (16.93%) while the lowest number was found in B1 (4.79%). For the tree stage of *Lagerstroemia parviflora*, the highest number was found at B5 (24.39%), followed closely by B1 (22.87%), while the lowest number (7.66%) was found at B2. *Tectona grandis* was the most abundant (24.41%) species in the control group (B0) at the tree stage and linearly increased with fire frequency classes. *Butea monosperma* at tree stage was highest in B2 (19.16%), followed closely by

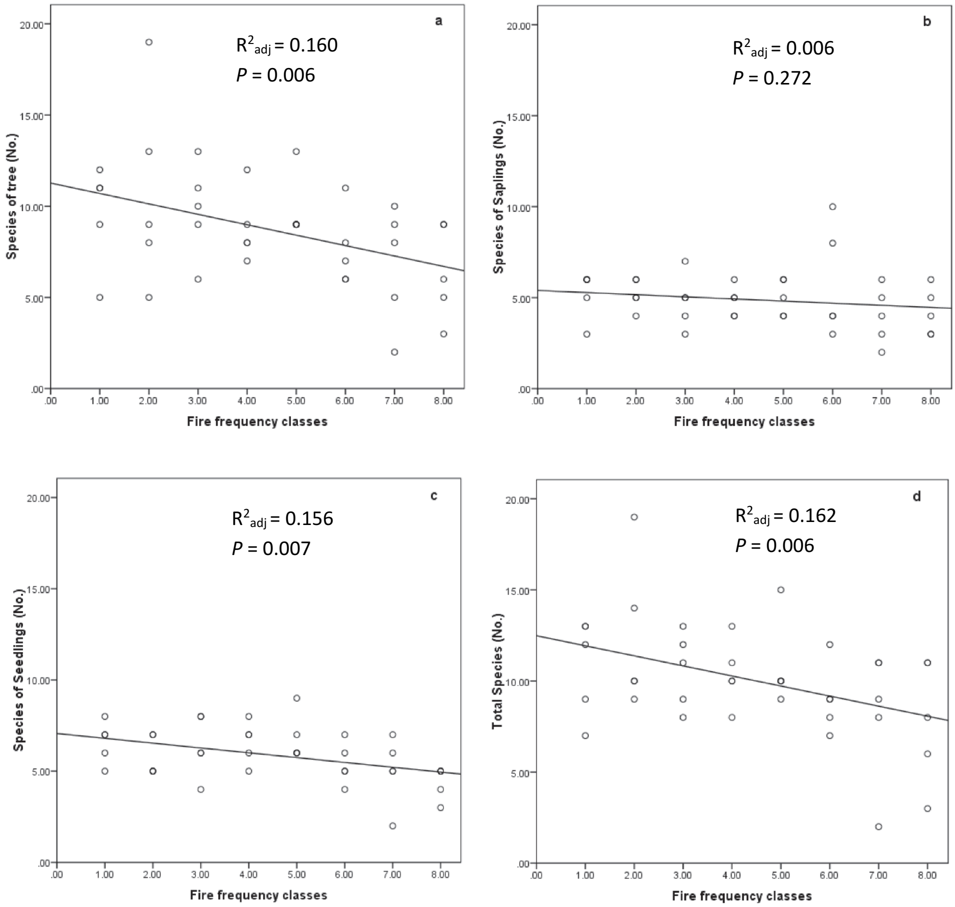

Figure 3. Relationship of forest fire frequencies with (a) number of tree species, (b) number of sapling species, (c) number of seedling species, and (d) total number of species including tree, sapling, and seedling.

the control class (18.58%), and the lowest was found at B4 (1.16%). At the sapling stage, B2 also showed the highest number of seedlings, followed by B3 (14.88%), and the minimum number was found in B6 (0.99%). For the sapling stage, *Lagerstroemia parviflora* were highest in B7 (32.21%), followed by B0 (24.34%), and the lowest was found at B2 (7.33%) (Table 2). At the sapling stage, *Tectona grandis* (24.34%) and *Lagerstroemia parviflora* (24.34%) were dominant but, at the seedling stage, *Diospyros melanoxylon* (34.60%) was dominant in the control plot (Table 2). The seedling stage of *Butea monosperma* contributed the highest numbers in B3 (16.50%) followed by B0 (13.03%) whereas the lowest number of seedlings was found at B1 (1.45%). The seedling and sapling stages of *Diospyros melanoxylon* were shown to be highest in the B0 class, whereas the lowest number of seedlings was recorded in B7. At the seedling stage, *Lagerstroemia parviflora* (20.60%) was found in the highest numbers in B7 followed by B1 (19.65%), and the fewest were found in B4 (3.37%).

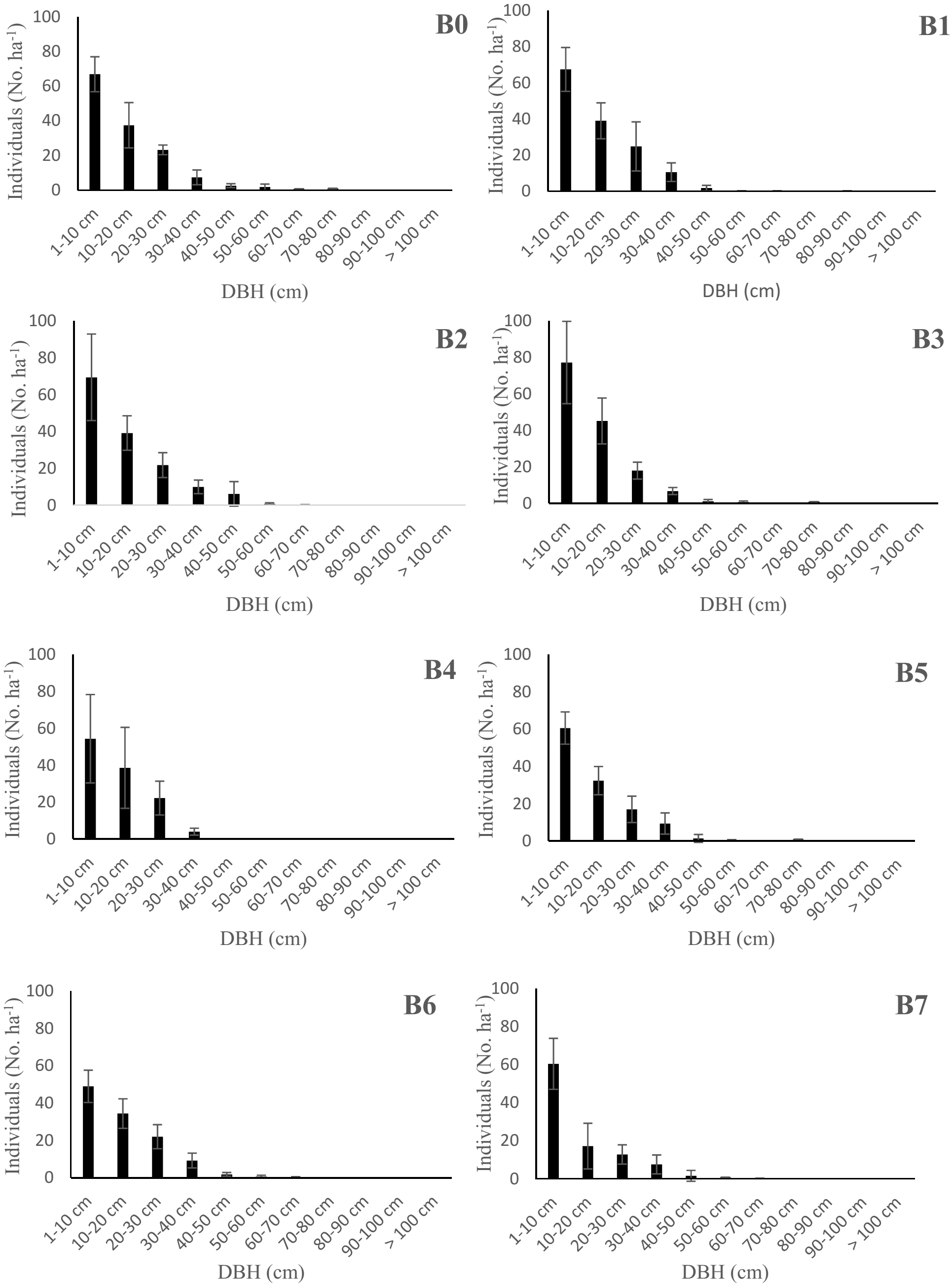

Figure 4. Stem diameter class distributions in burned and control fire classes.

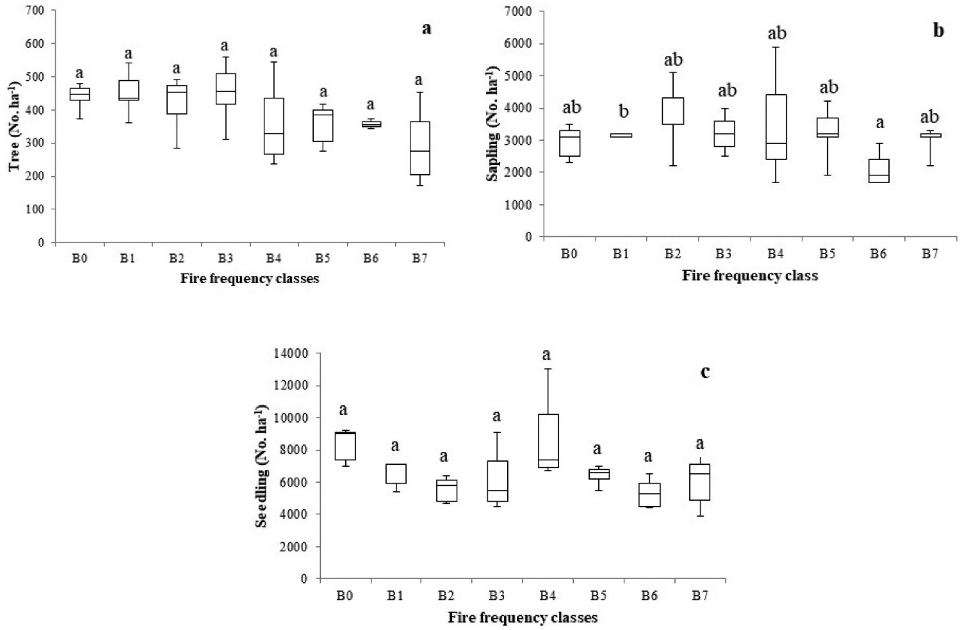

Figure 5. Box plots showing the number of individuals recorded per hectare: (a) tree, (b) sapling, and (c) seedling.

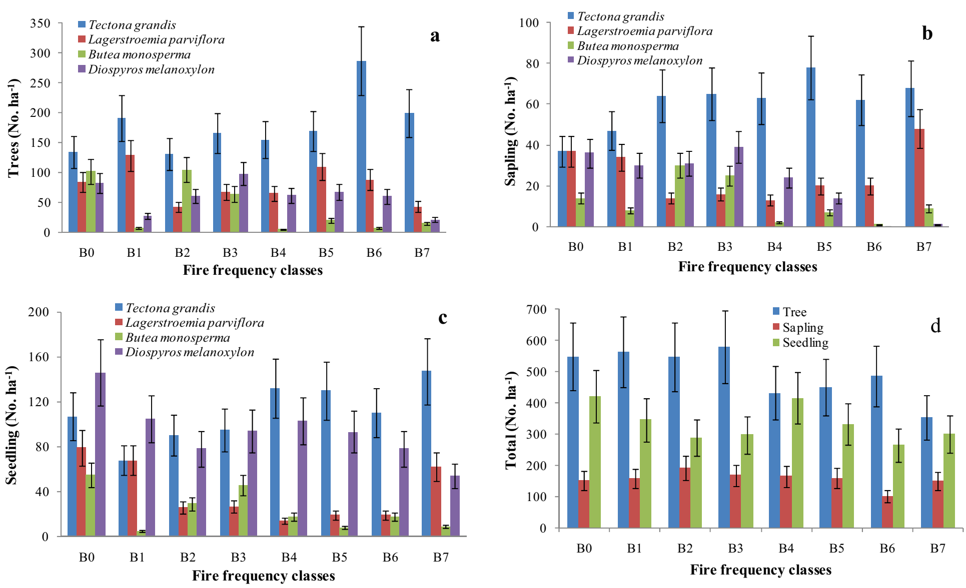

Figure 6. Comparison of four dominant tree species with fire frequency classes in three growth stages: (a) tree, (b) sapling, (c) seedling, and (d) total number of individuals in all (tree, sapling, and seedling) the growth stages.

Table 2. Top-most abundance of tree species present in all three growth stages (tree, sapling, and seedling) across all fire frequency classes.

			Abundance (%)							
S.N.	Species (Tree)	Family	B0	B1	B2	B3	B4	B5	B6	B7
1	*Butea monosperma*	Fabaceae	18.58	1.24	19.16	11.05	1.16	4.43	1.65	4.24
2	*Cassia fistula*	Fabaceae	N/P	N/P	1.09	N/P	0.23	N/P	1.23	1.13
3	*Diospyros melanoxylon*	Ebenaceae	14.94	4.79	11.13	16.93	14.35	14.86	12.35	5.93
4	*Flacourtia indica*	Salicaceae	1.28	4.43	2.74	4.66	0.93	N/P	N/P	1.41
5	*Lagerstroemia parviflora*	Lythraceae	15.30	22.87	7.66	11.74	15.05	24.39	18.11	12.15
6	*Phyllanthus emblica*	Phyllanthaceae	N/P	0.18	1.09	0.86	2.08	1.11	0.21	N/P
7	*Tectona grandis*	Verbenaceae	24.41	33.87	23.91	28.67	35.88	37.47	59.05	56.21
8	*Terminalia tomentosa*	Combretaceae	1.64	3.01	1.64	N/P	9.49	N/P	0.41	0.28
9	*Wrightia tinctoria*	Apocynaceae	N/P	4.79	2.37	N/P	5.56	N/P	0.41	N/P
10	*Ziziphus xylopyrus*	Rhamnaceae	5.46	2.30	5.47	N/P	N/P	2.66	1.03	7.34
	(Sapling)									
1	*Acacia catechu*	Fabaceae	1.97	0.63	2.09	1.19	N/P	N/P	4.95	N/P
2	*Butea monosperma*	Fabaceae	9.21	5.06	15.71	14.88	1.21	4.40	0.99	6.04
3	*Cassia fistula*	Fabaceae	N/P	4.43	1.05	N/P	N/P	3.14	9.90	5.37
4	*Diospyros melanoxylon*	Ebenaceae	23.68	18.99	16.23	23.21	14.55	8.81	N/P	0.67
5	*Flacourtia indica*	Salicaceae	5.26	1.27	4.71	5.36	4.24	N/P	N/P	3.36
6	*Lagerstroemia parviflora*	Lythraceae	24.34	21.52	7.33	9.52	7.88	12.58	19.80	32.21
7	*Phyllanthus emblica*	Phyllanthaceae	N/P	N/P	N/P	0.60	0.61	2.52	N/P	N/P
8	*Tectona grandis*	Verbenaceae	24.34	29.75	33.51	38.69	38.18	49.06	61.39	45.64
9	*Wrightia tinctoria*	Apocynaceae	N/P	12.66	7.85	N/P	22.42	N/P	N/P	N/P
10	*Ziziphus xylopyrus*	Rhamnaceae	7.24	1.27	4.71	N/P	N/P	1.26	0.99	4.03
	(Seedling)									
1	*Acacia catechu*	Fabaceae	N/P	N/P	N/P	0.34	N/P	N/P	N/P	N/P
2	*Butea monosperma*	Fabaceae	13.03	1.45	10.07	16.50	4.33	2.41	6.79	2.99
3	*Cassia fistula*	Fabaceae	N/P	N/P	1.04	1.68	0.96	N/P	1.13	4.32
4	*Diospyros melanoxylon*	Ebenaceae	34.60	30.35	27.08	31.65	24.76	28.01	29.43	17.94
5	*Flacourtia indica*	Salicaceae	2.84	0.58	0.69	3.70	1.68	N/P	N/P	N/P
6	*Lagerstroemia parviflora*	Lythraceae	18.72	19.65	9.03	9.09	3.37	5.72	7.17	20.60
7	*Phyllanthus emblica*	Phyllanthaceae	N/P	N/P	0.35	0.34	0.72	N/P	N/P	N/P
8	*Tectona grandis*	Verbenaceae	25.36	19.65	31.25	31.99	31.73	39.16	41.51	48.84
9	*Wrightia tinctoria*	Apocynaceae	N/P	17.92	12.85	N/P	30.29	N/P	1.89	N/P
10	*Ziziphus xylopyrus*	Rhamnaceae	0.95	8.96	2.43	N/P	N/P	6.63	7.92	2.99

N/P not present

Discussion

Diversity

In the present study, significant differences in species diversity were observed in PTR. While species diversity increased in the B2 fire frequency class, increasing fire frequency led to a decline in the diversity and increased dominance of certain fire-tolerant species. Our results show that species richness and stand density decreased in higher (B6 and B7) fire frequency classes which could be due to the result of the poor regeneration processes that decrease species diversity in higher fire frequency classes. Our results support similar findings reported in the tropical dry deciduous forest of Chhattisgarh (Jhariya et al., 2012), in Mudumalai Tiger Reserve (Kodandapani et al., 2008; Verma & Jayakumar, 2015), and Sathyamangalam Tiger Reserve (Sathya & Jayakumar, 2017). Decreased species richness was also reported by Saha and Howe (2003) and Saha (2002) in the dry deciduous forest of Central India. Our results also suggest that the fire frequency (B3 and B4) could be beneficial for the regeneration of tree species. This result is concurrent with other experimental studies by Saha and Howe (2003) in the dry deciduous forest of Central India and in the Central Himalayan regions (Pande et al., 2014). According to Kodandapani (2001), mid-frequency fires enhance greater regeneration of seedlings due to the release of chemicals and nutrients locked up in old herbages as well as increasing light intensity, thus allowing rapid seed growth and low mortality rates once they successfully cross from the seedling stage to the sapling stage. Expanded soil supplement and the removal of seed dormancy could also explain the findings regarding the germination of specific tree species (Goldammer, 1988; Saha, 2002).

Density

The results showed that the numbers of seedlings and saplings were lower in the single fire frequency class compared to the control class whereas the mid-fire frequency classes (B3 and B4) showed the highest density of seedlings which were higher than the control class. The survival of seedlings at B3 and B4 fire regimes demonstrates the high capacity of seedlings to persist in the dry forest and indicates that moderate fire is better for the regeneration of tree species. The benefits of moderate or low disturbance for species regeneration have also been reported by Khan et al. (1987) and Maram and Khan (1998). This is in contrast to studies by Gould et al. (2002); Mondal and Sukumar (2015) in Mudumalai Tiger Reserve which found increasing numbers of seedlings and saplings in a single-burnt class compared to the control class. Jhariya et al. (2012) reported that seedlings follow a similar trend in all fire frequency classes.

Regeneration

Our results indicate that the high frequencies of fire (B5 to B7) supported the regeneration of *Tectona grandis, Cassia fistula, Lagerstroemia parviflora*, and *Acacia catechu*, whereas B2 and B3 supported the regeneration of *Butea monosperma, Flacourtia indica*, and *Wrightia tinctoria*. The density of *Tectona grandis* showed a continued increase with increasing fire frequency demonstrating that forest fires are beneficial for *Tectona grandis*. B3 supported the regeneration of *Diospyros melanoxylon* only for tree and sapling stages, but no positive relationship with fire frequency classes was found at the seedling stages. The B1 class supported the regeneration of *Terminalia tomentosa* compared to the high-frequency classes possibly due to the species being less able to survive under the impacts of high fire frequencies compared to other frequency classes. Our results showed that while some species may tolerate fire, others may be disappearing. B4 and B5 fire frequency classes supported the regeneration of *Phyllanthus emblica* (Table 2). The seeds of *Phyllanthus emblica* have a long dormancy period (Mawalagedera et al., 2014) and thus appeared in the high fire frequency classes. The floristic composition of PTR was dominated by *Tectona grandis, Lagerstroemia parviflora, Butea monosperma*, and *Diospyros melanoxylon* in all three growth (trees, saplings, and seedlings) stages. Our results differ from other dominant species reported by Balch et al. (2013), Kodandapani et al. (2008), and Verma and Jayakumar (2015).

The lower number of seedlings and saplings is an indicator of low regeneration of species. Non-fire resistant or fire-sensitive species may decline in abundance and frequency possibly resulting in their local extinction in the long term. A decline in the abundance of fire-sensitive species may affect some important ecosystem functions. Hence, sustainable forest management practices require careful quantification and monitoring of fire frequency (M. Agarwala et al., 2016a, 2016b, 2017).

There are certain limitations of this study that require long-term studies at higher resolutions and additional variables. Certain edaphic and climatic factors and other environmental variables that cannot be controlled due to the nature of the study design was overcome by placing unburned plots close to burned plots and in the same vegetation type.

There are very limited studies in India on post-fire ecological dynamics (Kodandapani et al., 2008, 2009; Saha & Howe, 2003; Verma & Jayakumar, 2015; Verma et al., 2017). Few researchers have tried to study forest fire in the Western Ghats. For example, Kodandapani et al. (2004, 2008, 2009), Verma et al. (2015), and (2017) studied fire history, fire return interval, ecological impacts of fire, and conservation threats of forest fire in the Western Ghats. Mondal and Sukumar (2014) studied characteristic weather patterns associated with fire. Saha and Howe (2003) studied post-fire ecological dynamics in Central India. There is no study that tries to investigate the role of multiple fires on tree diversity and regeneration in the Central Indian forest. The current study will be a positive addition to the scientific literature and sustainable forest management.

Conclusion

Our results demonstrate that forest fire has different levels of effects on the recovery of tree species in the dry deciduous forest of Central India including the fact that a single fire event could not be beneficial for the regeneration of species. Results suggest that low fire frequency inhibited the regeneration of seedling densities but enhanced the species richness and tree density. Similarly, high fire frequencies also inhibited the growth of regenerating seedlings. This leads us to conclude that the recovery of tree species is affected in all fire frequencies, either high or low. All fire frequency classes (B1-B7) showed less diversity than the control except for the B2 class and showed increasing dominance of certain fire-tolerant species with increasing fire frequency. All fire frequency classes had an impact on the regeneration of tree species, either beneficial in B2 fire frequencies or detrimental in single and higher fire frequencies. In any ecosystem, plant species diversity and density are maintained by the healthy regeneration of species. This study forms a baseline dataset that may facilitate future in-depth studies related to forest fires and further research should continue into the different ecological aspects and effects of fire on vegetation in PTR.

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