

## Long-term Assessment of Fire Regime Across Different Forest Types

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### ABSTRACT

Worldwide, fire plays a crucial role in ecosystem patterns and processes. The fire regime varies across the biomes, and different ecosystems respond differently. Alteration in the fire regime affects the ecosystem negatively. In the absence of historical records, long-term fire studies are essential to understand the fire regime on a regional scale. Fires inside the wilderness area of Sathyamangalam Tiger Reserve (STR) occur as a result of anthropogenic artefacts. Twenty-five years of fire frequency study from satellite remote sensing revealed that fire is prominent in the dry deciduous and open grassy systems. However, active fire suppression policies in recent times have shown their effectiveness in controlling fire in forested areas. Remote sensing-based fire studies must be integrated with field-based quantification of fire regimes and various other effects to get more ecological insights.

**Key words:** Forest fire, Remote Sensing and GIS, Fire ecology, Fire regime, Fire frequency

### INTRODUCTION

Fire plays a crucial role in shaping ecosystem patterns and processes and has been present on Earth since the colonization of early land plants (Bond et al. 2005, Scott 2018). It influences the distribution of plants and animals and plays a crucial role in their evolution and maintaining ecosystem functions (Pausas and Keeley 2009). Fire is particularly significant in developing pyrophilic and flammable ecosystems in climate that is conducive to the growth and sustainability of forests (Bond et al. 2005). Fire benefits ecosystems by burning dead material, releasing trapped nutrients and promoting new growth and regeneration (Bond 2019). It also contributes to habitat heterogeneity and reduces competition among species (Pausas and Bond 2020). However, fire impacts ecosystems positively and negatively, influencing their structure, composition, and nutrient dynamics (He et al. 2019, McLauchlan et al. 2020). Based on their dependencies on fire, all terrestrial biomes can be broadly classified into two categories: fire-dependent and fire-sensitive biomes. Fire-sensitive biomes are not adapted to frequent fires and experience severe biodiversity loss and ecosystem degradation when fires occur (e.g., tropical rainforest) (Cochrane 2003). Contrastingly, fire-resistant biomes, such as savannas and

Mediterranean shrublands, require periodic fires to sustain biodiversity by preventing woody encroachment and promoting fire-adapted species (Bond and Keeley 2005). Fire also influences soil properties, affecting nutrient cycling and microbial communities differently across vegetation types (Certini 2005). While some ecosystems recover quickly due to fire-adapted traits, others experience long-term shifts in vegetation composition, leading to altered ecosystem functioning (Bernardino et al. 2021, Pausas et al. 2017, Pausas and Keeley 2019). Before the emergence of humans, fire was considered a natural process that played a significant role in shaping climate and fuel availability (Bowman et al. 2011). With the arrival of humans, fire regimes have been significantly modified due to human interference (Bowman et al. 2011). A fire regime encompasses specific characteristics such as frequency, intensity, severity, seasonality, size, type, extent, and spatial fire pattern (Bowman et al. 2011, Oddi 2018). Through time, all ecosystems and their inhabiting organisms have evolved under a specific fire regime, known as the 'historical fire regime' (Keeley and Pausas 2019, Pausas and Keeley 2019). Any alteration in the historical fire regime disrupts the balance between biotic and abiotic components, affecting the structure and composition of organisms reliant on that ecosystem (Keeley et al. 2011a). Since

ancient times, humans have modified natural fire regimes by promoting or suppressing fires to suit their needs (Bowman et al. 2020). For example, fire has long been used for hunting, gathering and land clearance. It is also used by modern-day humans, land managers, and forest administrators to reshape agricultural and pastoral fields, collect Non-Timber Forest Products (NTFPs), promote regeneration, and reduce fuel loads to prevent large wildfires (Bowman et al. 2009, 2020). The increasing reliance of people on natural systems commenced with the advent of the industrial age, which consequently influenced the fire regime. Human activities have altered the historical fire regime by promoting fire in fire-sensitive biomes and suppressing it in fire-dependent biomes (Alencar et al. 2015, Palmquist et al. 2014). Regardless of their dependencies or resilience to fire, these alterations have led to the degradation of ecosystem structure and function, negatively impacting species that rely on them (Keeley et al. 2011b, Veldman and Putz 2011).

Among all fire regime parameters, fire frequency is one of the most influential, as it directly or indirectly affects all other parameters and plays a key role in shaping the fire regime itself (Keeley et al. 2011a). As fire frequency increases, the interval between two successive fires, known as the fire return interval (FRI), decreases. This further reduces the chance for plants to attain the escape height (Bond et al. 2005). Contrastingly, a longer fire return interval between two successive fires leads to higher fuel load accumulation, subsequently increasing fire intensity (Williams et al. 1999, Zupo et al. 2022). Recurrent fires hinder younger plants from escaping the fire trap, opening the canopy and impeding the recovery process to the pre-fire state (Bond et al. 2012, Hoffmann et al. 2012). Changes in fire frequency can alter composition and structure, whether fires occur too frequently or too infrequently. An extended interval between fire events can lead to shrub encroachment or the thickening of woody components in open ecosystems (Roques et al. 2001). Reduced fire frequency in such biomes has resulted in a decrease in species richness (Palmquist et al. 2014). In savannas, complete fire exclusion can result in biodiversity loss and biome shifts; however, excessive fire frequency may also potentially endanger the biota (Andersen et al. 2006, 2012).

As an ecosystem process, fire is greatly influenced by variables like primary productivity, seasonality, fuel structure and ignition sources (Pausas and Keeley 2019). The fuel amount, spatial distribution, and moisture content greatly influence fire behaviour. Certain vegetation types are burned more efficiently than others (Bond 2019). As a result of this, the fire regime varies greatly across vegetation types (Kodandapani 2013). Different vegetation types may respond differently to a given fire regime, highlighting the need for forest-type-specific fire regime studies (Bond et al. 2005).

The alteration of the fire regime due to anthropogenic activities is well-documented globally (Bowman et al. 2009). Further climate change will intensify the alteration of the fire regime (Allen et al. 2017). The direction and underlying reasons for these changes show remarkable variation on a global scale, necessitating a regional solution to the fire problem. So, this study was carried out to document fire regimes across different forest types. Additionally, a comparative analysis of forest fires' spatial and temporal trends across forest types was performed.

## MATERIAL AND METHODS

### Study area

Sathyamangalam Tiger Reserve (STR), the fourth tiger reserve of Tamil Nadu, extends from 11.73306° and 11.60500° N to 76.83139° and 76.05694° E (Fig. 1), at the junction of the Western Ghats and the Eastern Ghats. Due to its unique geographical location, STR is a critical conservation landscape known for its rich biodiversity and significant tiger population. Expanded over an area of 1408.40 km<sup>2</sup>, STR encompasses diverse ecosystems, supporting a wide range of flora and fauna. Out of India's 16 major forest types, STR encompasses five, which are further divided into 15 distinct vegetation types (Champion and Seth 1968). The reserve forms an essential part of the Nilgiri Biosphere Reserve and the Nilgiri-Eastern Ghats Elephant Reserve. Situated at the confluence of the Eastern Ghats and the Western Ghats, STR serves as a crucial wildlife corridor, connecting Bandipur, Mudumalai, and Biligiri Ranganatha Swamy Temple (BRT) Tiger Reserve. This connectivity enhances genetic

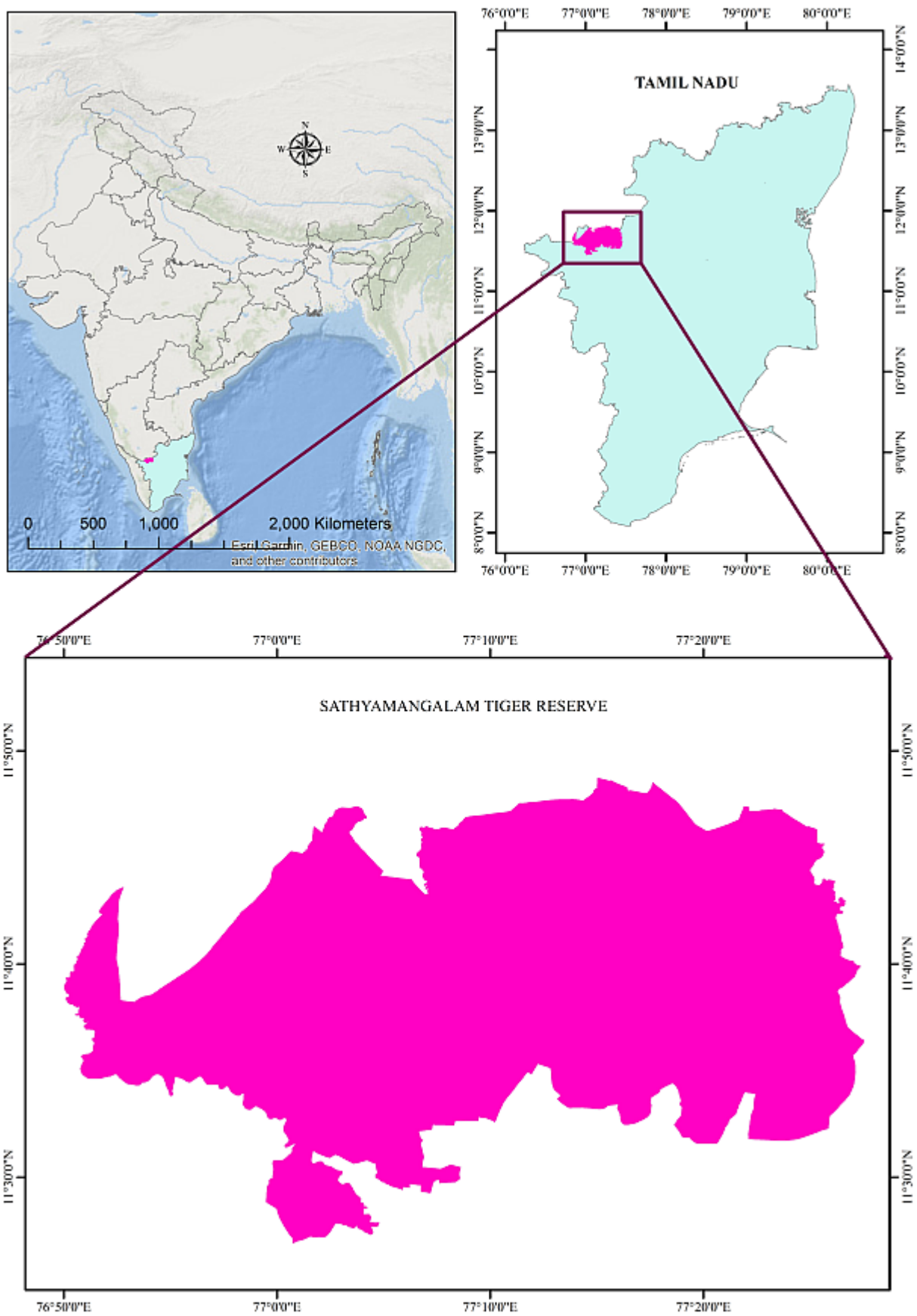


Figure 1. Geographical location of Sathyamangalam Tiger Reserve, Tamil Nadu, India

diversity and the movement of wildlife, reinforcing its ecological significance.

The altitude of STR ranges from 238 to 1742 m AMSL. The terrain is highly undulating and characterized by variable topography, including slopes, hills, streams, and one perennial river, Moyar. Metamorphic rocks such as Charnockites and Granite gneiss are widely found across the great gneissic pre-Cambrian age reserves. Major soil types include red, laterite, black cotton, and alluvial soils. STR's observed mean annual precipitation is 850 mm, and the mean annual temperature is 24°C. STR receives most of its precipitation from the north-east monsoon from October-December. Additionally, it experiences intermittent showers from the south-west monsoon from May to September. The dry season ranges from January to April, during which most fire incidents occur.

### Fire frequency mapping

According to the Forest Survey of India (FSI), STR harbours 15 distinct forest types. The accuracy of fire studies using satellite imagery is greatly influenced by the spatial and temporal resolution of the images (Nagendra and Rocchini 2008). Coarse-resolution satellite images may fail to detect small

fires, and not accounting for small fires can result in underestimating the burned area by 90-150% (Ramo et al. 2021, Randerson et al. 2012). Therefore, we selected Landsat satellite imagery for burned area mapping, a moderate-resolution satellite providing historical images from 1972 onwards. Satellite images of STR acquired by Landsat-5, 7, 8, and 9 (Path: 144, Row: 052) were downloaded from the USGS Earth Explorer website (<https://earthexplorer.usgs.gov/>). A time series data spanning 25 years, from 2000 to 2024, was downloaded (Fig. 2). All cloud-free images were downloaded and checked for fire scars to reduce omission errors. Post-processing, including layer-stacking and clipping, was conducted using ERDAS Imagine (Version-11). We opted for manual scanning and visual interpretation of burn scars to avoid confusion and misclassification with objects of similar spectral signatures (such as cloud shadows and deep ravines). All fire scars were digitized by creating false-colour composites (FCC) with a band combination of infrared-red-green and cross-verified with the band combination of shortwave infrared-infrared-green (in case of smoke and confusion due to active fire) in ArcGIS 10.8.

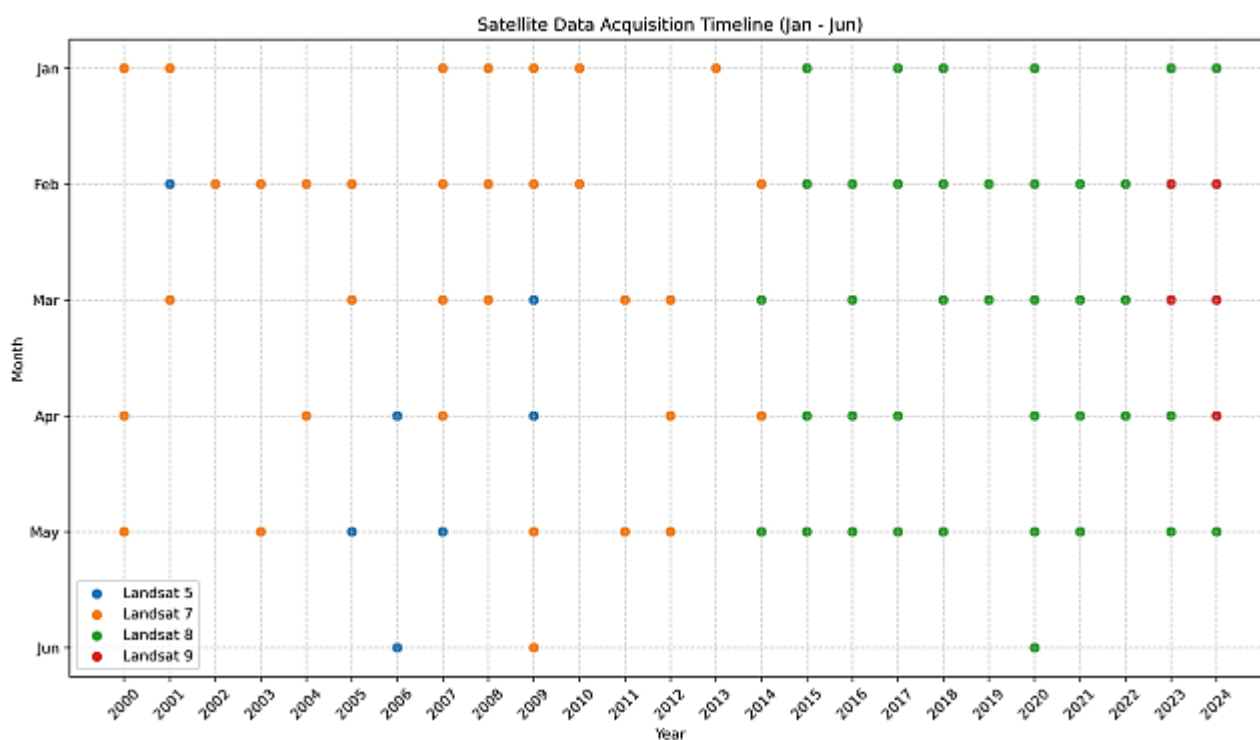


Figure 2. Details of satellite data acquisition timeline

Each digitized fire scar and unburned area was assigned unique identity values. Subsequently, year-wise annual burned area maps were prepared by considering all individual fire scars for the given year and converted to raster format. All 25 annual burned area maps were stacked to produce a single fire frequency map using the Raster calculator tool in ArcGIS 10.8. The composite fire frequency map stratified into eleven different fire frequency classes ranging from FF1 (burned once in the 25 years) to FF11 (burned 11 times during the study period) and one unburnt class (FF0) (Fig. 3). We omitted Southern moist mixed deciduous forest, Southern secondary moist mixed deciduous forest and Dry grassland from forest-type wise fire regime analysis due to low spatial extent (Table 1).

## RESULTS AND DISCUSSION

### Forest types of STR

As per the FSI Forest type map 2020, the major forest type of STR is the Southern dry mixed deciduous forest, which covers around 58% of the reserve and

is spread over 12474.32 hectares (ha). The floral composition of STR resembles the floral composition of the neighbouring Mudumalai Tiger Reserve (MTR), where a significant portion of the forest comprises deciduous trees (Dattaraja et al. 2017, Verma and Jayakumar 2015). West Coast semi-evergreen forest and Moist bamboo brakes make up 9.33 and 7.56% of the total area under vegetation cover in the reserve, respectively. West Coast semi-evergreen forest, Moist bamboo brakes and Southern moist mixed deciduous forest distributed across a high precipitation area mainly in the central-north region of the reserve (Sathya 2017). Another unique feature of STR is that it comprises a good and continuous patch of dry savanna covering an area of 10012.32 ha, which is 7.48% of the total geographical area of STR (Table 1). Generally, savanna in Asia is very patchy and often misclassified as degraded dry forests (Ratnam et al. 2019, 2016). Amongst other forest types, dry grassland spread across 1.73 ha only. This small spatial distribution of dry grasslands may be because of the classification error from satellite imagery due to the mixing of the spectral signature

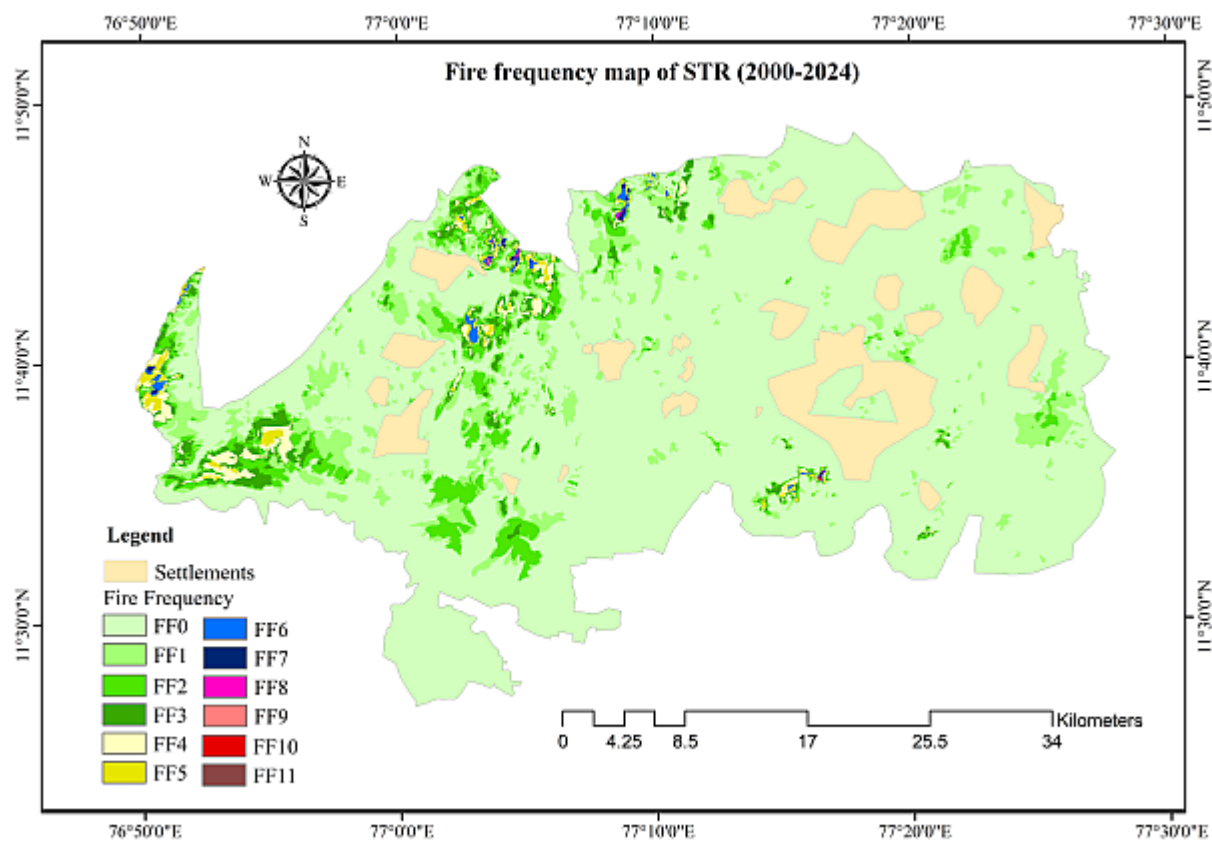


Figure 3. Fire frequency map of Sathyamangalam Tiger Reserve for the period of 2000 to 2024 (25 years)

Table 1. Forest types and their spatial extent in STR

S.N.	Forest types	Area (ha)	Area (%)
1	2A/C2 West Coast semi-evergreen forest	<b>12474.32</b>	<b>9.33</b>
2	2/E3 Moist bamboo brakes	<b>10107.19</b>	<b>7.56</b>
3	3B/C2 Southern moist mixed deciduous forest	11.98	0.01
4	3B/C2/2S1 Southern Secondary Moist mixed deciduous forest	1.09	0.001
5	4E/RS1 Riparian fringing forest	37.84	0.03
6	5A/C3 Southern dry mixed deciduous forest	<b>78117.70</b>	<b>58.40</b>
7	5/DS1 Dry deciduous scrub	2733.18	2.04
8	5/DS2 Dry savanna forest	<b>10012.32</b>	<b>7.48</b>
9	5/DS4 Dry grassland	1.73	0.001
10	5/E4 <i>Hardwickia</i> forest	423.88	0.32
11	5/1S1 Dry tropical riverain forest	2246.28	1.68
12	5/2S1 Secondary dry deciduous forest	3421.38	2.56
13	6A/C1 Southern thorn forest	9843.38	7.36
14	6A/C2 Carnatic umbrella thorn forest	4158.72	3.11
15	6A/DS1 Southern thorn scrub	83.40	0.06
16	TOF/Plantation	98.09	0.07
<b>Total</b>		<b>133772.49</b>	

of such vegetation with the neighbouring forest types (Reddy et al. 2015). Thorn forests and scrubs are prominent around the lower portion of STR. Two types of thorn forests, namely the Southern thorn forest and Carnatic umbrella thorn forest, spread across 9843.38 and 4158.72 ha, respectively. Two scrub forests are identified as dry deciduous scrub and southern thorn scrub, covering 2733.18 and 83.40 ha, respectively.

#### Fire frequency analysis

Fire is mainly observed during the dry seasons from January to May. Fire in STR mainly originated from anthropogenic artefacts. We did not encounter any fire incidents during the entire study period in the rainy season, both from satellite imagery and forest department records. The unavailability of cloud-free satellite images and the limitations of optical remote-sensing to look through clouds prevented us from verifying fire scars in the rainy season. Concerning the incidence of fire inside the vegetated areas of the reserve, approximately 20.38%, equating to 27236.61 ha, experienced at least once during the study period (Fig. 4). Out of the total area under vegetation cover, 79.60%, i.e., 10639.20 ha,

remained unburnt from 2000 to 2024 (Table 2). Further, in the reserve's burnt areas, the fire frequency ranges from 1 to 11 (FF1- FF11). Among the fire frequency classes, fire frequency 1 (FF1) has maximum fire extent, whereas fire frequency 11 (FF11) has minimum fire extent, i.e., 1.17 ha. The area under specific fire frequency linearly declined with increased fire frequency (Table 3).

#### Forest type-wise fire incidents in STR

When considering forest type-wise fire study, the Southern dry mixed deciduous forests exhibit the highest number of fire frequency classes and account for the largest burnt area during the study period, i.e. 15,537.69 ha (Table 4). Immediately following these forests, the Southern dry mixed deciduous forest and dry savanna forests have a burnt area of 4989.6 ha. The riparian fringing forest did not experience any fire during the 25-year study period. The *Hardwickia* forests were exposed to a one-time fire in the highest fire year, i.e., 2005 only, and the burnt area was 0.36 ha. As per fire frequency, Dry deciduous scrub, Secondary dry deciduous forests and West coast semi-evergreen forests fall under fire frequency class 7, while the dry savanna and moist

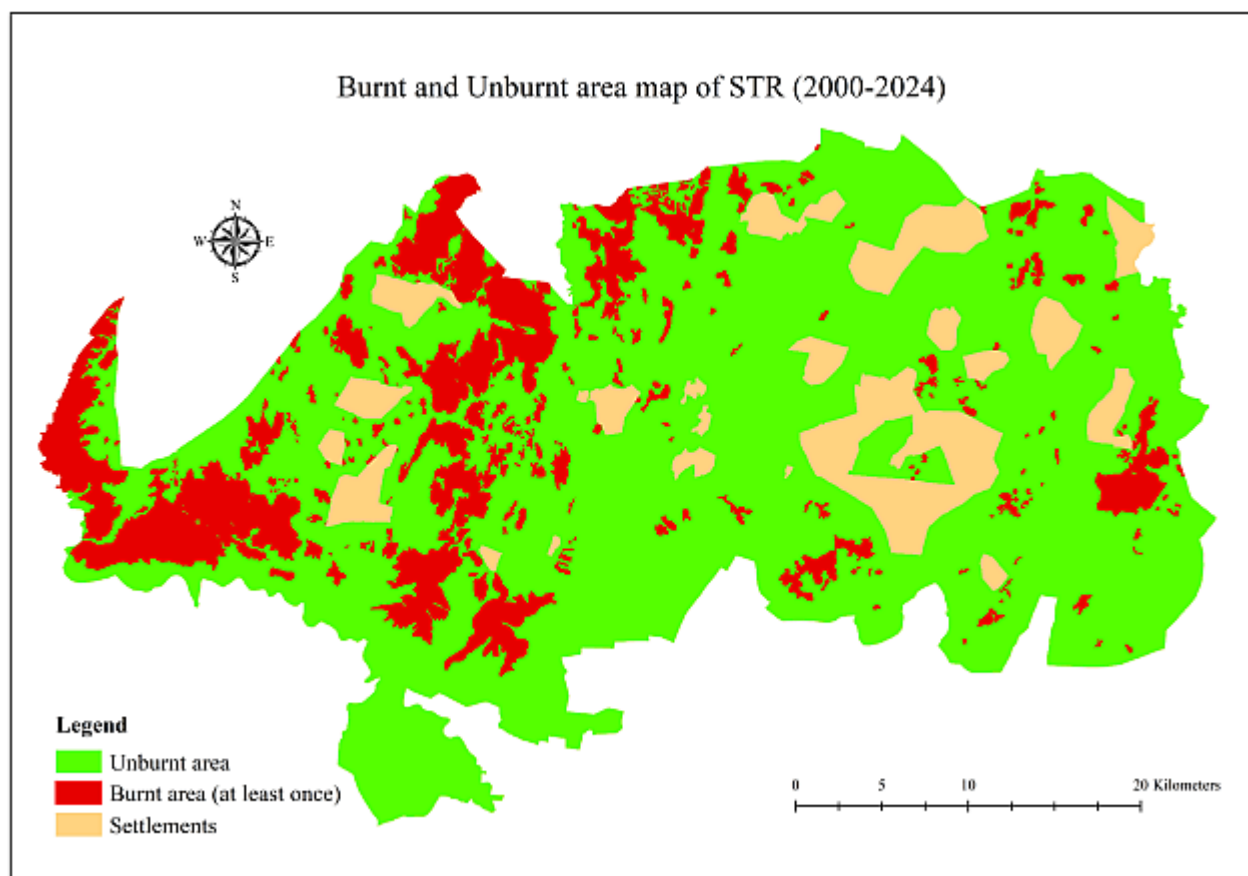


Figure 4. Burnt and unburnt area map of Sathyamangalam Tiger Reserve for the period of 2000 to 2024 (25 years)

Table 2. Burnt and unburnt area in STR

Burnt/ Unburnt	Area (ha)
Unburnt	106397.208
Burnt	27236.61

Table 3. Fire frequency and their spatial extent

Fire frequency	Area (ha)
FF0	106397.208
FF1	13620.69
FF2	6870.78
FF3	3219.3
FF4	2046.15
FF5	924.39
FF6	397.62
FF7	116.91
FF8	31.68
FF9	5.13
FF10	2.79
FF11	1.17

bamboo brakes are classified with a fire frequency of 6. All these forest types have a higher burnt proportion than the overall STR average, i.e. 20.38%. Regarding the proportion of burnt area, Dry deciduous scrub has 68.07% of the area burnt at least once. Dry savanna and Secondary dry deciduous forest showed a burnt area proportion of 49.85 and 24.04%, respectively.

Within the 25 years of the study period, the highest fire extent was observed in 2005 (Table 4). That year, 51% of Dry deciduous scrub and 23% of dry savanna were burnt by forest fire, the highest in terms of burnt area for both forest types. In 2009 and 2007, the burnt areas in STR were 8451.54 ha and 7988.58 ha, respectively. Fire-prone vegetation types such as Southern dry mixed deciduous forest, Dry deciduous scrub, and Secondary dry deciduous forest cover more than 70% of the vegetated area in STR (Table 1). A greater surface fuel load in these forests during the dry season makes them more susceptible to burning (Kodandapani et al. 2008). Dry tropical

Table 4. Forest type-wise fire frequency in STR. BAO : The area burnt at least once; BUP : Burnt Unburnt proportion

Forest type	Area (ha)	FF0	FF1	FF2	FF3	FF4	FF5	FF6	FF7	FF8	FF9	FF10	FF11	BAO	BUP
Dry deciduous scrub	2722.32	869.31	487.62	308.07	301.59	355.68	281.16	94.05	24.84	—	—	—	—	1853.01	68.07
Dry savanna forest	10008.36	5018.76	1725.21	1683.36	814.32	645.93	108.18	12.6	—	—	—	—	—	4989.6	49.85
Secondary dry deciduous forest	3374.1	2563.11	469.8	196.11	88.92	32.31	13.05	6.75	4.05	—	—	—	—	810.99	24.04
Southern dry mixed deciduous forest	78143.58	62605.89	8382.33	4017.87	1607.85	838.17	423.54	196.65	47.97	18.9	4.23	0.09	0.09	15537.69	19.88
West Coast semi-evergreen forest	12459.78	10727.1	1264.41	322.2	104.4	25.02	10.8	4.41	1.44	—	—	—	—	1732.68	13.91
Dry tropical riverain forest	2223.45	1968.75	171.72	71.1	8.73	3.15	—	—	—	—	—	—	—	254.7	11.46
Southern thorn scrub	82.89	76.5	0.36	0.36	1.62	4.05	—	—	—	—	—	—	—	6.39	7.71
Moist bamboo brakes	10127.7	9374.85	637.11	53.28	40.5	16.47	4.68	0.81	—	—	—	—	—	752.85	7.43
Southern thorn forest	9813.96	9693.63	74.88	20.97	23.85	0.63	—	—	—	—	—	—	—	120.33	1.23
Carnatic umbrella thorn forest	4130.46	4116.06	13.86	0.18	0.36	—	—	—	—	—	—	—	—	14.4	0.35
Hardwickia forest	423.09	422.73	0.36	—	—	—	—	—	—	—	—	—	—	0.36	0.09
Riparian fringing forest	36.9	36.9	—	—	—	—	—	—	—	—	—	—	—	0	0.00

rainforests did not experience any fire during the study period. This may be attributed to their proximity to water sources. Also, the running water bodies like rivers and streams act as natural firebreaks and prevent these forests from burning. The year-wise fire trend across STR showed a zig-zag pattern with years of greater fire extent consistently followed by years with a lower fire extent (Table 5). This trend suggests that the duration required for accumulating enough fuel for combustion is more than one year. Whether the amount of surface fuel or the distribution of fine fuels limits the fire extent can be a topic for further investigation.

After 2010, the cumulative burnt area in STR never exceeded 5000 ha. The forest department's active fire monitoring and fire suppression policy could be one reason. Furthermore, the current boundary of STR was added to the existing Sathyamangalam Wildlife Sanctuary in 2011. However, some portions of what is now STR were designated as part of the Wildlife Sanctuary in 2008. Further, Sathyamagalum Wildlife Sanctuary was declared as Santhymngalm Tiger Reserve in 2013. Tiger reserves in India receive the highest level of protection among protected areas. In addition, real-time monitoring of forest fire and fire alert systems (with the integration of advanced satellite remote sensing techniques and a geographical information system) such as the FSI Forest Fire Alert System (FAST 3.0) (<https://fsiforestfire.gov.in>) have enabled the forest staff to control the fire spread and mitigate fire that affects larger areas. In addition, strategic fire line clearances and firebreaks are being implemented to prevent fires from spreading from settlements and roads to wilderness areas.

## CONCLUSIONS

The study of STR reveals that the interplay between diverse topographic and bioclimatic variables contributes to a rich mosaic of forest types, each with its distinct fire regime. Topographic and bioclimatic variables vary markedly across the reserve, significantly contributing to its diverse floral assemblage. Our study showed that fire regime varies remarkably across forest types encompassing fire-dependent (open grassy ecosystems) and fire-independent ecosystems (close-canopied

Table 5. Forest type wise annual burnt area (ha) in STR

Forest type	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
West Coast semi-evergreen forest	0	141.12	5.13	8.73	49.32	94.23	11.88	257.31	5.94	278.46	3.33	27.45	89.55	88.83	685.53	161.19	135.54	34.11	0	148.41	1.98	15.57	7.83	8.73	113.94
Moist bamboo brakes	3.06	12.15	0	0	0	25.2	0	160.56	0	150.93	0	2.16	33.93	7.92	285.48	7.02	39.78	0	0	69.93	0	82.17	1.62	64.53	14.04
Riparian fringing forest	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Southern dry mixed deciduous forest	34.83	692.46	239.67	230.4	367.29	5282.64	388.89	5340.96	75.06	4940.1	3.24	124.65	1753.92	482.76	817.38	263.88	2512.53	107.1	64.26	2982.06	243.9	134.46	26.01	309.87	979.47
Dry deciduous scrub	65.16	587.61	0	21.51	0	1386.99	85.59	854.19	0	920.52	0	379.26	669.69	0.54	10.71	0	53.46	236.52	3.78	82.98	0	227.97	1.17	0	4.59
Dry savanna forest	1061.1	163.71	0	16.74	26.46	2293.74	651.24	1202.04	0	1845.81	0	1439.82	742.23	0	0	0	1276.29	2.07	0.9	17.1	0	22.23	0	0	4.5
<i>Harporhiza</i> forest	0	0	0	0	0	0.27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dry tropical riverain forest	2.43	19.8	0	0	11.43	72.45	18.72	14.04	0	85.14	0	33.21	16.74	0	0	0	38.34	1.17	0	34.65	0	4.14	0	0	0.54
Secondary dry deciduous forest	49.86	132.3	44.55	59.76	11.16	90.9	81.36	126	3.51	211.14	2.25	106.83	38.7	59.04	18.63	13.86	126.99	11.34	0	97.29	0.72	33.48	28.08	50.58	9.72
Southern thorn forest	5.13	0.27	0	0.54	0	47.61	53.73	25.29	0	11.07	0	48.78	0	0	0	0	0	0	0	0	0	0	0	0	0
Carnatic umbrella thorn forest	0	0	0	0	0	3.78	0	1.89	0	2.07	0	0	0	0	8.28	0	0	0	0	0	0	0	0	0	0
Southern thorn scrub	0	0	0	0	0	0	0	6.3	0	6.3	0	0	0	0	0	0	0	0	5.58	6.12	0	0	4.05	0	0

ecosystems). Thus, fire management actions should consider the ecology and well-being of the flora and fauna that rely on that forest. A one-size-fits-all fire policy may not be effective across all forest types and could negatively impact ecosystem structure and function. Our analysis indicates that forest fires in STR are small and patchy. Fire regime parameters should also be quantified through field studies along with moderate to high-resolution satellite imagery. Integrating field studies with GIS-based analyses will better equip authorities to implement effective fire management strategies.

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**Conflict of interest:** The authors declare no conflict of interest.

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