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An overview of tree ecology and forest studies in the Northern Western Ghats of India

Bhushan K Shigwan [1-2],
Aboli Kulkarni [1-3],
Vijayan Smrithy [1-2],
Mandar N Datar [1-2]

The forests of the Western Ghats (WG) of India are a highly diverse ecosystem though altered over time by human interference. The Northern Western Ghats (NWG) differ in bioclimatic and geological characteristics from the rest of the Western Ghats, featuring a mix of forested and open landscapes. Human activities such as shifting cultivation, cutting, lopping, periodic fire, constructions (road and dam), and mining have further increased their fragmentation, leading to a decrease in biodiversity. While the region has been extensively investigated for its floristic diversity, quantitative ecological studies are limited. This review seeks to identify research gaps and new research directions in the forest ecology of the NWG by compiling various periodical studies carried out in the region. It covers various works on vegetation types, species diversity and composition, and forest degradation due to anthropogenic activities. We provide compiled comparative vegetation types applicable to the region. The present review also discusses works carried out on forest areas under various protection regimes, such as legally protected areas, sacred groves, and private forests, using quantitative and remote sensing tools. We believe that understanding the NWG as an entire unit using uniform methods is essential, and this review serves as an important step in achieving this. It provides a comprehensive overview of the NWG, which can be used to plan out future research in this region.

Keywords: Fragmentation, Disturbance, Remote Sensing, Sacred Groves, Protected Areas

Introduction

Forests occupy around 31% of the Earth's surface and are among the most studied ecosystems (Raymond 2013, FAO/UNEP 2020). It is estimated that forests harbor more than 60% of all terrestrial animal and vascular plant species (Raymond 2013) and provide shelter to more than 75% of amphibians and birds. Therefore, the existence of these organisms directly depends on forests (FAO/UNEP 2020). The world's tropical regions have the most widespread forests and diverse ecosystems. Half of the tropical land (1.7 billion hectares) is covered with forests (Poker & MacDicken 2016). The occurrence of 60% of vascular plants indicates this region is an eminent reservoir of biodiversity (FAO/UNEP 2020). Several studies have been carried out in the tropics on tree diversity and composition of forests, addressing questions like spatial patterns (Condit et al. 2000), dominance and distribution (Pitman et al. 2001), beta diversity (Condit et al. 2002), structure and composition (Ganamé et al. 2019) and vegetation classification (Hall & Swaine 1976). Studies have shown that tropical tree diversity, floristic composition, and stand structure are influenced by environmental and geographic variables at local, regional, and global scales (Pennington et al. 2009, Blundo et al. 2012, Khaine et al. 2017).

Tropical regions of India have 22% of its geographical area occupied by forest and tree cover (FSI 2021). India is home to diverse forest types due to its wide range of climatic and geographical variations. They are classified according to climate, biogeography, and tree species composition (Champion & Seth 1968, Pascal 1988, Bahuguna et al. 2016). India is home to four world biodiversity hotspots, *i.e.*, regions with the highest diversity and number of endemisms, and are exposed to various anthropogenic disturbances, with the Western Ghats (WG) being one amongst them (Mittermeier et al. 2011).

Forests in the WG have been extensively studied for their floristic diversity (Ghate 2009, Nayar et al. 2014), tree composition and diversity across spatial (Ghate et al. 1998, Bawa et al. 2002) and temporal scale (Ayyappan & Parthasarathy 1999, Giriraj et al. 2010), forest dynamics (Elouard et al. 1997, Bhat et al. 2000), the effect of anthropogenic disturbance (Parthasarathy 2001, Muthuramkumar et al. 2006), diversity across altitudinal and latitudinal gradients (Rao et al. 2013), endemism (Gimaret-Carpentier et al. 2003, Pascal et al. 2004, Gaucherel et al. 2016) and effect of biotic and abiotic factors on vegetation (Page & Shanker 2018, 2020). The characteristic feature of the Western Ghats is a decrease in annual precipitation and an increase in the length of the dry period from the south to the north (Pascal 1988). Based on the geology and climatic variables, WG escarpments have been divided into northern (NWG), central (CWG), and southern (SWG) parts (Subramanyam & Nayar 1974, Pascal 1988). The NWG stands out due to its four months of rainfall, eight months of dry period, and lower elevations compared to CWG and SWG. The region is characterized by a unique mosaic of forested and open landscapes, with hills adorned by laterite and basaltic outcrops, creating a sea-

(1) Biodiversity and Paleobiology Group, Agharkar Research Institute, G.G. Agarkar Road, Pune- 411004, India.; (2) Savitribai Phule Pune University, Ganeshkhind, Pune-411007, India.; (3) Max Planck Institute of Plant Breeding Research, Carl Von Linne weg, Köln, Germany.

@ Mandar N Datar (mndatar@aripune.org)

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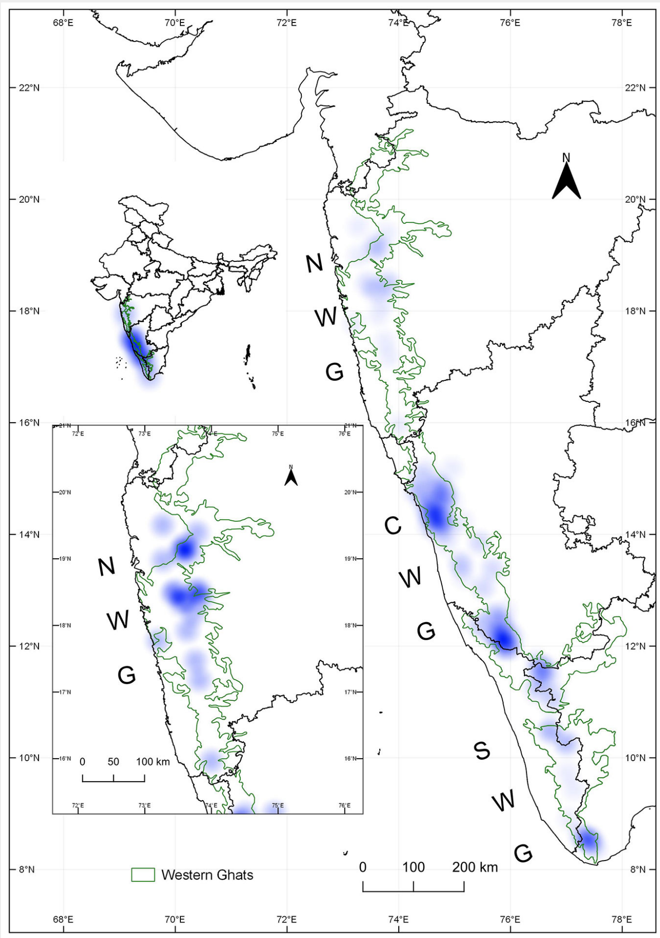

Fig. 1 - Map representing forest ecology studies of the Western Ghats, NWG-Northern Western Ghats, CWG-Central Western Ghats, and SWG-Southern Western Ghats (prepared based on literature).

sonal environment that sustains a diverse endemic herbaceous flora (Kulkarni et al. 2022). These open habitats are interspersed with patches of forest located in valleys, ravines, and plains. These forests are highly fragmented due to several anthropogenic activities. They are often only found in legally protected areas like sanctuaries and national parks and in community-protected areas like sacred groves and private lands. Despite their fragmented distribution, these forests act as repositories for medicinal plants, endemic species, and wild relatives of crop plants (Ghate et al. 2004). Except for a few sporadic ecological works in the forest fragments of NWG, it remains understudied mainly in terms of forest tree diversity, endemism, phytosociology, and influence of environmental and physical factors on vegetation compared to its counterparts (CWG and SWG – Fig. 1). This review is aimed to gain a comprehensive understanding of the forest ecology of NWG by compiling the various works carried out in the region. By doing so, it seeks to identify the research gaps in order to plan future studies in NWG. Thus, this review serves as an essential step in better understanding the fragmented and understudied tropical region in the biodiversity hotspot of WG and in aiding the conservation of its already fragmented patches.

Study area: Northern Western Ghats

The NWG lies between the latitudes 15° 48′ - 21° 00′ N and is about 750 km long, *i.e.*, one-third of the total length of the WG escarpment. The north-south boundaries of NWG are marked by the Tapti River, Gujarat, in the north, and the Kali River in Uttar Kannada of Karnataka state in the south (Pascal 1988). NWG occupies about 62,270 km² (33.75%) of the area and differs in geology, topography, and climate from its counterparts (Sawarkar 2014). Geologically, the entire NWG is composed of a massive Deccan basalt trap with a narrow coastal belt on the west and plateaus and plains on the east. The crest of NWG rises to 1600 m a.s.l., with the highest peak (Kalsubai – 1646 m) in Maharashtra. Low elevated Konkan coasts and certain high elevated areas in the latitude below 18° N have laterite caps that were weathered from the duricrusts (Kulkarni et al. 2022). NWG has four months of rainfall (July-October) and a prolonged eight months dry period. It receives rainfall of up to 5000 mm year^{-1} in the high-elevation mountain regions. The seasonal and rainfall variations influence the vegetation of NWG.

Literature search

A comprehensive literature survey was carried out to retrieve information about the past and present works on the forest ecology of NWG. Online resources (Web of Science® and Google Scholar®), books, research papers, review articles, and various reports were used. More emphasis was given to the studies conducted at a regional and local scale in NWG.

The Web of Science database (WOS 2023) was used to find relevant literature. A keyword search was conducted using the terms "Forest", "India", "Western Ghats", and "Northern Western Ghats" at different levels of literature search (Tab. 1). The keywords "Forest AND Northern Western Ghats" resulted in 85 studies focusing mainly on faunal investigations, geoscience, agronomy, soil science, and zoology. "Forest AND Northern Western Ghats AND Plants" resulted in 27 papers, which were on topics like forestry, environment science, mycology, limnology, ornithology, and new species discovery. After further scrutiny of forest vegetation studies, only eight studies related to the scope of the present review were found using WOS.

From the extensive literature search with Google Scholar and the Web of Science, a total of 159 publications were found for WG with an emphasis on NWG. A heat map of the 159 publications was prepared using the software QGIS to visualize the spatial distribution of literature (Fig. 1). The publications were selected with priority topics related to forest or tree vegetation, diversity, structure, composition, and driving factors (climatic, physical, and disturbance) from protected areas, sacred groves, and private forests across the Western Ghats. As the focus was exclusively on tree and forest ecology, the floristic studies (flora, checklists, inventories) were excluded. Fur-

Tab. 1 - Number of publications retrieved through Web of Science (WOS 2023).

Keywords	No. of Publications		
	As topic	As title	All fields
Forest	498,542	158,914	-
Forest and India	8,872	1,623	-
Forest and Western Ghats	1,562	242	-
Forest and Northern Western Ghats	92	0	-
Forest and India and Plant	1,919	74	5,295
Forest and Western Ghats and Plant	455	11	543
Forest and Northern Western Ghats and Plant	24	0	27

ther, to understand the scope of forest ecological studies, we reviewed a total of 34 exclusive publications from NWG, ten from NWG-WG, and 115 from WG. We classified those 34 publications into four categories: quantitative, qualitative, reports/ general articles, and remote sensing/GIS (Tab. 2).

Early attempts to understand NWG forests

The literature on ecological studies of forests of NWG is sporadic, beginning with Brandis (1883) describing how moisture and rain influence the forests and their distribution across India and Burma. Brandis's later work (Brandis 1897) mainly focused on forest cutting for timber, silviculture, and the beginning of the conservation of forests by the British Indian government. The vegetation of hill stations and pristine forest areas from regions like Mahabaleshwar, Matheran, Bhimashankar and Kolhapur were studied first (Satyanarayan & Mudaliyar 1959, Puri & Mahajan 1960, Gadgil & Vartak 1977). Other studies from the Pune region and around Pune city in NWG have documented the vegetation of dry tropical forests using quantitative methods (Puri & Jain 1960, Puri & Patil 1960, Brahme & Tetali 1986).

Classifying forests in NWG

Champion & Seth (1968) provided an exhaustive classification of 16 major type groups and 221 sub-type groups based on criteria such as physiognomy, structure, function, floristic composition, climate-moisture, rainfall, temperature, geography-elevation, location, and aspects. Out of these types, NWG shows seven major types and 11 sub-types (see Tab. S1 and Tab. S2 in Supplementary material). Additionally, each type was further classified based on dominant or characteristic species of that forest type, known as the "floristic series". The floristic series of a given plant community has a specific order of species, beginning with dominant and co-dominant species, followed by characteristic or climax species. However, many of these floristic series were created with limited data and a lack of confirmation from quantitative surveys, leading to confusion regarding forest management.

Bahuguna et al. (2016) revised the forest classification system by Champion & Seth (1968) that had been in place for over six decades. This study validated each forest type by conducting field observations that considered factors such as species composition, biotic pressure, management intervention, and climate influence. As a result, the survey modified the forest types to 10 major groups and 44 sub-groups, with NWG containing seven types (see Tab. S2 in Supplementary material).

Puri & Mahajan (1960) conducted a comprehensive local level study in the Mahabaleshwar forests of NWG, and identified four types of communities based on the percentage of occurrence of the species (community type mentioned in Tab. S3 – Supplementary material). However, no other quantitative information was considered in this categorization which was based solely on the percentage of occurrence of the species. Ghate et al. (1998) later, while classifying forests of WG, proposed a new type of "stunted semi-evergreen forest" for NWG, based on samples from 11 sites, of which four were semi-evergreen forests.

Tab. 2 - Distribution of the studies on NWG in different categories.

Category	No.	Region	Topic	Study by
Qualitative	1	Central Kokan	Sacred grove	Blicharska et al. 2013
	2	Matheran-Mahabaleshwar	Hilly forest	Bharucha & Ferreira 1941
	3	Pune	Sacred grove	Kulkarni et al. 2018
	4	Pune	Thorn forest assessment	Burns 1931
	5	Ratnagiri	Private forest	Patel & Agoramoorthy 2014
	6	Ratnagiri	Sacred grove	Takahashi et al. 2012
	7	Sindhudurg	Sacred grove	Patwardhan et al. 2021
	8	Sindhudurg	Vegetation characteristic	Dalavi et al. 2021
	9	Tansa	Protected forest	Veach et al. 2003
Quantitative	10	Amboli	Diversity, Structure and Composition	Tadwalkar et al. 2020
	11	Chandoli	Diversity, Structure and Composition	Kanade et al. 2008
	12	Koyna WLS, Chandoli NP, Radhanagari WLS, Phansad WLS and Mahabaleshwar	Dispersal mechanism	Tadwalkar et al. 2012
	13	Matheran	Vegetation type	Satyanarayan & Mudaliyar 1959
	14	Pune	Carbon sequesration	Hangarge et al. 2012
	15	Pune	Carbon sequesration	Konkane et al. 2018
	16	Pune	Dispersal mechanism	Watve et al. 2003a
	17	Pune	Diversity, Structure and Composition	Kasodekar et al. 2019
	18	Pune	Diversity, Structure and Composition	Puri & Jain 1960
	19	Pune	Diversity, Structure and Composition	Puri & Patil 1960
	20	Pune	Diversity, Structure and Composition	Watve et al. 2003b
	21	Pune	Ecological Impact assessment	Brahme & Tetali 1986
	22	Pune	Ecological Impact assessment	Punalekar et al. 2010
	23	Ratnagiri	Plant diversity	Gawade et al. 2018
	24	Satara	Diversity, Structure and Composition	Joglekar et al. 2015
	25	Satara	Diversity, Structure and Composition	Puri & Mahajan 1960
	26	Satara	Forest dynamics	Gadgil & Vartak 1977
Remote sensing & GIS	27	NWG	Forest cover	Panigrahy et al. 2010
	28	NWG	Forest fragmentation	Kale et al. 2010
	29	NWG	Foresty types-biomass	Das & Singh 2016
	30	Satara	Forest cover	Jaybhaye et al. 2021
	31	Harschandragad WLS	Forest fragmentation	Jaybhaye et al. 2022
Report & general	32	NWG	Forest landscape	Sawarkar 2014
	33	NWG	Habitat diversity	Ghate 2015
	34	NWG	Private forest	Kulkarni & Mehta 2013

A few researchers have attempted to analyze the vegetation structure and composition at the entire WG level (Pascal 1988, Ghate et al. 1998, Pascal et al. 2004). Pascal (1988) classified wet evergreen forests into various vegetation types based on their composition and floristic series. He used species or groups of species from the same genus, taking into account their abundance, ecological importance, and characteristic species to differentiate wet evergreen forests. He designated *Memecylon umbellatum–Syzygium cumini–Actinodaphne angustifolia* type for the mid-elevation forest of NWG based on northernmost sampling at Goa (16° N). However, vegetation further north of Goa was assumed to be the same type based on two hill station studies Mahabaleshwar (18° N – Puri & Mahajan 1960) and Matheran (19° N – Satyanarayan & Mudaliyar 1959) for the semi-evergreen forest. This type is compatible with "Montane sub-tropical forests" and "Western sub-tropical broad leaved hill forests" described by Champion & Seth (1968).

Recent studies examining the semi-evergreen forests of the NWG at local levels have identified various types and sub-types based on the Pascal (1988) classification (Watve 2001, Watve et al. 2003b, Kanade et al. 2008). Watve (2001) and Watve et al. (2003b), while investigating the fragmented forest in the Mulshi region, identified the vegetation types as *Dimpcarpus–Aglaia–Ficus nervosa* and *Memecylon–Xantolis–Actinodaphne* apart from *Memecylon umbellatum–Syzygium cumini–Actinodaphne angustifolia* (M-S-A) type. Similarly, vegetation studies in Chandoli National Park (Kanade et al. 2008) and Koyna Wildlife Sanctuary (Joglekar et al. 2015) from NWG have reported a poor representation of *Actinodaphne angustifolia*, leading to the suggestion of a new sub-type of M-S-A as *Memecylon–Syzygium–Olea*. A recent study by Tadwalkar et al. (2020) proposed a new type for the Amboli reserve forest area, *Memecylon–Syzygium–Diospyros.* Contrary to the standard definition of the floristic series, a few studies above considered only dominant and co-dominant species when determining the sub-types. The dominant and co-dominant species were obtained from the Importance value index (IVI) of quantitative studies, which is the combined relative value of density, frequency, and dominance (basal area) of each species.

Tab. 3 - A list of Protected Areas from Northern Western Ghats (modified from ENVIS 2022).

States	Protected Areas	Name	Designated on Year	Area (km^2)
Gujarat	Wildlife Sanctuary	Purna	1990	160.84
Goa	Wildlife Sanctuary	Bhagwan Mahavir	1967	133
	Wildlife Sanctuary	Bondla	1969	8
	Wildlife Sanctuary	Cotigao	1968	85.65
	Wildlife Sanctuary	Dr. Salim Ali Bird (Chorao)	1988	1.78
	Wildlife Sanctuary	Madei	1999	208.48
	Wildlife Sanctuary	Netravali	1999	211.05
	National Park	Molem	1992	107
Maharashtra	Wildlife Sanctuary	Bhimashankar	1985	130.78
	Wildlife Sanctuary	Kalsubai Harishchandragad	1986	361.71
	Wildlife Sanctuary	Karnala Fort	1968	4.48
	Wildlife Sanctuary	Koyana	1985	423.55
	Wildlife Sanctuary	Phansad	1986	69.79
	Wildlife Sanctuary	Radhanagari	1958	351.16
	Wildlife Sanctuary	Sudhagad	2014	77.13
	Wildlife Sanctuary	Tamhini	2013	49.62
	Wildlife Sanctuary	Tansa	1970	304.81
	Wildlife Sanctuary	Tungareshwar	2003	85
	National Park	Chandoli	2004	317.67
	National Park	Sanjay Gandhi NP	1983	86.96
	Conservation Reserves	Anjaneri	2017	5.69
	Conservation Reserves	Tillari	2020	29.53
	Conservation Reserves	Toranmal	2016	96.43
Karnataka	Wildlife Sanctuary	Bhimgad	2010	190.42
	Wildlife Sanctuary	Dandeli	1987	886.41
	National Park	Anshi	1987	417.34
Total area	-	-	-	*4804.28*

The vegetation/community type studies conducted in NWG showed that floristic series are different at the local scale. However, many fragments, valleys, and other protected areas occupied by semi-evergreen and deciduous forests are yet to be described in the NWG region. A more holistic approach to all other forest types in the NWG can lead to the precise identification of various vegetation types and subtypes.

Tree diversity, community structure and composition

Earlier floristic records, such as checklists and floras were not intended to collect quantitative data and did not assess the diversity, community structure and composition of local or regional areas. One of the early quantitative tree ecological works by Satyanarayan & Mudaliyar (1959) carried out at Matheran, showed that *Syzigium cumini* and *Syzigium heyneana* were dominant species. *Memecylon umbellatum* was ranked fifth in terms of its dominance and was known as a fast-growing secondary species in open canopy areas.

Watve et al. (2003b) investigated forest fragments in the Mulshi region of NWG using the transect cum quadrat method for studying the structure and composition. They recorded 52 species and a Shannon diversity index of 2.1 to 3.83; however, the species richness was low (12-20) at a local level. Though species diversity and dominance were comparatively lower in the other climax forests, a fair composition of evergreen species was observed in those forest pockets. To summarize, the quantitative studies carried out from 1960 to 2020 in NWG used various sampling methods, including random quadrats and transects of various sizes; the studies recorded 49-107, 444-4200 individuals with a Shannon diversity of 0-3.83. The basal area ranged from 6-72 m^2 ha^{-1} (Tab S3 in Supplementary material).

Studies on the regeneration of forests are limited in NWG. Some of them are species-specific or qualitative observations (Tetali & Tetali 2017) on the regeneration of secondary forests. However, regeneration status across different forest types of NWG is currently understudied.

Protected areas

In India, various protected areas and other forest types have undergone extensive studies to evaluate their vegetation diversity, composition, dynamics, and impact of human disturbances (Nath et al. 2005, Sagar et al. 2008, Uniyal et al. 2010, Naidu & Kumar 2016). The northern part of the Western Ghats and Konkan region alone harbour 27 Protected Areas (PA) spanning 4804 km^2 (Tab. 3). While qualitative studies classified forest types in some PAs, quantitative studies are fewer and more scattered compared to the Southern Western Ghats. A study using a belt transect at Chandoli National Park reported around 109 woody species and a new forest sub-type (Kanade et al. 2008). Similar research was also conducted in Koyna Wildlife Sanctuary (Joglekar et al. 2015) and Amboli Reserve Forest (Tadwalkar et al. 2020). Comparative account are given in Tab S3 (Supplementary material).

A few recent studies have explored a variety of ecological questions related to woody species in the Western Ghats. Watve et al. (2003a), using the transect cum quadrat method, investigated the seed dispersal mechanism in tree species from Mulshi and showed the dominance of zoochory in 108 species that were documented. Tadwalkar et al. (2012) examined the dispersal mode of 185 woody species from various protected areas, such as Koyna WLS, Chandoli NP, Radhanagari WLS, Phansad WLS, and Mahabaleshwar Ecological Sensitive Area and observed that the dispersal of zoochorous species is affected by disturbance.

Community protection or Sacred groves

Sacred groves (SG) are traditionally conserved patches of forests managed by local people and dedicated to a deity (Gadgil & Vartak 1975). These groves have been protected for long periods of time. They are subjected to various taboos prohibiting the cutting of trees or hunting of animals, as it is believed that it may incur the deity's wrath upon the village. These forests often contain rare and endangered species of plants, as well as giant lianas and trees (Gadgil & Vartak 1975, Ghate et al. 2004).

SGs are found across many parts of India, from Meghalaya in the northeast to Rajasthan in the west and various regions of WG (Gadgil & Vartak 1975). The WG is an abode of SGs, mainly distributed in mosaics of human habitation or agricultural lands or attached to long tracts of forest. Studies have been conducted to investigate the diversity of these sacred groves (Page et al. 2010), as well as their socio-economic implications (Chandrakanth et al. 2004). Comparisons of the diversity of sacred groves to other landscapes in SWG have also been explored (Ambinakudige & Sathish 2009).

Maharashtra is home to a number of sacred groves, ranging from 233-2800 in an area of 3570 hectares, mostly concentrated in the NWG and Konkan regions (Gadgil & Vartak 1980, Deshmukh 1999). There has been considerable research conducted on the socio-ecological (Blicharska et al. 2013, Patwardhan et al. 2021), floristics, conservation, vegetation, and ethnobotanical aspects of these sites (Ghate et al. 2004). There have also been some local studies conducted on their phytosociology (Gawade et al. 2018), carbon-biomass (Hangarge et al. 2012, Konkane et al. 2018), and degradation (Kulkarni et al. 2018).

Anthropogenic disturbances and forests of NWG

Anthropogenic disturbances in tropical forests around the world have become a pressing concern, posing significant threats to biodiverse ecosystems, which are diverse and impactful across the world. One of the major threats of tropical forests is selective logging, resulting in structural degradation, leading to alteration of ecosystems, and depletion of biodiversity (Edwards et al. 2014, Magrach et al. 2016). Additionally, mining activities, including gold mining (Sonter et al. 2017), open-pit mining activities (Pratiwi Narendra et al. 2021), and the development of plantation and crop monocultures (Edwards et al. 2013) have been shown to drive extensive deforestation, posing significant and potentially underestimated risks to tropical forests worldwide.

Despite affecting biodiversity, these human-caused activities have substantial consequences for the carbon cycle and climate change. For example, tropical forests that have undergone deforestation are recognized as a continuous net carbon source to the atmosphere, thereby contributing to carbon emissions, despite their initial status as carbon sinks (Mills et al. 2023). In addition, there is a lack of documentation regarding the carbon deposited in deadwood along a landscape-scale degradation gradient in tropical forests, suggesting that carbon stocks in degraded tropical forests may be underestimated (Pfeifer et al. 2015).

The majority of threats identified on a global scale align with observations in the Western Ghats. Recognizing the Western Ghats as biodiversity hotspots emphasizes both their rich diversity and the detrimental impact of human activities on the environment (Mittermeier et al. 2011). These activities, including shifting cultivation, cutting, lopping, periodic fires, construction (road and dam) for hydroelectric projects, and mining, have led to the significant destruction of forest cover in the region (Rao et al. 2013, Ghate 2015, Datar et al. 2019). In the Southern Western Ghats, Parthasarathy (2001) documented a moderate degree of anthropogenic influence on forest structure and species richness along elevation and slope. Muthuramkumar et al. (2006) identified disturbances as a major factor responsible for the negative influence on floristic structure and composition in the fragments of tropical wet evergreen forests. Anthropogenic disturbances have a profound effect on evergreen forests in the coastal areas of the Central Western Ghats, resulting in the local extinction of evergreen species and vegetation changes in secondary forests, and such forests also show less carbon sequestration potential (Rao et al. 2013).

Though NWG is a natural mosaic of forest fragments and human-dominated open habitats like outcrops and grasslands, limited studies have been conducted to investigate the effects of degradation on vegetation composition. One such isolated study in Tansa Wildlife Sanctuary reported a decrease in biomass, tree height, and density due to human disturbance (Veach et al. 2003). However, this study was based solely on observations and did not quantify the disturbance. A local study in the Mulshi area of NWG showed that despite the fragmentation, a patch of forest could harbor a large diversity of plant species (Kasodekar et al. 2019). A study investigating the effect of disturbance on the dispersal mode of woody species showed a decreasing trend in zoochory in disturbed areas (Tadwalkar et al. 2012). Watve (2001) and Watve et al. (2003b) studied forest fragments in the Mulshi region of NWG to analyze the impact of fragmentation on species richness, community dominance, and dispersal. In a recent study, Page & Shanker (2018) investigated the effect of the environment on the species composition of woody evergreen plants across the latitudinal gradient of WGs, including a few forest sites from the NWG. However, the influence of the environment on woody species from other forest types in the NWG is yet to be explored.

Community-protected areas like sacred groves are more prone to human intervention, yet very scanty research is available on tree species and disturbance in NWG. Kulkarni et al. (2018) showed that diversity decreases with increasing disturbance in a study conducted on 15 sacred groves of NWG.

Remote sensing and GIS studies

Leading-edge methodologies such as satellite remote sensing images and Geographical Information Systems (GIS) have revolutionized vegetation mapping studies worldwide. This rapid and cost-effective technique proves invaluable for mapping vegetation types and monitoring changes (Navalgund et al. 2007). In India, various attempts have been made to classify vegetation, monitor land use patterns, and estimate carbon sequestration potential (Joshi et al. 2006, Reddy et al. 2015, Roy et al. 2015, Kale et al. 2016, Ramachandra & Bharath 2020). Joshi et al. (2006) used phenological physiognomic vegetation type and multi-temporal satellite data to identify 35 vegetation classes, including 14 forest cover types in India. Similarly, Reddy et al. (2015) characterized 29 land use/land cover classes with 14 forest types and presented the percentage of vegetation cover across forest types and biogeographic zones. Roy et al. (2015) studied vegetation mapping for nearly one and a half decades using remote sensing. This research resulted in the classification of around 100 vegetation types, which were compared with vegetation maps from global studies and made publicly available (Roy et al. 2015).

In another GIS-based study focusing on the WG, Ramachandra & Bharath (2020) studied carbon sequestration and revealed that the forests of the WG region hold an estimated 1.20 MGg of carbon. There have been several other regional and local GIS-based studies with similar objectives, such as vegetation mapping, forest cover change, biomass, and fragmentation, across the WG (Kale et al. 2010, Panigrahy et al. 2010, Das & Singh 2016, Kale et al. 2016, Jaybhaye et al. 2021, 2022). Using remote sensing data, Ramachandra & Bharath (2020) found that there had been a 5% and 10% loss of evergreen and intact forests, respectively.

Panigrahy et al. (2010) conducted a forest cover change investigation in the NWG of Maharashtra over the period 1985-2005 and reported a yearly reduction of 0.5% in dense forest cover due to anthropogenic pressures. Kale et al. (2010) investigated the potential corridors and forest fragments adjoining protected areas in the nine protected areas of NWG. Das & Singh (2016) focused on forest diversity in four districts of NWG, estimating a total of 95.2 M tons of biomass from some vegetation types. More recently, Jaybhaye et al. (2021, 2022) conducted local studies in the Kas-Panchgani plateaus and the Harishchandragad Wildlife Sanctuary, respectively, and documented the loss of forest cover in the NWG over time.

Privately protected forests are an important source of refuge for biodiversity. Private forest refers here to "revenue lands that are privately owned, not used for agriculture, horticulture, construction, water, or other non-forest activities, and support some form of standing tree growth of native species or are capable of doing so with adequate protection and/or rehabilitation" (Kulkarni & Mehta 2013). Studies on private forests in the NWG are few and far between. Patel & Agoramoorthy (2014) highlighted their importance in the Ratnagiri region of the NWG, while Kulkarni & Mehta (2013) conducted a comprehensive study on private forests in five districts of the NWG, using remote sensing and GIS to track the extent, distribution, and dynamics of land use, and provide strategies for conservation and identify biodiversity corridors.

Future prospects and conclusion

In conclusion, the forest fragments of the northern Western Ghats are understudied compared to the southern and central regions. Although there have been a few studies on woody species diversity, composition, structure, and dispersal mode from some specific locations and regions, there is a need for further research into other unexplored regions of NWG. In particular, quantitative methods are needed to study the tree diversity and composition, and a large-scale investigation into all forest types of NWG is necessary to validate the earlier classification. By doing so, we can gain a better understanding of the floristic series of NWG. Additionally, studies should focus on forest regeneration, carbon sequestration, effect of physical and climatic factors on vegetation across forest fragments of NWG and compare the tree diversity and disturbance across different protection regimes, such as Protected Areas, Reserved Forests, Community-protected areas (sacred groves), and Private Forests. By doing so, we can better manage and conserve these forests for the continued benefit of mankind.

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Supplementary Material

Tab. S1 - Forest types occurring in Northern Western Ghats (NWG) and their details according to Champion & Seth (1968) with addition of latest literature and own observations.

Tab. S2 - Vegetation type applicable to forests of NWG according following studies.

Tab. S3 - Overview of quantitative studies from NWG.

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