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The Impact of Forest Disturbance on Tree Diversity, Biomass Carbon Accumulation, and Soil Nutrient Characteristics in Tripura, Northeast India

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ABSTRACT
This study examined the impacts of forest disturbances on tree diversity, carbon biomass storage, and soil nutritional attributes in the tropical moist mixed deciduous forests of Tripura, a region in North-East India. Based on the degree of disturbance, representative sites for the least disturbed natural forest (LDNF) and highly disturbed natural forest (HDNF) are identified. LDNF was more species diverse than the HDNF and exhibited an elevated tree density value of 162 stems ha^{-1}, primarily comprising *Microcos paniculata*. In contrast, in HDNF, the tree density was 255 stems ha^{-1}, primarily comprising *Shorea robusta. Careya arborea* and *Sterculia villosa* had the lowest tree density, at 5 stems ha^{-1}. The dominant species of LDNF is *Schima wallichii* (IVI=28.06), and *S. robusta* (IVI=59.77) in HDNF. *S. wallichii* (128.72 Mg ha^{-1} biomass, 64.36 Mg ha^{-1} carbon) showed significantly high biomass and carbon contribution among all species in LDNF. *S. robusta* (161.33 Mg ha^{-1} biomass, 80.67 Mg ha^{-1} carbon) contributed maximally in HDNF. Shannon-Wiener tree diversity index ranged from 2.05 to 2.70, the mean tree density from 648 to 955 stems ha^{-1} and the mean biomass carbon from 218.42 to 338.42 Mg ha^{-1} in the study area. While LDNF recorded higher soil organic carbon storage, HDNF exhibited higher carbon loss through harvesting and burning. As indicated by the correlation matrix, the depletion of the biomass reservoir wielded a noteworthy influence on both the carbon content within biomass and the characteristics of soil profiles. Disturbance plays a crucial role in regulating the ecosystem's biodiversity and its capacity to sequester carbon.

Key words: Carbon stocks, Diversity indices, Forest Disturbances, Management strategies

INTRODUCTION

Natural and man-made disturbances have a significant impact on the ecological structure and functioning of forests (Gogoi and Sahoo 2018). The population structure, tree variety, and natural regeneration of forest ecosystems are all affected by these disturbances (Dutta and Devi 2013). Predominantly instigated by human activities, the extensive disruptions in forested landscapes underscore the need to understand the intricate dynamics of when and how these disturbances impact the integrity of ecosystems, thereby influencing their capacity to provide indispensable services to society (Gogoi and Sahoo 2018, Wu and Loucks 1995). Illegal logging, overexploitation of forest resources, encroachment, and unregulated grazing represent a subset of anthropogenic elements capable of inflicting harm upon natural forest ecosystems; simultaneously, natural factors such as fires, storms, and the encroachment of invasive species also contribute to these ecological disturbances (Dutta and Devi 2013). Nations in the process of development, where tropical forests predominantly thrive, encompass some of the most compromised forest ecosystems globally (Gogoi and Sahoo 2018, Murali et al. 1996). The preservation of biodiversity and the utilization of tropical forest resources by humans often stand in conflict within developing nations (Singh 1998), while human-driven habitat destruction and degradation of tropical forests are the foremost contributors to the decline in global biodiversity (Dutta and Devi 2013). In light of the growing threat to biodiversity, it is crucial to understand how anthropogenic disturbances impact natural communities and their structural characteristics (Lalfakawma et al. 2009).

The Islands of Andaman and Nicobar, including the Eastern Himalaya, Northeastern India (along the), and some parts of the Western Ghats mountain range, combined fall under the tropical rainforest category (Gogoi and Sahoo 2018, Maduppa and Raman 2010).

Unfortunately, these beautiful rainforests are increasingly vulnerable to both man-made and natural forces. Several factors contribute to their degradation, including monoculture plantations, deforestation, the connectivity of roads and trains, industrialization, resource extraction from forests and other natural resources, developmental activities, and climate change. This represents a significant loss for the global biodiversity cycle. Habitat fragmentation resulting from human activities and its subsequent conversion remain pivotal factors driving the depletion of tropical forests. Deforestation in the highlands is so severe that it has a detrimental impact on the region's economy and ecosystem. The destruction of natural forests for human use also undermines crucial carbon sinks that are essential for stabilizing the climate in the future. It is important to protect and preserve these vital ecosystems for the benefit of future generations (Deb et al. 2020).

To gain deeper insights into the impacts of disturbances on the carbon cycles of regional forests, it is essential to classify natural ecosystems based on the severity of disturbances. This classification enables an evaluation of how disturbance components affect the capacity of these forests to sequester carbon. The present investigation focused on two distinct disturbance regimes in the forest ecosystems of the Sepahijala Wildlife Protected Forest area, aiming to understand the role of disturbances in influencing biodiversity attributes and their impact on carbon biomass contribution. The study also examines the impacts of disturbance on soil attributes and the relationship between various vegetation indicators and soil quality parameters, aiming to provide a better understanding of the role of disturbances on forest structural and functional attributes. This understanding may aid in the sustainable management of this vital Earth resource.

STUDY SITES

We selected two forest sites within the Sepahijala Wildlife Sanctuary, differing in the degree of disturbance, namely, the least-disturbed natural forest (LDNF) and the highly-disturbed natural forest (HDNF). The LDNF is located at 23.6670 N to 91.3200 E, and the HDNF is situated between 23.6500 N and 91.2940 E (Fig. 1). The area features

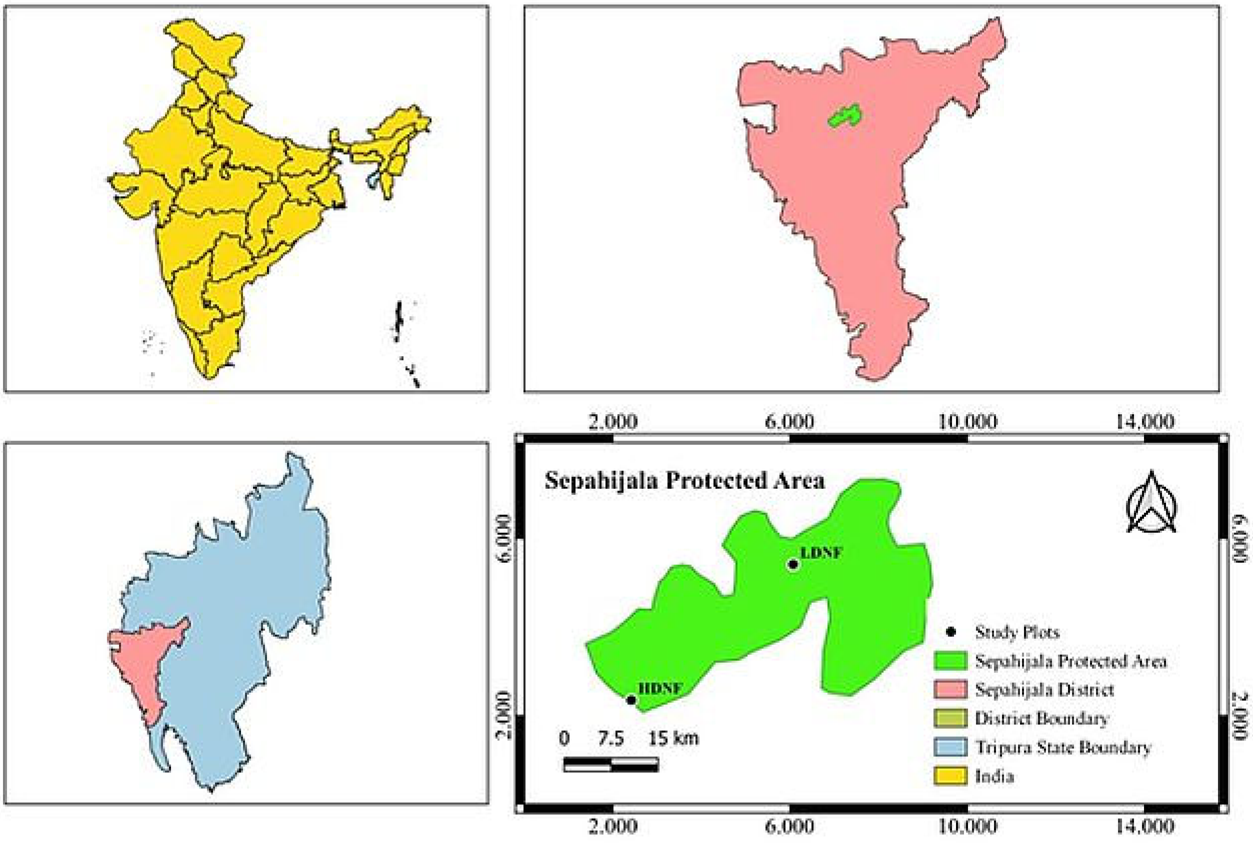

Figure 1. Map of the study area showing the location of sampling sites

a dense canopy comprising species characteristic of a moist mixed deciduous forest, as documented by Champion and Seth (1968). The study site encounters a blend of tropical monsoonal weather and subtropical humid conditions. The average temperature varies from 21 to 38°C in the summer and from 13 to 27°C in the winter, while the yearly rainfall ranges from 1922 to 2855 mm (https://www.en.climate-data). The forests are almost exclusively composed of species like *Artocarpus chama* Buch.-Ham. ex Wall., *Schima wallichii* Choisy, *Microcos paniculata* L., *Bambusa cacharensis* Schrad. ex J.C. Wendl., and *Terminalia bellirica* (Gaertn.) Roxb., *Shorea robusta* Gaertn., *Eucalyptus maculata* Hook., *Tectona grandis* L.f., *Holarrhena antidysenterica* (L.) Wall. ex A. DC., *Artocarpus lacucha* Buch.-Ham., *Syzygium cumini* (L.) Skeels, *Litsea glutinosa* (Lour.) C.B. Rob., *Litsea monopetala* (Roxb) Pers., *Lagerstromia speciosa* (L.) Pers., *Dillenia pentagyna* Roxb., *Ficus hispida* L.f., *Careya arborea* Roxb., *Lannea coromandelica* (Houtt.) Merr., *Aquilaria malaccensis* Lam., *Syzygium cerasoides* (Roxb.) Raizada and some other species patches along with vast numbers of bamboo breakes (such as *B. cacharensis, B. pallida* and *B. balcooa*). Forest floors were found to be almost devoid of annual and perennial flowering plants, tree seedlings, shrubs, herbs, and climbers. This natural dense forest area is also the vast habitat for numerous wildlife species, including Birds, Deer, Foxes, Monkeys, Phayre’s langur, Wild pigs, and Wild cats, along with many other animals, reptiles, and edible native taxa. Beyond these, Sepahijala WLS has been preserved for the famous Spectacles monkey and Clouded leopard of this state (Anonymous 2025).

METHODS

Sampling technique

We employed a non-destructive ground sampling approach to assess the vegetation and aboveground tree biomass in these two forests. In each of these sites, we established three permanent sample plots (250 x 250 m) (Singh and Dadhwal 2009). For the enumeration of tree diversity and biomass, each plot was subdivided into four sub-plots (each measuring 31.62 x 31.62 m) and two tiny quadrants (1 x 1 m) at each corner of the sub-plots for standing litter burn biomass. For the quantification of belowground dead-root biomass, soil samples were collected from 40 representative plots using a metallic soil corer (5.6 cm internal diameter). Finally, to gather field data for each forest type, we established a total of 24 tree plots, 48 quadrats for litter and burn biomass, and 72 soil samples.

Tree diversity and other vegetation indicators

The data records for the vegetation assessment were obtained using both qualitative and quantitative analysis methods. The quadrates were randomly set up for this purpose. During the vegetation survey, considerable portions of the tree species thriving in the wild were successfully identified. To facilitate this process, we gathered the distinct plant species, including their reproductive constituents, onto a newspaper and subsequently compiled them into a herbarium format designed for transportation to the laboratory for meticulous identification. The Department of Botany at Tripura University was consulted to identify the voucher specimens obtained with the help of Flora of Tripura State (Deb 1981). The diameter at breast height (DBH) measurements were recorded for all tree specimens with a diameter exceeding 10 cm, taken at a height of 1.37 m above the ground. These DBH measurements were subsequently used to analyse key variables, including basal area and tree density. To calculate species richness (S), we used the protocol developed by Magurran (1988). To compute the species diversity index (H’), species evenness index (e), and species dominance index (Cd), we applied the methods introduced by Shannon-Weiner (1963), Pielou (1975), and Simpson (1949), respectively. Conforming to the approach outlined by Curtis (1959), we also assessed various plant community metrics encompassing density, basal area, frequency, and the importance value index (IVI). The basal area at each specific site was defined as the cumulative cross-sectional area of all stems within 1 ha of land. In contrast, stem density represented the count of individual trees with a diameter of 10 cm or less at breast height.

Biomass and carbon stock estimations

We employed a non-destructive random sampling method to quantify the biomass and carbon reservoirs of numerous tree species. The computation of aboveground tree biomass (AGTB) was accomplished through the utilization of the Nath et al. (2019) allometric equation, while the belowground biomass (BGB) was estimated following the default formula outlined by IPCC (Anonymous 2019). In tandem, the biomass of understorey shrubs and herbs was assessed by subjecting samples to oven-drying at 105°C for 48 hrs. The computation of leaf litter biomass on the forest floor (LB) was executed using the phytomass formula formulated by Ajtay et al. (1979). Belowground root biomass (RB) was estimated according to the protocol outlined by McKell et al. (1961). The cumulative belowground biomass (BGB) encompassed the aggregation of both BGB and belowground root biomass (BGRB). In contrast, the aggregate aboveground biomass (AGB) entailed the summation of aboveground tree biomass (AGTB), LB, and the biomass of understorey herbs and shrubs. The overall biomass, denoted as TB, was calculated as the summation of AGB and BGB. Pursuant to the procedure outlined by Brown et al. (1989), 50% of the total biomass was acknowledged as the carbon stock representation. Through the summation of biomass carbon attributed to diverse components (AGB + BGB + understorey herbs and shrubs biomass + forest floor LB + belowground RB), an evaluation of the vegetation's carbon stock was conducted.

Anthropogenic disturbances

The assessment of anthropogenic disturbances within the forest ecosystems involved evaluating various parameters, including standing tree density (stems ha^{-1}), density of cut stumps (stems ha^{-1}), and the proportion of live trees exhibiting lopped branches, as outlined by Bhat et al. (2012). Additionally, the analysis incorporated two distinct disturbance indices: one based on the density of cut stumps (DI TD) and the other based on the total basal circumference of cut stumps (DI TBC), as established by Murali et al. (1996). The DI TD, a critical metric, was calculated by dividing the count of cut stumps per hectare by the total count of standing stems per hectare, and then multiplying the result by 100. Similarly, the DI TBC was calculated by dividing the combined basal circumference of all cut stumps within the forest by the sum of basal circumferences of all standing stems, and the result was multiplied by 100. To facilitate a comprehensive analysis, the forested areas under scrutiny were categorized into two distinct groups. The first group represented a highly disturbed natural forest (HDNF) characterized by an open canopy structure and situated beyond the buffer zone of a protected area. In contrast, the second group comprised a less disturbed natural forest within the confines of a designated protected zone (LDNF). The LDNF was chosen as a comparative reference point for the study.

Soil sampling and analyses

For a comprehensive soil profile analysis, soil samples were gathered from each designated study plot within the timeframe spanning September 2021 to April 2022. Each study plot encompassed four consecutive mini-plots, covering an area of 31.6 m^2 each. From these mini-plots, a total of four soil samples were collected. This collection process was facilitated using a metallic soil core measuring 20 cm in length, complete with an inner diameter of 5.6 cm. The sampling strategy involved extracting soil samples from three distinct depths within the soil profile: 0-20, 20-40, and 40-60 cm. This approach was consistently applied across each soil profile. In total, 72 soil samples were collected, comprising four quadrats, three soil profiles, and three soil replicates, encompassing both study sites (LDNF and HDNF) in the analysis. We took three replicates at each sampling site, combined and homogenized them to create a composite sample. In alignment with methodological rigour, three separate replicates were collected from each sampling site. These replicates were subsequently combined and thoroughly mixed to generate a homogenized composite sample, facilitating a robust and representative analysis of the soil samples. The gathered soil samples were carefully deposited into plastic zipper bags and promptly labelled on-site, after which they underwent air-drying at an ambient room temperature of 25-35°C. Subsequently, the samples were sieved through a mesh with a pore size of <1 mm, effectively eliminating stones, roots, and sizable organic remnants. Following this process, the soil samples underwent comprehensive analysis to assess their physical and chemical properties. We employed a diverse range of methodologies to assess the soil's characteristics comprehensively. To determine the soil colour, the Munsell Charts (Anonymous 1994) was used, while soil texture was evaluated using the Bouyoucos soil hydrometer method (Bouyoucos 1962). Soil moisture content (SMC) was calculated using the procedure described by Blake and Hedge (1986), and bulk density (BD) was determined through the soil-core method. The pH of the soil was measured according to the methodology proposed by Anderson and Ingram (1994). To quantify available Nitrogen (AVN), Subbiah and Asija's (1956) method was employed, while available phosphorus (AVP) availability in the soil was analysed using the approach outlined by Olsen et al. (1954). To ascertain the concentration of soil organic carbon (SOC%) within each sample, the rapid titration method devised by Walkley and Black (1934) was employed. Finally, soil organic carbon stocks (Mg ha^{-1}) up to a depth of 1 m were calculated using the formula by Blanco-Canqui and Lal (2008).

SOC Stock (Mg ha^{-1}) = 104 (m^2 ha^{-1}) × soil depth (m) × BD (g cm^{-3}) × SOC% /100

Data analyses

The study recorded the floristic composition and indices, total carbon stock of various tree components (including plants, roots, and litter), soil organic carbon (SOC) stock, soil nutrient properties, and anthropogenic variables. To assess the statistical significance of the difference between the mean values, a Z-test was performed using Microsoft Excel 2016. Additionally, the study employed PAST-Statistics Software to generate the correlation matrix (Hammer et al. 2001).

RESULTS

Detailed disturbance variables of the forest sites

Artocarpus chama, *Schima wallichii*, *Microcos paniculata*, *Bambusa cacharensis*, and *Terminalia bellirica* were common in both forest types. Some other major tree species occurring were: *Shorea robusta*, *Eucalyptus maculata*, *Tectona grandis*, *Holarrhena antidysenterica*, *Artocarpus lacucha*, *Syzygium cumini*, *Litsea glutinosa*, *L. monopetala*, *Lagerstromia speciosa*, *Dillenia pentagyna*, *Ficus hispida*, *Bombax ceiba*, *Acacia auriculiformis*, *Careya arborea*, *Lannea coromandelica*, *Bambusa pallida*, *B. balcooa*, *Aquilaria malaccensis*, *Syzygium cerasoides*, along with a significant amount of bamboo breaks, etc. The forest floor was almost devoid of annual and perennial flowering plants, tree seedlings, shrubs, herbs, and climbers. The HDNF was only 2-3 km from nearby communities, while the LDNF was more than 4-6 km from a human

Table 1. Details of the forest sampling sites in the Sepahijala protected area, Tripura

Physiographic and disturbance variables	LDNF	HDNF
Latitude	23.67 N	23.65 N
Longitude	91.32 E	91.29 E
Altitudinal range	58 m asl	52 m asl
Forest type	Moist mixed deciduous	Moist mixed deciduous
Distance from human settlements (km)	4-6	2-3
Cutting	Limited	Often
Lopping	Low	Moderate
Grazing	Not permitted	Often and high
Road connectivity	Present	Present
Alien invasion	High	Low
Degradation	Very low	Moderate
Human disturbances	Very low	High
Fire	Moderate	High
Collection of non-timber forest products	Limited and restricted	Often

LDNF = least-disturbed natural forest, HDNF = highly-disturbed natural forest

Table 2. Density (stem ha^{-1}), basal area (m^2 ha^{-1}) and, importance value index (IVI) of species in the two forest types of Sepahijala protected area

Tree species	**Family**	**Density**		**Basal area**		**IVI**	
		LDNF	**HDNF**	**LDNF**	**HDNF**	**LDNF**	**HDNF**
Acacia auriculiformis A. Cunn. ex Benth.	Fabaceae	15	-	1.09	-	10.06	-
Acanthus ilicifolius L.	Acanthaceae	5	-	0.18	-	3.96	-
Albizia lebbeck (L.) Benth.	Fabaceae	10	-	0.85	-	8.61	-
Artocarpus chama Buch.-Ham. ex Wall.	Moraceae	15	10	3.35	0.941	16.60	11.92
Artocarpus lacucha Buch.-Ham	Moraceae	-	35	-	4.903	-	22.56
Aquilaria malaccensis Lam.	Thymelaeaceae	-	15	-	0.916	-	10.23
Bambusa balcooa Roxb.	Poaceae	18	-	0.17	-	3.91	-
Bambusa pallida Munro	Poaceae	-	107	-	0.315	-	26.82
Bambusa cacharensis R.B. Majumdar	Poaceae	150	63	0.97	0.482	17.62	16.90
Bombax ceiba L.	Malvaceae	62	-	1.76	-	14.34	-
Careya arborea Roxb.	Lecythidaceae	15	5	0.84	0.402	9.22	10.12
Cassia fistula L.	Fabaceae	5	-	0.10	-	3.14	-
Cassia siamea Lam.	Fabaceae	5	-	0.21	-	4.33	-
Dillenia pentagyna Roxb.	Dilleniaceae	12	7	3.10	1.569	17.66	20.16
Eucalyptus maculata Hook.	Myrtaceae	65	-	9.85	-	16.10	-
Ficus hispida L.f.	Moraceae	12	-	0.51	-	8.25	-
Holarrhena antidysenterica (L.) Wall. ex A. C.	Apocynaceae	30	-	1.26	-	10.03	-
Lannea coromandelica (Houtt.) Merr.	Anacardiaceae	15	-	1.27	-	9.05	-
Lagerstroemia parviflora Roxb.	Lythraceae	5	-	0.15	-	3.76	-
Lagerstroemia speciosa (L.) Pers.	Lythraceae	13	-	2.18	-	14.58	-
Litsea glutinosa (Lour.) C.B. Rob.	Lauraceae	15	-	1.81	-	12.46	-
Litsea monopetala (Roxb) Pers.	Lauraceae	-	10	-	0.607	-	16.09
Microcos paniculata L.	Malvaceae	162	15	5.14	0.311	24.98	7.20
Schima wallichii Choisy	Theaceae	150	10	17.72	1.349	28.06	14.98
Shorea robusta Gaertn.	Dipterocarpaceae	-	255	-	22.921	-	59.77
Sterculia villosa Roxb. ex Sm.	Malvaceae	-	5	-	1.097	-	20.54
Syzygium cerasoides (Roxb.) Raizada	Myrtaceae	-	18	-	1.461	-	15.62
Syzygium cumini (L.) Skeels	Myrtaceae	8	-	0.87	-	7.90	-
Tectona grandis L.f.	Lamiaceae	53	-	4.57	-	13.06	-
Terminalia bellirica (Gaertn.) Roxb.	Combretaceae	35	55	1.04	1.499	11.52	20.53
Vitex peduncularis Wall. ex Schauer	Lamiaceae	-	13	-	1.179	-	15.66
Unidentified-1	Fabaceae	20	-	0.55	-	8.26	-
Unidentified-2	Unknown	35	-	1.35	-	11.97	-
Unidentified-3	Unknown	25	-	0.79	-	10.57	-
Unidentified-4	Unknown	-	22	-	0.224	-	10.89

LDNF = least-disturbed natural forest, HDNF =highly-disturbed natural forest, IVI = Importance value index population and was exposed to fewer effects of disturbance factors. The consequences of cutting, lopping, grazing, forest fires, degradation, NTFP collection, and human disturbances are all relatively higher or more numerous in this undisturbed forest plot (Table 1).

Tree composition, Species distribution and its Diversity indices

A total of 35 distinct tree species across 19 families were found in both the forest types. LDNF had highest tree density with *Microcos paniculata* having 162 stems ha^{-1}, closely followed by *S. wallichii* and *B. cacharensis*, both having 150 stems ha^{-1}. *S. robusta* had highest tree density at 255 stems ha^{-1}, and *C. arborea* and *Sterculia villosa* presenting the lowest values at 5 stems ha^{-1} in HDNF (Table 2). *S. wallichii* had maximum basal area (17.72 m^2 ha^{-1}), and *C. fistula* had the lowest basal area (0.10 m^2 ha^{-1}). In HDNF, *S. robusta* had the highest basal area (22.92 m^2 ha^{-1}), while an unidentified species (Unidentified-4) had the lowest basal area (0.22 m^2 ha^{-1}) (Table 2). *S. wallichii* showed higher dominance with an IVI value of 28.06 in LDNF, followed by *M. paniculata* (IVI = 24.98) and *D. pentagyna* (IVI = 17.66). In HDNF, the highest and lowest species dominance values were recorded for *S. robusta* (IVI = 59.77) and *M. paniculata* (IVI = 7.20), respectively (Table 2).

A total of 26 distinct tree species spanning 18 families were identified within LDNF, whereas HDNF showcased 16 tree species originating from 13 families (Table 3). Tree mean density was higher in LDNF with a count of 955 stems ha^{-1}, as opposed to HDNF's 648 stems ha^{-1}, although this discrepancy did not reach statistical significance ($p = 0.41$). The mean basal area mirrored this pattern, with LDNF exhibiting 61.68 m^2 ha^{-1} and HDNF displaying 40.17 m^2 ha^{-1} (Table 3). LDNF had a higher Shannon-Wiener tree diversity index. However, it was not statistically significant at $p = 0.20$, and Simpson's dominance index was marginally higher in HDNF stands ($p = 0.16$) for the protected tree species. However, LDNF had a significantly higher diversity of tree species compared to HDNF. Pielou's evenness index values demonstrated only a slight difference ($p = 0.05$), with higher values observed in LDNF compared to HDNF.

Distribution of biomass and carbon stocks

The distribution of biomass and carbon stocks among different species exhibited variations between the LDNF and HDNF sites (Fig. 2). The range of biomass distribution in LDNF was 0.62-128.72 Mg ha^{-1}, and in HDNF it was 1.30-161.33 Mg ha^{-1}. Similarly, the carbon distribution in LDNF ranged from 0.31 to 64.36 Mg ha^{-1}, and in HDNF, it ranged from 0.65 to 80.67 Mg ha^{-1}. In the LDNF, *Schima wallichii* emerged as the dominant contributor to both biomass and carbon, 128.72 and 64.36 Mg ha^{-1}, respectively (Fig. 2). This was closely followed by *E. maculata*, *M. paniculata*, and *T. grandis*. Conversely, in the HDNF site *S. robusta* was the primary influencer, presenting 161.33 Mg ha^{-1} of biomass and 80.67 Mg ha^{-1} of carbon. An unidentified species had the lowest biomass and carbon values within the LDNF, measuring merely 1.30 and 0.65 Mg ha^{-1}, respectively.

Table 3. Differences in the structural attributes and diversity indices of the forest sites

Parameters	**LDNF**	**HDNF**	**p-value**
Tree density (stems ha^{-1})	955 (30.16)	648 (7.43)	0.41
Basal area (m^2 ha^{-1})	61.68 (4.99)	40.17 (1.33)	0.40
Species richness (S)	26	16	-
Number of families (N)	18	13	-
Shannon-Wiener's diversity index (H')	2.70 (0.016)	2.04 (0.024)	0.20
Simpson's dominance index (Cd)	0.10 (0.002)	0.21 (0.009)	0.16
Pielou's evenness index (e)	0.83 (0.005)	0.74 (0.008)	0.05

Values are significant at $p<0.05$ level, LDNF = least-disturbed natural forest, HDNF = highly-disturbed natural forest. Values within the parenthesis represent standard error of means

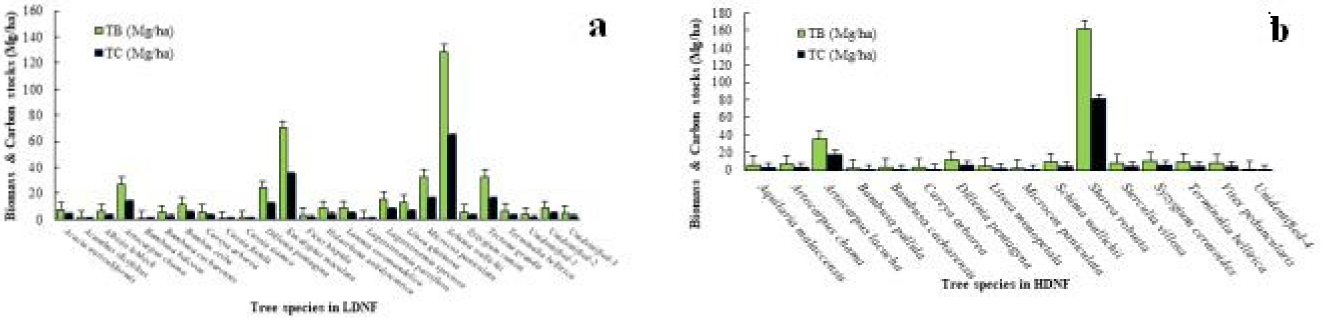

Figure 2. Distribution of biomass and carbon stocks in different tree species of Sepahijala protected area (a) least-disturbed natural forest (LDHF) and (b) highly-disturbed natural forest (HDNF). (TB; Tree biomass, TC; Tree carbon, LDNF; least-disturbed natural forest, HDNF; highly-disturbed natural forest)

Biomass and carbon storage in different pools

LDNF stand exhibited higher mean tree biomass carbon stocks in all components, excluding the burn biomass and harvested biomass pools (Table 4). LDNF stand (338.42 Mg ha^{-1}) demonstrated a significantly greater ($p<0.001$) aboveground biomass stock compared to the HDNF stand (218.42 Mg ha^{-1}). The belowground biomass pool also showed a comparable trend. The aboveground tree litter was insignificantly ($p = 0.31$) higher in LDNF than HDNF. The distinction in belowground root biomass between LDNF and HDNF did not show statistical significance ($p = 0.16$) (Table 3). Biomass resulting from forest floor burns did not differ significantly ($p = 0.17$), although it was greater in the LDNF compared to the HDNF. Similarly the harvested biomass carbon stocks were significantly higher ($p < 0.001$) in HDNF (32.01 Mg ha^{-1}) compared to LDNF (12.46 Mg ha^{-1}). The total tree biomass for LDNF (455.94 Mg ha^{-1}) was greater, though statistically not significant ($p = 0.48$) from HDNF (321.70 Mg ha^{-1}) (Table 4).

We recorded significantly greater aboveground carbon storage (AGC) in LDNF as compared to HDNF, (169.21 Mg C ha^{-1} in LDNF, and 109.21 Mg C ha^{-1} in HDNF). Similar pattern was observed in the belowground carbon (BGC) also, where LDNF displayed a value of 49.07 Mg C ha^{-1} as compared to 31.67 Mg C ha^{-1} by HDNF (Fig. 3). The root carbon pool and litter had increased carbon deposition in LDNF. However, HDNF experienced losses in the burned and harvested biomass pools, resulting in lower carbon stocks. There was no statistically significant distinction observed in soil organic carbon (SOC) stock (0-60 cm) between LDNF and HDNF, with LDNF recording a value of 140.50 Mg C ha^{-1} and HDNF measuring 121.63 Mg C ha^{-1} (Fig. 3). AGC, BGC, LTC, RTC, BBC, HBC, and SOC each contributed to the ecosystem's carbon stock in LDNF, with AGC being the most significant contributor at

Table 4. Biomass stock in different components of the natural forest sites

Biomass components	LDNF	HDNF	p-value
Above ground biomass (Mg ha^{-1})	338.42 (28.06)	218.42 (8.28)	<0.001
Below ground biomass (Mg ha^{-1})	98.14 (8.14)	63.34 (2.40)	<0.001
Above ground litter biomass (Mg ha^{-1})	3.06 (0.52)	2.78 (0.50)	0.31
Below ground root biomass (Mg ha^{-1})	1.02 (0.09)	0.87 (0.06)	0.16
Forest floor burn biomass (Mg ha^{-1})	2.84 (0.61)	4.28 (0.88)	0.17
Harvested tree biomass (Mg ha^{-1})	12.46 (1.67)	32.01 (3.90)	<0.001
Total biomass (Mg ha^{-1})	455.94 (54.68)	321.70 (34.41)	0.48

Values are significant at $p<0.05$ level, LDNF = least-disturbed natural forest, HDNF = highly-disturbed natural forest. Values within the parenthesis represent standard error of means

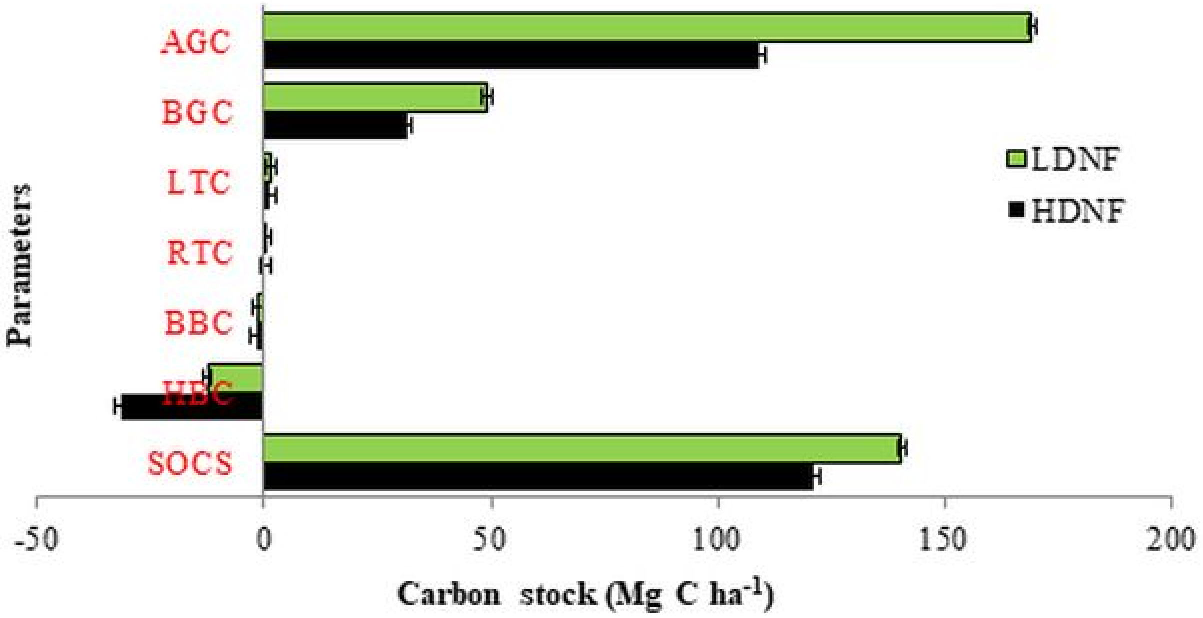

Figure 3. Distribution of carbon stocks (Mg C ha^{-1}) in different ecosystem components of two different disturbance regimes natural forest sites. (AGC; aboveground carbon, BGC; belowground carbon, LTC; litter carbon, RTC; root carbon, BBC; burn biomass carbon, HBC; harvested biomass carbon, SOCS; soil organic carbon stock)

48% followed by SOC (40.49%), BGC (14.14%), LTC (0.44%), RTC (0.14%), BBC (-0.40%), and HBC (-3.59%). In HDNF, AGC and SOC both made the most significant contributions, at 47.34 and 52.48%, respectively, followed by BGC (13.75%), LTC (0.60%), RTC (0.18%), BBC (-0.92%), and HBC (-13.90%) (Fig. 3).

Soil nutrient properties

While the least-disturbed natural forest had soil with dark greyish red to dusky red to dark red, the highly-disturbed natural forest had soil with dusky red to dark red (Table 4). The soil moisture content decreased with increasing depth in both forest types, but significantly varied ($p < 0.001$). The least-disturbed forest area (with moisture levels ranging from 16.54 to 18.70%) consistently maintained higher moisture content compared to the highly-disturbed site (which recorded moisture levels between 13.20 and 13.82%). The soil texture within the least-disturbed natural forest predominantly was clayish to sandy clayish and in the highly-disturbed natural forest it was sandy loam or sandy clayish loam. Soil bulk density in the least-disturbed forest (ranging from 1.19 to 1.34 g cm^{-3}) was comparatively lower than those found in the highly-disturbed forest (ranging from 1.30 to 1.34 g cm^{-3}), though the variation is not statistically significant ($p=0.29$). In the least-disturbed forest, the water-holding capacity reached its peak within the 40-60 cm depth range, and the lowest in the 0-20 cm depth range (42.96%). Conversely, in the highly-disturbed forest, the water holding capacity increased gradually with increasing soil depth (ranging from 40.38 to 50.24%), though it did not show any statistical significance. The soil pH exhibited a non-significant upward trend ($p=0.10$) with increasing depth across both forest types. Similarly, soil organic carbon also showed non-significant decrease ($p=0.14$) with soil depth increase, regardless of the forest type (Table 5). The concentration of soil organic carbon was higher in the least-disturbed forest (measuring 2.02%) as compared to highly-disturbed forest. Soil available nitrogen, showed non-significant ($p=0.39$) increasing pattern within the least-disturbed forest (ranging from 142.58 to 188.16 kg ha^{-1}) with decreasing depth. Conversely, in the highly-disturbed forest site, no discernible trend was evident (with values spanning from 117.08 to 148.68 kg ha^{-1}). The available phosphorus in the soil showed an opposite trend in

Table 5. Soil nutrient properties of the two forest sites

Soil properties	**LDNF**			**HDNF**			**p-value**
Soil depth	0-20 cm	20-40 cm	40-60 cm	0-20 cm	20-40 cm	40-60 cm	
Color	Dark reddish gray	Dusky red	Dark red	Dusky red	Dark red	Dark red	-
Texture	Clay	Clay	Sandy clay	Sandy loam	Sandy loam	Sandy clay loam	-
SMC (%)	18.70 (0.49)	17.87 (0.23)	16.54 (0.24)	13.82 (0.18)	13.58 (0.34)	13.20 (0.37)	<0.001
BD (g cm^{-3})	1.19 (0.03)	1.25 (0.01)	1.34 (0.04)	1.30 (0.02)	1.32 (0.03)	1.34 (0.02)	0.29
WHC (%)	42.96 (0.52)	46.44 (0.14)	52.48 (0.28)	40.38 (0.10)	44.12 (1.31)	50.24 (0.54)	0.32
pH	5.04	5.12	5.24	5.14	5.26	5.36	0.10
SOC (%)	2.02 (0.02)	1.84 (0.05)	1.70 (0.032)	1.68 (0.01)	1.74 (0.07)	1.50 (0.10)	0.14
AVN (Kg ha^{-1})	188.16 (10.86)	154.71 (4.18)	142.58 (2.66)	117.08 (3.62)	137.98 (12.54)	148.68 (8.14)	0.39
AVP (Kg ha^{-1})	135.34 (2.08)	120.72 (2.16)	110.48 (2.34)	88.08 (1.37)	98.22 (2.01)	106.12 (2.24)	0.10

LDNF = Least disturbed natural forest, HDNF = High disturbed natural forest, SMC = Soil moisture content, BD = Bulk density, WHC = Water holding capacity, SOC = Soil organic carbon, AVN = Available nitrogen, AVP = Available phosphorus. Values are significant at $p<0.05$ level, while values within the parenthesis represents standard error of means

both forest types, and varied between 110.48 and 135.34 kg ha^{-1} and 88.08 and 106.12 kg ha^{-1} in LDNF and HDNF, respectively. This difference was statistically non-significant with at p-value of 0.10 (Table 5).

Anthropogenic count and biomass losses

The sites with minimal disturbance had 955 stems ha^{-1}, while the sites with significant disturbance had 645 stems ha^{-1} (Table 5). However, the tree mortality parameters (cut stump density, broken stump density, and natural dead tree density) were found to be considerably (p=0.04, 0.07, and 0.05) higher in HDNF (92 stems ha^{-1}, 30 stems ha^{-1}, and 45 stems ha^{-1}), and the disturbance index for tree density was 5.23 for the LDNF and 14.26 for the HDNF. It is also worth noting that the standing tree biomass was much larger in LDNF (338.42 Mg ha^{-1}) than in HDNF (218.42 Mg ha^{-1}), but the cut stump and broken tree biomass were both higher in HDNF. The disturbance

Table 6. Density, biomass and disturbance index in moist deciduous forests in Sepahijala protected area

Tree & Disturbance components	**LDNF**	**HDNF**	**p- value**
Standing tree density (stem ha^{-1})	955 (30.16)	645 (7.43)	0.41
Cut stump density (stem ha^{-1})	50 (3.31)	92 (2.43)	0.04
Broken stump density (stem ha^{-1})	13 (0.56)	30 (1.79)	0.07
Naturally dead trees density (stem ha^{-1})	25 (1.27)	45 (1.41)	0.05
Total tree density (stem ha^{-1})	1043 (231.54)	812 (147.92)	0.46
Standing tree biomass (Mg ha^{-1})	338.42 (28.06)	218.42 (8.28)	<0.001
Cut stump biomass (Mg ha^{-1})	6.53 (2.08)	17.59 (2.58)	<0.001
Broken stump biomass (Mg ha^{-1})	0.91 (0.07)	4.06 (2.51)	0.07
Naturally dead tree biomass (Mg ha^{-1})	5.02 (0.70)	10.36 (2.76)	0.20
Total tree biomass (Mg ha^{-1})	350.88 (83.57)	250.43 (52.01)	0.47
Disturbance index			
DI TD (%)	5.23	14.26	0.05
DI TBC (%)	1.93	8.05	0.02

LDNF = Least disturbed natural forest, HDNF = High disturbed natural forest, DI TD = Disturbance index in tree density, DI TBC = Disturbance index in tree biomass carbon. Values are significant at $p<0.05$ level, while values within the parenthesis represents standard error of means.

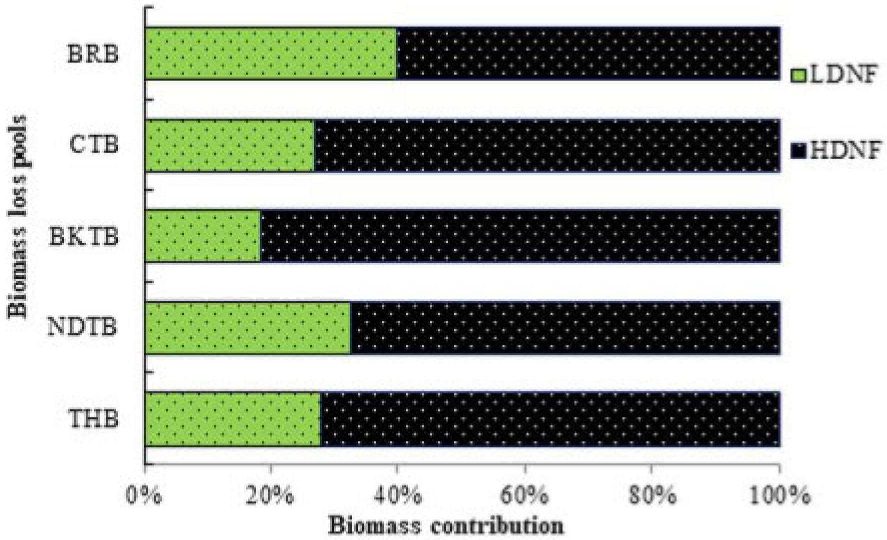

Figure 4. Contribution of biomass losses in two different disturbed forest ecosystem. BRB = Burn biomass, CTB = Cut tree biomass, BKTB = Broken tree biomass, NDTB = Natural dead tree biomass, THB = Total harvested biomass

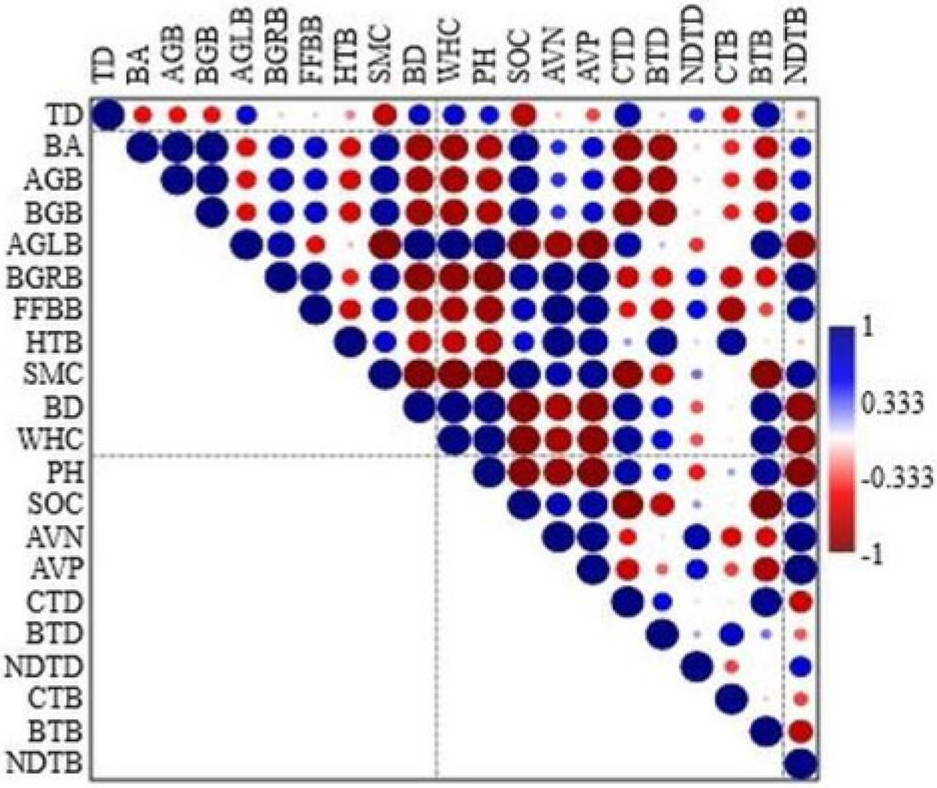

Figure 5. Correlogram plot showing the correlation between the trees structural attributes, tree biomass carbon stock, anthropogenic biomass losses, and soil nutrient properties (0-60 cm). Coloured circle (Dark blue-significant positive correlation, light blue-insignificant positive correlation, Dark brown-significant negative correlation, light brown-insignificant negative correlation, and small coloured circle show insignificant correlation. TD; Tree density, BA; Basal area, AGB; Above ground biomass, BGB; Below ground biomass, AGLB; Above ground litter biomass, BGRB; Below ground root biomass, FFBB; Forest floor burn biomass, HTB; Harvested tree biomass, SMC; Soil moisture content (0-60 cm), BD; Bulk density (0-60 cm), WHC; Water holding capacity (0-60 cm), SOC; Soil organic carbon (0-60 cm), AVN; Available nitrogen (0-60 cm), AVP; Available phosphorus (0-60 cm), CTD; Cut tree density, BTD; Broken tree density, NDTD; Natural tree density, CTB; Cut tree biomass, BTB; Broken tree biomass, NDTB; Natural dead tree biomass

index for tree biomass carbon was also highest in HDNF (8.05), while in the LDNF, the disturbance index was lowest (1.93) (Table 6). It is clear that the HDNF had a significant larger biomass losses compared to the LDNF site (Fig. 4). Specifically, the forest floor burn biomass (BRB) was found to be the highest in HDNF, accounting for 60% of the biomass loss. The contribution of cut tree biomass (CTB) was also higher in HDNF (76%). The natural dead and broken trees (NDTB and BKTB) in HDNF contributed to 91 and 74% of biomass loss, respectively. Overall, the total harvested biomass (THB) contribution was found to be greater in HDNF (77%), while it was lower in LDNF (23%) (Fig. 4). These findings suggest that the HDNF may be more susceptible to biomass losses due to disturbance, and thus may require additional conservation efforts to maintain its ecological balance.

Correlation matrix

The analysis of Pearson correlation coefficient revealed several significant and strong positive correlations between the tree biomass carbon and various tree characteristics, soil nutritional values, and other anthropogenic variables (Fig. 5). AGB stock ($r = 0.99$, $p<0.05$), BGB stock ($r = 0.99$, $p<0.05$), SMC stock ($r = 0.89$, $p<0.05$), and SOC % ($r = 0.92$, $p<0.05$) were all found to be significantly and positively correlated with basal area content. Similarly, the SMC stock and SOC percentage showed a high and substantial positive correlation between the AGB and BGB stocks ($r = 0.88$, $p < 0.05$), while the CTD stock and BTD stock formed a negative correlation ($r = -0.89$, $r = -0.87$, $p < 0.05$). Additionally, there was a high and significant positive association found between AGLB and BD ($r=0.99$, $p<0.05$), WHC ($r=0.99$, $p<0.05$), pH ($r=0.98$, $p<0.05$), and BTB stock ($r=0.92$, $p<0.05$). On the other hand, the FFBB stock ($r=0.96$, $p<0.05$), SMC stock ($r=0.90$, $p<0.05$), SOC % ($r = 0.87$, $p<0.05$), AVN ($r = 0.97$, $p<0.05$), and AVP ($r = 0.99$, $p<0.05$) were all significantly and favourably connected with the BGRB (Fig. 5). The remaining biomass component variables including FFBB, HTB, CTB, BTB, and NDTB, also showed their strong and substantial positive connection with various parameters like AGLB, BGLB, CTD, BTD, SOC, pH, AVN, and AVP. The correlogram for the soil nutrients pool indicated a substantial positive correlation between the SMC content and SOC ($r = 0.99$, $p < 0.05$), AVP ($r = 0.91$, $p < 0.05$), and NDTB stock ($r = 0.90$, $p < 0.05$). The BD stock showed a strong correlation with WHC, PH, CTD, and BTB stock ($r = 0.95$, $p < 0.05$) (Fig. 5). Additionally, pH had a significant correlation with CTD. It is interesting to note that both WHC concentration and SOC concentration had significant positive connections with pH ($r = 0.99$, $p<0.05$), CTD ($r = 0.89$, $p<0.05$), BTB ($r = 0.94$, $p<0.05$), AVP ($r = 0.89$, $p<0.05$), and NDTB ($r = 0.87$, $p<0.05$), respectively. Finally, both AVN and AVP showed a strong and positive correlation with NDTB stock ($r = 0.97$, $p < 0.05$). Overall, these findings can provide valuable insights into the relationships between various variables and inform future research and management efforts.

DISCUSSION

Forest disturbance and stand diversity attributes

Forest disturbances whether natural (such as wind throw, landslides, fire outbreak) or anthropogenic (logging, shifting cultivation and land conversion) significantly influence tree diversity and composition (Lalfakawma et al. 2009, Deb et al. 2021, Miambo et al. 2023, Behera et al. 2023, 2025a). When humans remove biomass from forests at a rate that is sustainable for the forest, the natural recovery of tree species can still be hindered by other human disturbances. Even after a disturbance, non-native tree species may take over and alter the forest's structure. A moderate level of disturbance can promote species diversity by creating gaps and enhance resource heterogeneity, which facilitate the recruitment of light-demanding species alongside shade-tolerant species. This aligns with intermediate disturbance hypothesis (Connell 1978) which suggests that diversity is maximized at intermediate disturbance levels. However, frequent or severe disturbances often lead to species loss, by creating dominance of a few opportunistic species, and the decline of the late-successional species, thereby reducing Shannon-Wiener diversity, species richness and evenness while the undisturbed forests maintain higher structural and compositional complexity. These differences are clearly reflected in the stand structural diversity attributes of the two forest types differing in disturbance regimes (Tables 2, 3). The LDNF exhibited a broader spectrum of species compared to the HDNF. This further evinces that the tree diversity is strongly linked to the variations in site quality and other factors as also argued by Thangjam et al (2022).

When our data were compared with other workers in the Indian sub-continent, it was found that our species-level tree density records were slightly higher than those reported in the earlier study by Gogoi and Sahoo (2018) in the Jeypore Reserve Forest (RF), Dehing-Patkai Rainforest, Dibrugarh Forest Division, Assam, Northeast India. However, they are comparatively lower than those found in the study of the Uttarakhand Forest area (Tiwari et al. 2019). Similarly, species-level tree dominance and basal area records were significantly higher than those reported by Deb et al. (2020) in three different disturbed natural forest plots in Tripura. As expected, various disturbances operating in ecosystems can disrupt the natural cycle of biomass and biodiversity production. The lower tree densities and basal area in HDNF than LDNF were due to the presence of more juvenile stand composition and exposure to natural and man-made disturbances in the former site. When juxtaposed with tropical wet evergreen forest stands subjected to human impact, our analysis unveiled that the less disturbed woodlands exhibited a notable profusion in tree species density (Bhuyan et al. 2003). Variables such as stand age, density, crown size, and site index were identified as influential factors shaping the basal area of tree species (Deetlefs 2010). Remarkably, the average basal area within the LDNF and HDNF sites investigated in this study surpassed the value reported in the adjacent Himalayan dry temperate forests, as well as in the sub-montane, montane, and sub-alpine zones (Haq et al. 2019, Malik et al. 2016). Nonetheless, it is noteworthy that these figures were slightly lower than the basal area observed in the natural forest cover of Uttarakhand, India (Kaushal et al. 2021). Notably, the tree density observed in our study areas was significantly greater than that documented in tropical forests of Tripura and the Bhuban Hills of Assam (Deb et al. 2020, Borah et al. 2014). Conversely, the tree density was comparatively lower than that recorded in the dry temperate forest of the Keran valley in the Kashmir Himalaya (Haq et al. 2019).

Our investigation has also revealed that long-term ecological and evolutionary processes intricately shape the diversity of trees within a forest ecosystem. These processes subsequently exert a profound influence on the overall community composition and structural dynamics (Verma et al. 2004, Singh et al. 2016, Haq et al. 2019). Notably, our study underscores that the forest site with the least human-induced disturbances exhibited a higher Shannon-Wiener diversity index value (2.70), in stark contrast to the heavily disturbed site (2.04). This discrepancy in values directly signifies a substantial divergence in the abundance and variety of tree species between the two sites. Furthermore, indices quantifying species richness and evenness displayed notably superior values within the least disturbed forest area compared to the highly disturbed counterpart. Interestingly, as the magnitude of disturbance escalated, a discernible reduction in tree species richness became evident. These discerning outcomes align with prior investigations conducted in the Uttarakhand and Manipur regions (Tiwari et al. 2019, Gogoi and Sahoo 2018), which similarly reported elevated diversity index values. However, it is also important to note that our findings differ from those of Raghubanshi and Tripathi (2009) and Deb et al. (2020), which were conducted in diversely disturbed forests spanning the Vindhyan highlands of the Indo-Gangetic plains and Tripura. Contrary to expectations, the forested area that has experienced the most significant degradation paradoxically exhibits better accessibility and transportation infrastructure compared to the less disturbed site (Deb et al. 2020). This might be the reason for higher tree species richness in the least disturbed sites. According to recent studies, the diversity values we have recorded demonstrate a noteworthy increase compared to previously reported figures from both disrupted and undisturbed natural forest sites (Singh et al. 2016, Rawat et al. 2018, Haq et al. 2019, Deb et al. 2020). Nonetheless, it is noteworthy that the disturbance index remained higher within the Biligiri Rangaswamy Temple Wildlife Sanctuary (BRTWLS), as reported in the study conducted by Murali et al. in 1996. In instances where forest ecosystems experience disturbances, degradation, and fragmentation, the local environment can become less hospitable for keystone resident species while becoming more favourable for forest immigrants, as discussed by Haq et al. (2019). These local-level structural changes can wield a significant influence on the indigenous forest species, potentially leading to shifts in floristic composition and the long-term functioning of the ecosystem. Recognizing the repercussions of such changes is crucial for safeguarding our natural environment, as emphasized by Shaheen et al. (2015) and Haq et al. (2019).

Effect of disturbance on biomass and C distribution

Disturbance regime is known to directly alter the aboveground and belowground biomass by changing the stand structure, density and crop composition (Thong et al. 2019, Gogoi et al. 2020), thus there were distinct variations in total biomass and carbon contributions between two forest stands in the present study. In HDNF, logging and clearing nevertheless reduced biomass, and these disturbances often released substantial carbon into the atmosphere. Many authors have opined that the recovery of biomass will depend on disturbance intensity, soil fertility and regenerative capacity of the forests (Thong et al. 2019, Gogoi et al. 2020, Singh et al. 2023.). Studies in tropical and sub-tropical regions have also shown that biomass and C recovery may take several decades in secondary forests, depending on the management and protection status of the area (Ahirwal et al. 2021a, Singh et al. 2023). Since forest biomass is the primary reservoir of terrestrial carbon, the disturbances would significantly affect C storage and fluxes (Thong et al. 2019). Many studies have shown that the land conversion and other disturbances have reduced the C stock in vegetation and soils while increasing C emissions (Ahirwal et al. 2022, Sahoo et al. 2019, 2023). This truly reflects why the LDNF stores more amount of biomass C than HDNF in the present study. Further high wood-density species like *S. wallichii* contributed more carbon per unit of biomass compared to low density species like *E. maculata.* Thus, the forests having species mixture with high density (LDNF) can maximize both short term C sequestration and long term C storage. Further, the superior value of diversity indices, biomass pools, and soil profiles in LDNF than HDNF implies that forest disturbances exert a substantial influence on the reduction of carbon and other ecological factors. These findings align with a prior investigation conducted within our region (Deb et al. 2020). The C allocations in different pools (AGB, BGB, SOC, litter, deadwood) is affected by systems with diverse and functionally complementary species that tend to exhibit higher productivity, and having least disturbances such as fire, and felling/harvested biomass. . Interestingly, both forest types showed that AGB makes a relatively larger contribution to the total biomass C stock (47.44-48.77%). Furthermore, the amount and relative contribution of BGB (13.75-14.14%) to the total biomass C stock played a significant role in belowground C storage. Similarly, decreased trash and root growth contributed to the formation of this biomass. Further, HDNF contributed somewhat more biomass from forest floor burns than LDNF (0.92%>0.40%). The higher stem density was correlated with increased overall averages of aboveground carbon, belowground carbon, litter biomass carbon, soil organic carbon, and total carbon accumulated depicting that arresting disturbance will bring significant improvement to the ecosystem health in term of forest structure, composition and soil health (Deb et al. 2020).

Our investigation revealed a tree biomass carbon stock ranging from 218.42 to 338.42 Mg ha^{-1}, a range notably surpassing that of a previous study conducted in Tripura (Deb et al. 2020), yet slightly lower than the findings reported by Gogoi et al. (2021). Litter output was found to be higher in LDNF than in HDNF in both above- and belowground pools, due to plant productivity, phenology, and seasonality (Das et al. 2022). Mature stands' tree density and basal area composition also had an impact on litter output. The litter generation figures in the present study showed comparability with prior biomass analyses published for the Forest ecosystems of Tripura and Mizoram, as evidenced by studies conducted by Das et al. (2022), Deb et al. (2020), and Gogoi et al. (2020). The two main disturbed pools of this ecosystem, burn biomass and harvested biomass, were found to be higher in HDNF than LDNF. The controlled forest fire produced the majority of the burn biomass. As expected, forest fires contribute to the emergence of new grasses and reduce the dominance of herbaceous vegetation. In addition to this, burning of the forest floor generates a significant amount of burned biomass, which can be an excellent source of phosphorus for soil profiles (Das et al. 2023). Moreover, the HDNF site documented the most substantial harvested biomass (32.01 Mg ha^{-1}), a significant difference when compared to the harvested biomass of the LDNF natural forest area (12.46 Mg ha^{-1}). The bulk of the gathered biomass consisted of naturally fallen, cut, and fractured trees from a forest ecosystem. In the two forest ecosystems studied, it was found that the cut trees generate a significant amount of biomass carbon, accounting for 52.41-54.95% of the carbon content in the harvested biomass pool. The biomass contribution from broken trees was also observed, ranging from 7.30 to 12.68%. Interestingly, naturally dead trees produced more biomass in the HDNF ecosystem and stored 32.36-40.29% of the harvested pool's biomass production. The primary reasons for harvesting in these ecosystems included the extraction of NTFP products, the cutting of bamboo and tree seedlings for domestic use, and natural disasters such as strong winds, tropical cyclones, drought, and tree diseases. SOC stocks exhibited a notable increase at the LDNF location (140.50 Mg C ha^{-1}) in contrast to the HDNF site (121.63 Mg C ha^{-1}), attributed to a higher litter decomposition rate within LDNF. It is intriguing to observe that the LDNF forest exhibits enhanced tree and undergrowth diversity compared to the HDNF forest site, which is characterised by a restricted range of tree species. According to research, the accumulation of litter on the forest floor plays a crucial role in supplying soil organic matter, as highlighted by Das et al. (2022), within these ecological systems. LDNF forest exhibits elevated SOC levels relative to HDNF, a disparity likely attributed to the higher litter decomposition rate within the LDNF site. The quantity of carbon present in the soil results from the equilibrium established between the input of forest floor litter and its subsequent decomposition, as evidenced by investigations by Williams et al. (2017), Ahirwal et al. (2021b) and Das et al. (2022). Our estimated values for cut stumps, broken stumps, and naturally fallen trees were significantly greater than those reported in earlier research, but lower than those reported by Malik et al. (2016).

Effect of disturbance on soil properties and nutrient storage

Soil properties and nutrient storage are intricately linked to the vegetation status, species composition and ongoing disturbances operating in an ecosystem (Pandey et al. 2022, Behera et al. 2025b).The removal of vegetation cover due to disturbance exposes the soil to erosion and leaching, leading to decline in total N, available P and exchangeable K. The HDNF had relatively lower values of nutrient properties that reflect the forest was subjected to repeated disturbances causing depletion of nutrients. On the other hand, the LDNF exhibited higher SOC, available N and Pindicating better nutrient retention and soil health. The soil color variations between the forests further indicated the status of soil health. The red colouration was suggestive of elevated levels of oxidised ferric iron oxides, whereas the presence of greyish shades suggested poorly drained soil conditions and extended periods of saturation throughout the soil profile. Moreover, the soil texture in the LDNF was mostly clay to sandy clay types, while the soil at the HDNF site was sandy loam to sandy clayish loam. These findings are consistent with the Asola-Bhatti Wildlife Sanctuary (ABWLS) study from Delhi, India, which also observed a similar soil colour gradient (Sharma and Chaudhry 2018).

The higher SMC in LDNF than HDNF may be due to the low gradient of forest disturbance and the ineffective deposition of the litter layer on the soil's upper surfaces. The SMC values in our study were significantly higher than those at four different sites with different disturbance regimes in the Asola-Bhatti Wildlife Sanctuary (ABWLS) in Delhi, India (Sharma and Chaudhry 2018), but quite similar to those in a study by Deb et al. (2020) in three different disturbed natural forest plots in Tripura. Across the four distinct disturbance regimes within the Asola-Bhatti Wildlife Sanctuary, the highly disturbed natural forest exhibited a range of bulk density values (1.30-1.34 g cm^{-3}) surpassing the values of the least-disturbed natural forest site (1.25-1.34 g cm^{-3}) within our study area. Although these values notably exceeded those reported by Deb et al. (2020), they remained notably lower than those observed in the investigation conducted by Sharma and Chaudhry (2018). The lower value of bulk density in soil profiles could be attributed to the efficiency of water content within the soil particles. Based on the data collected, the LDNF site (47.29%) has a slightly greater average soil water retention capacity than the HDNF site (44.91%). This is likely due to the LDNF site having higher pore spaces and less compaction, which allows for better water retention. Additionally, the LDNF site has greater control over decomposition rates and associated humus functions.

The soil profile in LDNF appears to be more acidic than at the HDNF location, with a pH of 5.13 compared to 5.25. This difference is attributed to the appropriate soil moisture and higher litter decomposition in LDNF, which has had fewer anthropogenic disturbances than HDNF. Notably, the values recorded in this study are significantly lower than those reported in previous research (Sharma and Chaudhry 2018, Deb et al. 2020). The soil organic carbon concentration in LDNF (1.70-2.02%) was non-significantly higher than in HDNF (1.50-1.74%), which may be attributed to increased litter formation and enhanced decomposition of material across the soil layers. The analysis reveals a significant disparity between the findings of the present study and those documented by Deb et al. (2020) and Hrahsel and Sahoo (2024). In their investigation, Deb et al. (2020) examined three disrupted natural forest plots in Tripura, along with four locations exhibiting diverse disturbance patterns within the Asola-Bhatti Wildlife Sanctuary in Delhi, as observed and documented by Sharma and Chaudhry in 2018. Our analysis has revealed a consistent downward trajectory in soil organic carbon across all soil profiles within the forest ecosystems. This phenomenon may be attributed to the swift leaching of vital soil nutrients, essential minerals, and decomposed organic matter from the uppermost soil layer to the lower strata. Higher soil available nitrogen (AVN) stock at LDNF, compared to the HDNF reflects the degraded status of the soil at the later than the former. These AVN results, however, were insignificantly higher than the AVN values (0-45 cm) observed in Tripura's natural forest ecosystems under three different disturbance regimes, as reported by Deb et al. (2020). Our study also found similar results for soil available phosphorus (AVP) stock (0-60 cm), with greater ranges observed in the LDNF (110.48-135.34 kg ha^{-1}) and smaller stocks in the HDNF site (88.08-106.12 kg ha^{-1}).

Anthropogenic pressure, disturbance indices and management implications

Anthropogenic pressure refers to the range of human activities that directly or indirectly affect natural ecosystem (Lalfakawma et al. 2009). These pressures significantly alter the structure, species composition and function of the ecosystem and therefore understanding the relationship between anthropogenic pressure and diversity indices is crucial for assessing ecosystem health and guiding conservation strategies. The Sepahijala protected forest region is home to a variety of tree species, including popular timber plants like *A. chama*, *S. wallichii*, *T. bellirica*, *S. robusta*, *T. grandis*, *As lacucha*, *S cumini etc.*, and some bamboo species like *B. cacharensis, B. pallida*, and *B. balcooa.*These species provide numerous tangible (productive) ecosystem services and therefore they are selectively harvested for the construction of houses, fences, stairs, fuelwood, and other home necessities. Research undertaken by Kaushal et al. (2021), Baboo et al. (2017), Dutta and Devi (2013), Pradhan et al. (2007), and Sapkota et al. (2009) has revealed the presence of these tree species across diverse woodland regions. However, in the present study on tree density disturbance index could be significantly higher in HDNF (8.05) than the LDNF (1.93) bringing substantial difference to the population structure in species-specific ways. Furthermore, the HDNF has experienced more forest fires than the LDNF due to its location farther from the protected buffer zone, resulting in some man-made fires and a regulated fire cycle by the forest department. These wildfires are a natural part of many forest ecosystems and can help clear out dead vegetation; release nutrients locked in plant matter, and promote the growth of fire-adapted species. The high disturbance index resulted in reduced species richness, lower biomass, carbon storage and altered soil nutrient properties. We therefore recommend that Sepahijala Wildlife Sanctuary be prioritized for restoration at the HDNF site while designating the LDNF as the core conservation areas. Further, efforts should be made to involve the communities around the sanctuary to participatory forest management to reduce pressures by promoting sustainable resource extraction and alternative livelihoods. Besides, regular assessments using the disturbance indices can ecological health and guide adaptive management strategies at Sepahijala Wildlife Sanctuary.

CONCLUSIONS

We assessed the effect of disturbance on tree diversity, carbon biomass stock, and soil nutritional characteristics in Sepahijala Wildlife Sanctuary. Our findings revealed that disturbances altered soil nutritional characteristics, tree diversity, biomass carbon stock, and floristic composition of the forest ecosystems in the sanctuary. The values of species richness, Shannon-Weiner diversity, carbon stock and soil properties were significantly lower at HDNF site than LDNF indicating participatory and policy-driven approaches to restore the forest ecological health and long-term ecological sustainability.

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