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RESEARCH

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Tree diversity, population structure, biomass accumulation, and carbon stock dynamics in tropical dry deciduous forests of Eastern India

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Abstract

Background Tropical dry deciduous forests are crucial for biodiversity conservation and carbon storage but are increasingly threatened by human activities and climate change. This Study evaluates tree diversity, population structure, and biomass carbon stock across five forest ranges of eastern India.

Methodology A stratified random sampling approach was implemented using a 5 km × 5 km grid for vegetational attribute studies. Tree diversity was assessed within 0.1 ha (31.62 m × 31.62 m) plots, while biomass estimation focused on trees with ≥ 10 cm. girth at breast height. Population structure and biomass estimation were analyzed across six defined girth classes, employing standardized protocols to ensure accurate carbon stock estimation.

Results A total of 80 tree species belonging to 68 genera and 33 families were recorded, with Fabaceae emerging as the dominant family. Significant variation in species richness (32–52 species), tree density (804–1332 trees/ha), and basal area (18.28–24.92 m^2/ha) was observed across the five forest ranges. Kolabira forest range (3.45) and Bagdihi forest range (3.37) exhibited the highest diversity indices, highlighting their ecological significance and carbon sequestration potential. Mid-sized trees (32–101 cm) contributed the most to biomass accumulation, while the lower densities in other size classes suggest selective exploitation. Total biomass was highest in Belpahar forest range (129.63 Mg/ha) and lowest in Jharsuguda forest range (86.73 Mg/ha), with a corresponding biomass carbon stock of 58.47 MgC/ha and 40.76 MgC/ha, respectively, emphasizing spatial variations in carbon storage across these dry deciduous forests.

Conclusion The findings highlight the ecological significance of tropical dry deciduous forests and underscore the urgent need for conservation strategies to safeguard biodiversity and enhance carbon storage. In parallel, the study offers a valuable scientific foundation for advancing forest management practices and shaping policies to address biodiversity loss and climate challenges in this vital region of India.

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Keywords Tropical dry deciduous forests, Tree diversity, Population structure, Carbon stock, Conservation strategies

Introduction

Tropical forests, among the richest ecosystems on Earth, support approximately two-thirds of global biodiversity [1, 2]. These forests play a critical role in sustaining both local and global biodiversity and mitigating climate change by providing essential ecosystem services, such as carbon sequestration, soil conservation, and water regulation [3–5]. Ecosystems within tropical forests, characterized by their high species diversity, support organisms with efficient resource acquisition traits, which significantly contribute to biomass and carbon storage [6–11]. This relationship aligns with the "niche complementarity" hypothesis, proposed by Harper [12] and Tilman et al. [6] which postulate that increased species diversity enhances resource use efficiency, thereby boosting biomass carbon accumulation in species-rich ecosystems. Furthermore, diverse species compositions in forest stands can enhance carbon sequestration through varied growth patterns and productivity rates, collectively promoting biomass accumulation and soil carbon retention [13–16]. By performing these vital functions, forest ecosystems play a key role in stabilizing ecological processes and regulate climate dynamics [17, 18]. Accordingly, biodiversity and carbon sequestration research have become focal points in present-day ecological studies [19].

India's tropical forests are a repository of exceptional biological diversity, playing a vital role in global climate regulation, maintaining the carbon cycle, and delivering crucial ecosystem services that are essential for both community welfare and ecological balance. However, increasing deforestation and changes in land use, primarily driven by the escalating demands of a growing population, are severely disrupting these ecosystems and compromising their self-regenerative capacity [20]. From 2001 to 2018, the country faced an annual deforestation rate of 3.0%, leading to a 19.1% reduction in tree cover [21]. Forest areas have been increasingly converted into agricultural land or used for infrastructure development, which has significantly impacted native tree species and diminished the carbon sequestration capacity of these environments [22, 23]. Despite these challenges, India has experienced a modest increase in total carbon stocks, reaching approximately 7,285.5 Mt up by 81.5 Mt rise compared to previous assessments. The annual carbon stock increment is estimated at 40.75 Mt, equivalent to 149.42 Mt of CO_2. Among various forest carbon pools, soil organic carbon constitutes the largest share (55.06%), followed by above-ground biomass (32.69%), below-ground biomass (10.09%), litter (1.48%), and dead wood (0.78%) [24, 25]. However, this growth is uneven, as more than 40% of India's forests remain degraded and under-stocked due to intensifying human activities and urbanization [25, 26].

As of 2024, global temperatures continue to exhibit alarming upward trends, making 2024 the warmest year ever recorded [27]. While international efforts such as the Paris Agreement and activities under the UNFCCC represent significant initial steps in addressing climate change, they remain insufficient for fully achieving effective climate mitigation. Current Nationally Determined Contributions (NDCs) also lack the necessary ambition to constrain global temperature rise within the critical threshold of 1.5 °C [28]. As part of NDC under the Paris Agreement, India has committed to voluntarily creating an additional carbon sink of approximately 0.03Pg of CO_2 by 2030. Achieving this target aligns with India's broader ambition to attain net-zero emissions by 2070 but will require expanding forest cover by approximately 25–30 million hectares, equivalent to nearly one-third of the country's existing green cover. Tropical forests, comprising approximately 86% of India's total forest area [21], play a pivotal role in enhancing carbon sequestration, emphasizing the need for their effective conservation and management to achieve the long-term NDC targets [29]. However, there is a lack of comprehensive data on land use and carbon fluxes, resulting in significant gaps in regional carbon accounting. Nature-based solutions such as reforestation, conservation, restoration, and sustainable management of tropical forests are increasingly recognized as cost-effective strategies to control carbon emissions and climate change [30]. To support adaptive management and policymaking, regular monitoring of carbon reserves and biodiversity in these forests is essential [31]. This need is especially urgent for India, the world's third-largest greenhouse gas emitter (6.8%), after China and the United States [32, 33].

Jharsuguda, often called the "Powerhouse of Odisha", is a key industrial area supported by its rich coal deposits, thermal power plants, and various industries. The Confederation of Indian Industry (CII) has identified Jharsuguda as a major center for industrial growth in Odisha, ranking it first in the state's Industrial Performance Index [34]. However, this rapid industrial growth has caused serious environmental issues, including deforestation, habitat loss, and pollution [35]. These problems have led to biodiversity loss and increased carbon dioxide emissions beyond what natural forests can absorb. However, despite its intended benefits, the effectiveness of Joint Forest Management (JFM) in Odisha has been limited due to weak community participation, inadequate funding, and unresolved conflicts over resource rights [36]. There are no specific studies have been conducted regarding the district's biodiversity or the threats it faces from coal exploration and land degradation. However, recent research has highlighted that, Jharsuguda district experienced a major land use land cover (LULC) shift in last few decades with severe forest degradation, increased fragmentation with alarming increases in Non-forest and built up areas [37]. Such findings warrant an urgent need to study the increasing pressure on Jharsuguda's remnant forests with more scientific research to better understand the status of forest biodiversity, species composition, and its potential to regulate climate change by sequestering carbon dioxide from the environment [19, 31, 38–40].

In this context, the present study represents the first comprehensive assessment of biodiversity and carbon stock across five forest ranges in the district. By integrating evaluations of floristic diversity, biomass estimation, and carbon sequestration potential, an approach not previously undertaken in this district, addresses an important knowledge gap. Furthermore, it establishes baseline data critical for future ecological monitoring and targeted conservation initiatives. By quantifying carbon stocks, this research emphasizes the forests' substantial role in regional and national climate action strategies. Ultimately, this study highlights the significance of preserving tree diversity and enhancing carbon storage, thus informing policy decisions and contributing to global efforts in combating climate change and promoting biodiversity conservation [5, 17, 22].

Materials and methods

Study area

This study focuses on Jharsuguda district, located on the eastern coast of Odisha, India, between latitudes of 21° 31' *N* and 22° 03' *N* and longitudes of 83° 27' E and 84° 23' E. (Fig. 1a and b). Covering a total geographical area of 2,114 sq. km, the district is bordered by Sundargarh to the north, Bargarh to the south, Sambalpur to the east, and Chhattisgarh to the west [41]. Tropical dry deciduous forests cover 21.64% of Jharsuguda's area, with Sal (*Shorea robusta*) mixed dry deciduous forests being the main vegetation type [42, 43]. These forests, making up 38% of India's tropical forests, are a major forest type in the country [21]. As per the District Disaster Management Plan [44], the region receives an average annual rainfall of 1,099.36 mm, with temperatures ranging from 18 °C to 32 °C and relative humidity levels between 15.6% and 99.1%. The district has an average elevation of 230 m above mean sea level (AMSL). The study was conducted in five distinct forest ranges of Jharsuguda forest division: Bagdihi, Belpahar, Brajrajnagar, Jharsuguda, and Kolabira, each varying in vegetation density, species composition, and anthropogenic influences [41]. Furthermore, the forests here contribute substantially to Odisha's biodiversity, hosting flora and fauna that support the livelihoods of local communities and provide ecosystem services essential for climate regulation [43]. The tropical dry deciduous forests of Jharsuguda are part of the larger

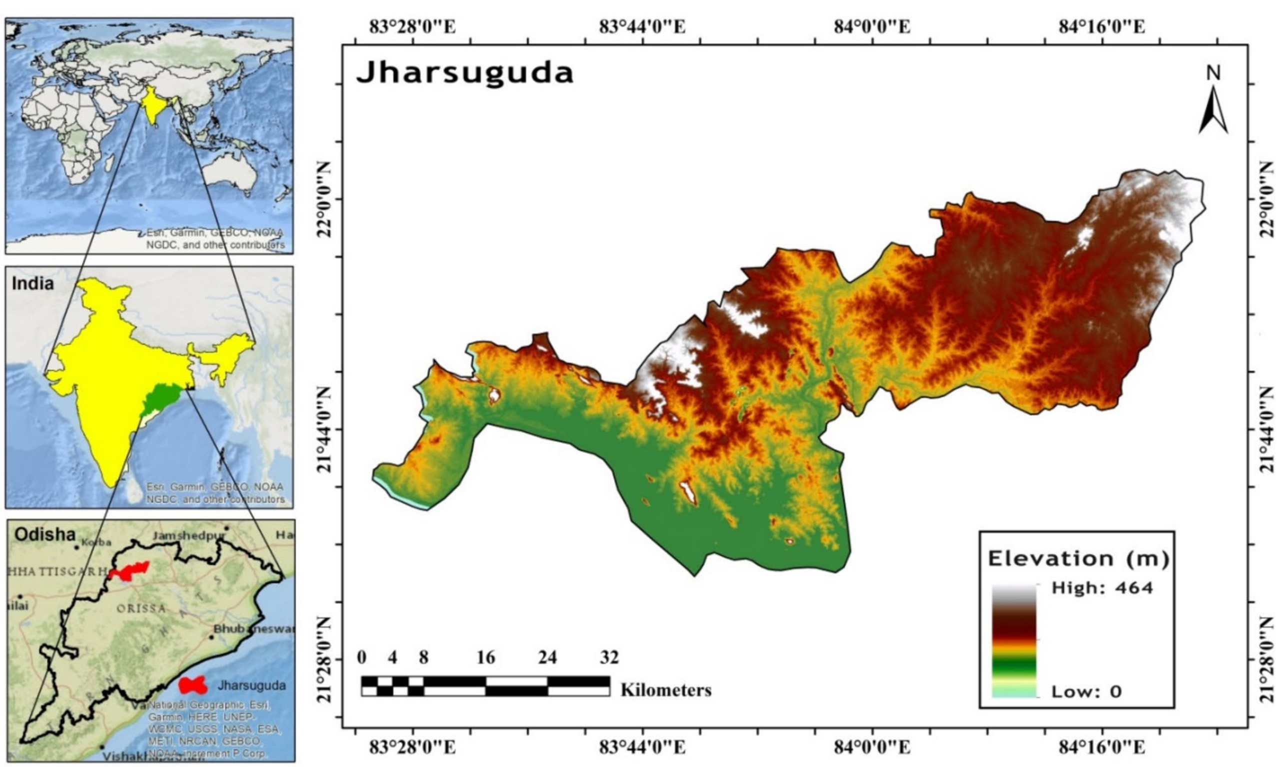

Fig. 1 (**a**). Geographic representation of the study area depicting the digital elevation model

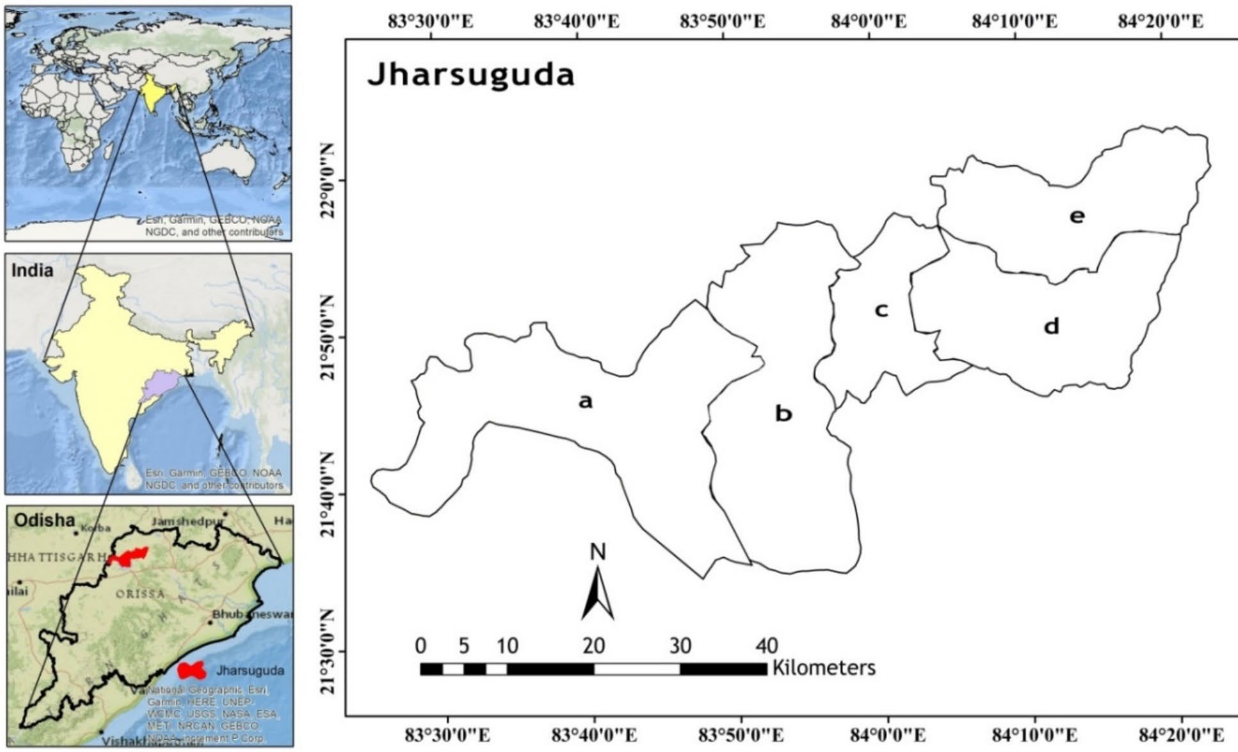

Fig. 1 (**b**). Map depicting the geographical boundaries of the five forest ranges studied within Jharsuguda district: (**a**) Belpahar, (**b**) Brajrajnagar, (**c**) Jharsuguda, (**d**) Kolabira, and (**e**) Bagdihi

northern Eastern Ghats ecosystem, which comprises rich and diverse flora, including economically significant species such as *Terminalia arjuna*, *Diospyros melanoxylon*, *Madhuca indica* [41] and many more. These forests provide vital ecosystem services, including carbon storage in both above-ground and below-ground biomass, and they support a range of traditional uses for local communities [45, 46]. Due to their seasonal climate, these forests experience a cyclic shedding of leaves, allowing for nutrient recycling within the ecosystem and promoting soil fertility, which sustains diverse understory vegetation. However, these forest ranges are facing pressure from deforestation and land-use changes, particularly due to industrialization and urban expansion in Jharsuguda, a region known for its mining and industrial activities [47–49].

Sampling methods

To assess tree diversity and population structure across the five forest ranges of Jharsuguda, a grid based stratified random sampling method was employed. In this study, a total of 246 grids (5 Km. × 5 Km.), specified by their geocoordinates, were taken into consideration (Fig. 2). The field survey was meticulously planned using Survey of India topographic sheets, recent road maps from Google Earth Pro, and satellite data from the Bhuvan platform, which collectively facilitated accurate site selection and efficient navigation within the forest ranges [50, 51]. Prior to each day's fieldwork, GPS (Global Positioning System) coordinates (latitude and longitude) for selected sites were reviewed to optimize field operations. In addition, collaboration with forest officers and local residents provides valuable insights into terrain conditions and forest characteristics, facilitating informed sampling and helping the team navigate the forests effectively.

Tree species composition was documented from September 2023 to February 2024 within five sample plots (250 m × 250 m) established in each of the five studied forest ranges using a randomized sampling approach, totaling 25 plots clearly marked in deep blue (Fig. 2). Within each 25 plots, four smaller subplots measuring 31.62 m × 31.62 m (0.1 ha) were further delineated (100 plots) as shown in the figure (Fig. 3), ensuring methodological consistency [52,53]. Tree species within each subplot were identified on-site using the standard flora reference by Saxena and Brahmam (1994), and botanical nomenclature was updated according to the World Flora Online (https://www.worldfloraonline.org) database [54], accessed on 23rd October 2024, with additional verification by forest department experts. Sampling points were selected randomly, ensuring a minimum distance of 1 km between each point. All sampling points were positioned within the forest, maintaining at least 50 m distance from the forest boundary to minimize potential buffer effects.

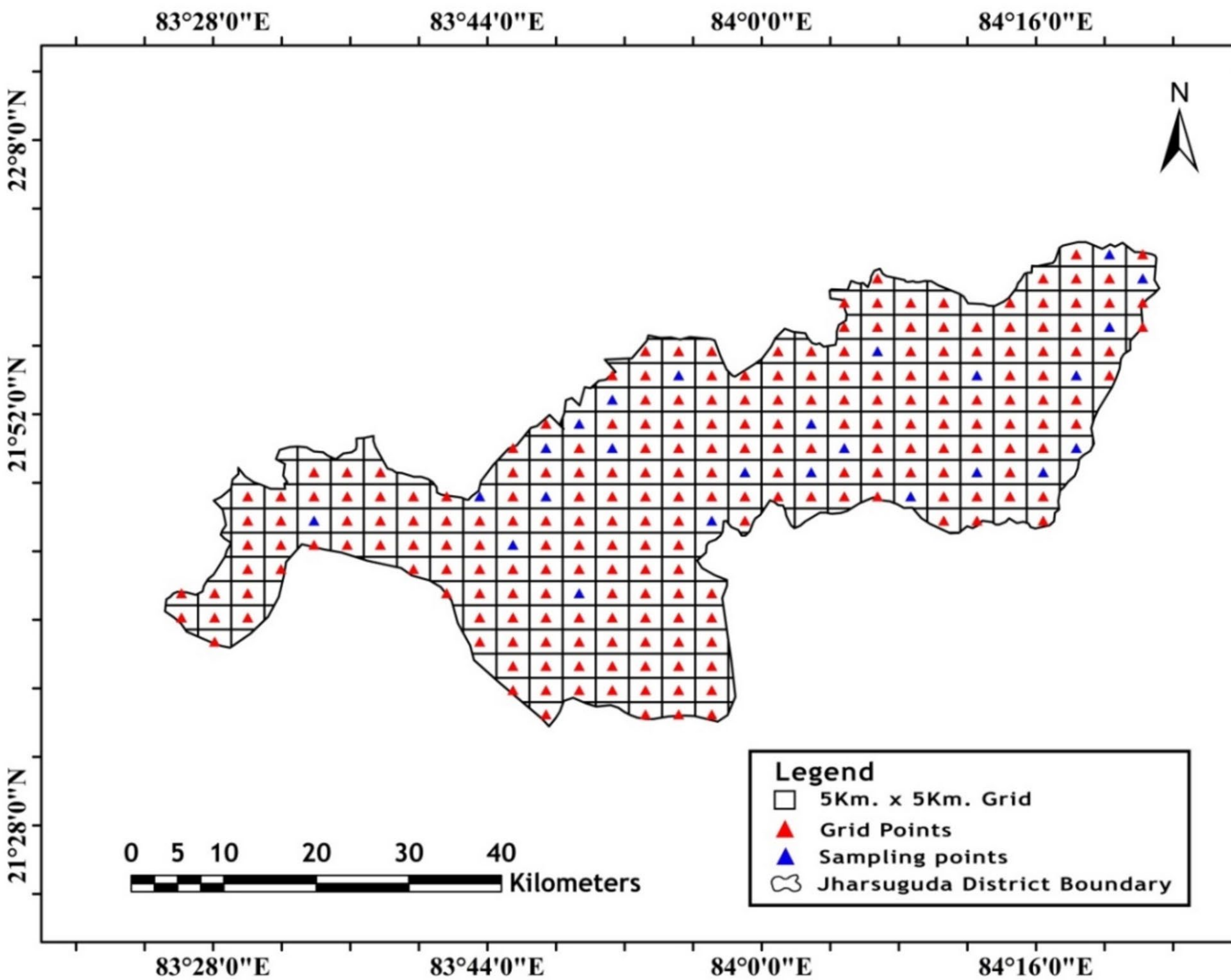

Fig. 2 Workflow visualization of grid cells and sampling points

Data analysis

All tree species with a girth at breast height (GBH) of 10 cm or more within each plot were quantitatively assessed for frequency (F), density (D), basal area (BA), and Importance Value Index (IVI) using established methods [55]. The IVI values provided a basis for calculating various diversity indices, offering insights into the ecological characteristics of each site. species diversity ($\overline{\mathrm{H}}$) was calculated using the Shannon-Wiener index, which captures diversity based on the Shannon-Wiener information function [56]. Additionally, the concentration of dominance (Cd), also known as Simpson's index, was measured to evaluate species dominance within the community [57]. Finally, evenness was assessed using Pielou's evenness index, which indicates how evenly individuals are distributed among species [58].

To assess the population structure of tree species across the five forest ranges in the study area, we employed the circumference at breast height (CBH) method. This involved measuring the girth of each tree at 1.37 m above ground level, ensuring a standardized approach to capture the size distribution of trees within each plot. Each tree was categorized based on its girth, which allowed for a detailed analysis of population structure according to defined size classes.

The following GBH classes were used: (A) 10–31 cm (sapling), (B) 32–66 cm (bole), (C) 67–101 cm (post bole), (D) 102–136 cm (mature tree), (E) 137–171 cm (over mature tree) and (F) ≥ 171 cm (old tree) [43, 59, 60]. For each girth class, the number of individuals was recorded, and the percentage density of individuals in each class was calculated. This classification provided insights into the age distribution and regeneration status of tree species within the forest, offering a valuable understanding of the structural composition and ecological dynamics in the study area.

$$Density = \frac{No.\,of\,individuals\,in\,each\,girth\,class}{Total\,No.\,of\,individuals\,in\,all\,girth\,class} \times 100$$

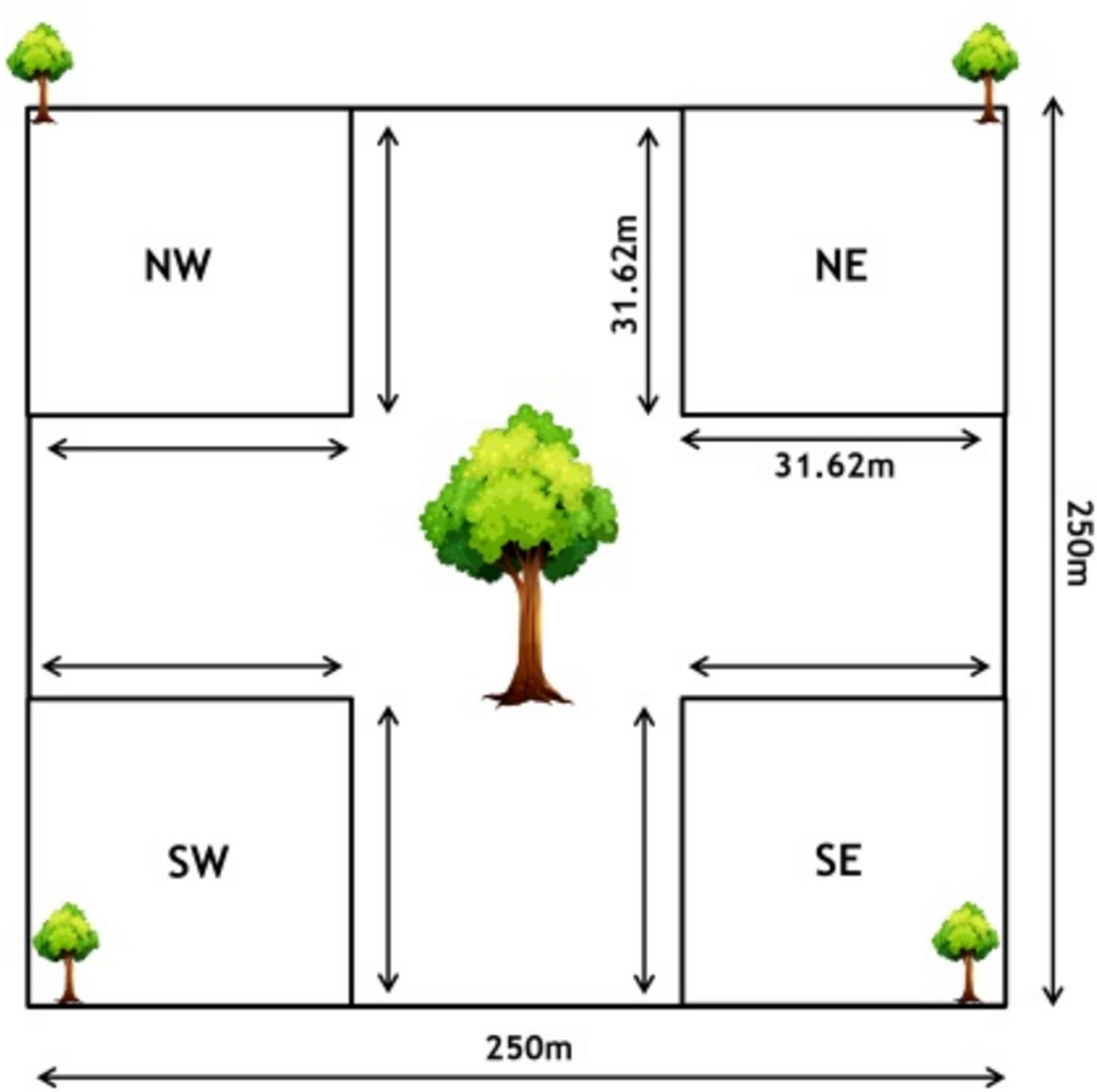

Fig. 3 Tree sampling layout showing four 0.1 ha plots within each 250 m × 250 m sampling unit

Due to strict restrictions on tree harvesting within wildlife sanctuaries, sacred forests, and protected areas, the biomass and carbon stock assessments in the study were conducted using non-destructive sampling techniques. Above-ground biomass (AGB) was estimated using standard allometric equations specifically developed for mixed-species stands, ensuring accurate biomass calculations without disturbing the forest ecosystem [61, 62]. Tree diameter at breast height (DBH), measured at 1.37 m above the ground, served as the primary input for these equations.

To determine AGB, we applied the allometric equation developed by Chave et al. [63, 64], which has been widely validated in tropical dry forests for mixed-species compositions. In this equation, the biomass value per tree is calculated using the DBH measurement for each sampled tree. This method allowed us to reliably estimate biomass and carbon stocks across various tree species within the five forest ranges while adhering to conservation regulations. The non-destructive approach also ensured that the ecological integrity of the study area remained undisturbed, aligning with sustainable forestry practices [51].

$$AGB_{est} = \exp \left[-1.803 - 0.976E + 0.976\ln(\rho) + 2.673\ln(D) - 0.0299[\ln(D)]^2\right]$$

where E = Chave's Environmental Index.
and D = diameter at breast height (DBH) for each tree measured at 1.37 m above the surface.

Individual species-specific wood densities are listed in Table S1.

The below-ground biomass (BGB) was estimated by applying a root-to-shoot ratio of 0.26, or 26% of the AGB, as suggested by Cairns et al. [65] and Ravindranath and Ostwald [66].

$$BGB = 0.26 \times AGB$$

This approach allowed us to quantify the above-ground, below-ground, and total biomass (sum of AGB and BGB) for all tree species with GBH of ≥ 10 cm across the five study sites based on tree diameter measurements. To convert biomass into carbon stock, we used formulas developed by various researchers, such as those recommended by [67] and [68], which are widely accepted for tropical forests. Based on the principle that approximately 47% of the dry weight of living biomass is carbon, the carbon stock was calculated by multiplying the total woody biomass of trees and shrubs by a factor of 0.47 [67, 68]. This percentage represents the carbon content within the biomass, allowing for an accurate estimate of carbon storage. The formula used for estimating carbon stock was as follows:

$$Total\ Biomass\ Carbon\ Stock = Total\ Bimass \times 0.47$$

The normality of the data was first assessed using the Shapiro-Wilk test. Since the data did not meet the assumptions of normality required for parametric analyses, the non-parametric Kruskal-Wallis test (KWT) was used to evaluate the statistical significance of differences in tree density, basal area, and biomass across the five forest ranges. All statistical analyses and data visualizations were performed using R Studio (Version 4.4.0).

Chave's Environmental Index (E) was calculated using the BIOMASS package in R Studio [69]. The bioclimatic variables used included temperature seasonality (TS, Bioclimatic Variable 4) and climatic water deficit (CWD, Bioclimatic Variable 15), both obtained from the WorldClim dataset [70]. The E value was then computed based on the latitude and longitude of the location of interest.

Results

Stand characteristics and tree diversity

An inventory of tree species across the Jharsuguda Forest Division documented a total of 80 species, representing 68 genera and 33 families, distributed across the five forest ranges (Table S2). In the five study sites, Fabaceae emerged as the dominant family, represented by 15 species, followed by Rubiaceae with 6 species, Combretaceae and Malvaceae with 5 species each, and Anacardiaceae with 4 species. Families like Moraceae, Phyllanthaceae, and Rhamnaceae were represented by 3 species each, while nine families had two species. The remaining 18 families were monospecific, indicating diverse yet uneven tree distribution in the Jharsuguda forest division.

Among these sites, Bagdihi Forest Range (BFR) exhibited the highest tree species richness, with 52 species from 25 families. In contrast, Jharsuguda Forest Range (JFR) showed the lowest diversity, with 31 species representing 20 families. Kolabira Forest Range (KFR) recorded a species composition similar to BFR, with 51 species across 27 families. The Brajrajnagar Forest Range (BRFR) and Belpahar Forest Range (BEFR) had intermediate levels of diversity, with 32 species from 21 families and 41 species from 20 families, respectively. Tree density, measured as the number of individuals per hectare, is highest in JFR (1332 trees/ha), followed by BRFR (1033 trees/ha), which suggests greater tree abundance in these ranges. The species accumulation curve suggests BFR and KFR accumulate higher species with areas followed by a medium rate of accumulation in BEFR and least in BRFR and JFR (Fig. 4). This suggests BFR and KFR is more species rich as compared to remaining forest ranges in district.

However, basal area, defined as the cross-sectional area of all trees per hectare, was highest in BEFR (24.92 m^2/ha) and BFR (24.89 m^2/ha). The higher basal area accompanied by lower tree density in these sites suggests the presence of larger or more mature trees compared to other sites. In contrast, JFR exhibited the lowest basal area (18.28 m^2/ha) with higher tree density, indicating a predominance of younger or smaller-statured tree species. The Shannon's diversity index ($\overline{H}$) value for tree species reported from this study ranged from 3.00 in JFR to 3.45 in KFR. Furthermore, species evenness index (E') was found to be in the range of 0.86 (BFR and JFR) to 0.88 (KFR) and concentration of dominance (Cd) of these studied areas ranged from 0.05 (KFR) to 0.08 (JFR) with intermediate values in the rest of the sites. The various structural attributes including density, species richness, number of families, basal area, and species diversity indices were analyzed and summarized in Table 1.

Across the five forest ranges in the Jharsuguda Forest Division, highlights key ecological metrics for dominant tree species, demonstrating variations in frequency, density, basal area, and Importance Value Index (IVI). In JFR, *Shorea robusta* reaches a peak density of 396 trees/ha and an IVI of 69.73, underscoring its strong structural presence with significant ecological role. Also *Buchanania*

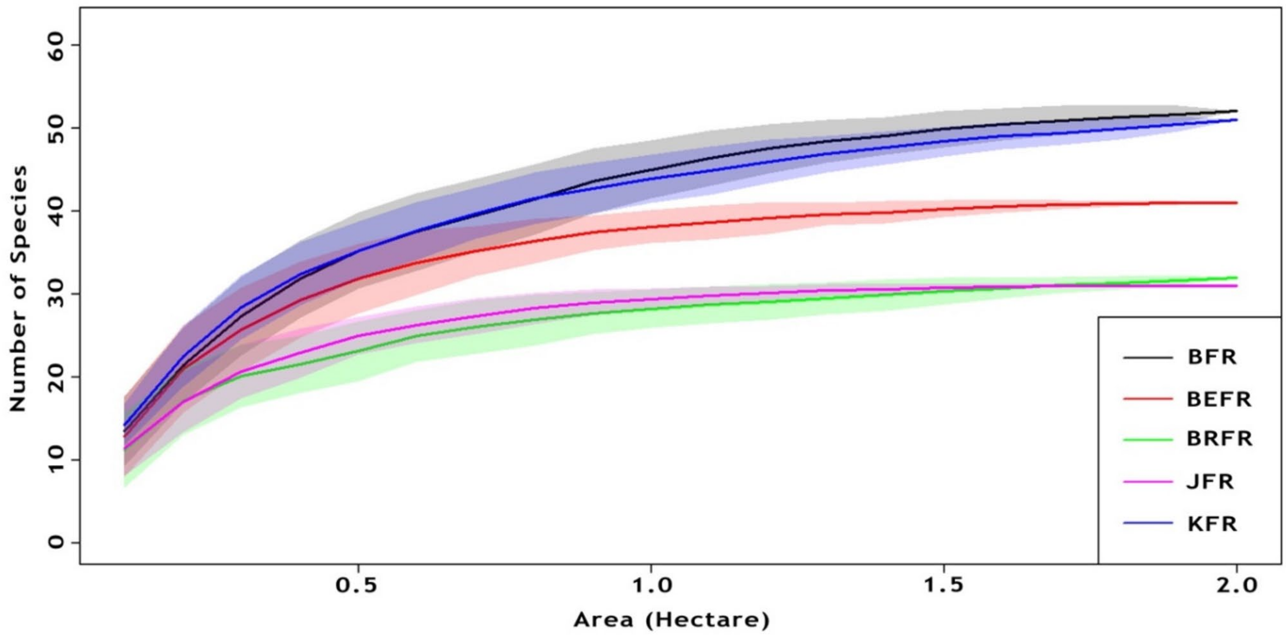

Fig. 4 Species accumulation curves for the different forest ranges within Jharsuguda district

Table 1 Biodiversity metrics for five surveyed forest ranges in the study sites

Parameters	BFR	BEFR	BRFR	JFR	KFR
Species Richness (Nos.)	52	41	32	31	51
Family (Nos.)	25	20	21	20	27
Density (Nos./ha)	804	869	1033	1332	943
Basal Area (m^2/ha)	24.89	24.92	19.95	18.28	21.80
Shannon's Diversity Index ($\overline{H}$)	3.37	3.24	3.05	3.00	3.45
Simpson's Dominance Index (Cd)	0.06	0.07	0.07	0.08	0.05
Pielou's Evenness Index (J')	0.86	0.87	0.87	0.86	0.88

cochinchinensis and *Dalbergia sissoo* appear as secondary species, though with significantly lower densities and basal areas compared to *Shorea robusta*, indicating a dominance of young or mid-aged trees. Meanwhile, *Terminalia elliptica* and *Briedelia retusa* contribute modestly to JFR's species composition, adding to its ecological complexity. In the BEFR, *Shorea robusta* also shows strong dominance with an IVI of 61.77 and a basal area of 8.45 m^2/ha, which is the highest among all sites. Each forest range also has a unique composition of secondary species that contribute to its structural diversity. In BFR, *Buchanania cochinchinensis* and *Terminalia elliptica* stand out with high frequencies, though their densities and basal areas are much lower than those of *Shorea robusta*, reflecting their role as co-dominant but smaller-statured species. *Lannea coromandelica* also contributes to BFR's diversity, with a moderate density and IVI. In BRFR, *Shorea robusta* reaches its highest frequency (90%) and is accompanied by *Cleistanthus collinus* and *Lannea coromandelica*, which provide additional structure and diversity, with IVI values of 21.37 and 19.70, respectively. The high density of *Cleistanthus collinus* (137 trees/ha) in BRFR suggests a substantial presence of mid-sized individuals, further diversifying the forest's population structure. KFR displays a different structural dynamic, where *Shorea robusta* shows a lower density (150 trees/ha) than in other sites but still holds the highest IVI (43.05) in this range. Secondary species like Cleistanthus collinus and Semecarpus anacardium provide structural diversity, with moderate densities and basal areas that complement the dominant role of *Shorea robusta* (Table 2). No significant differences in tree density were found among the forest ranges (KWT: $H = 7.24$, $df = 4$, $p = 0.12$). However, basal area varied significantly across the five ranges (KWT: $H = 9.66$, $df = 4$, $p = 0.04$).

Tree population structure and distribution patterns

The analysis of population structure revealed that tree density varied significantly across different girth classes at each study site (Fig. 5). These density patterns indicate distinct differences in tree population structure, particularly between younger and older growth stages, shedding light on regeneration processes and maturity levels across the areas studied. In JFR, tree density showed a clear decline with increasing girth class, following the order $A > B > C > D > E > F$, suggesting a high proportion of younger trees and a scarcity of larger, older trees. In contrast, the remaining four study sites exhibited a more irregular pattern. In these sites, tree density increased from the sapling class (A) to the bole class (B), then progressively declined through the higher girth classes, following the pattern $A < B > C > D > E > F$. This trend

Table 2 Main species-specific ecological metrics in the study sites

Species	Frequency (%)	Density (Nos./ha)	Basal Area (m^2/ha)	IVI	Total Biomass (Mg/ha)
Bagdihi Forest Range (BFR)					
Shorea robusta	70	136	8.14	54.86	100.80
Buchanania cochinchinensis	85	93	1.43	23.69	11.81
Terminalia elliptica	65	32	1.24	13.83	15.05
Lannea coromandelica	70	35	1.01	13.66	10.08
Chloroxylon swietenia	35	37	1.57	13.52	17.38
Belpahar Forest Range (BEFR)					
Shorea robusta	80	186	8.45	61.77	99.62
Terminalia elliptica	65	52	1.84	18.61	20.15
Morinda citrifolia	60	44	1.35	15.31	10.73
Lannea coromandelica	65	34	1.15	13.77	10.45
Semecarpus anacardium	60	41	0.52	11.64	3.84
Brajrajnagar Forest Range (BRFR)					
Shorea robusta	90	226	5.48	57.47	57.49
Cleistanthus collinus	40	137	0.90	21.37	5.67
Lannea coromandelica	80	59	1.35	19.70	13.43
Buchanania cochinchinensis	90	67	0.84	18.79	6.69
Terminalia elliptica	70	38	0.93	14.63	9.61
Jharsuguda Forest Range (JFR)					
Shorea robusta	70	396	6.24	69.73	63.51
Buchanania cochinchinensis	80	80	0.81	17.14	7.08
Dalbergia sissoo	35	53	1.82	16.89	18.90
Terminalia elliptica	80	64	0.77	15.75	8.22
Briedelia retusa	80	50	0.53	13.38	4.89
Kolabira Forest Range (KFR)					
Shorea robusta	55	150	5.03	43.05	58.10
Cleistanthus collinus	35	113	0.79	18.18	4.76
Lannea coromandelica	80	43	1.29	16.38	13.21
Semecarpus anacardium	65	61	0.84	15.13	6.48
Terminalia elliptica	70	40	1.16	14.77	8.74

indicates a concentration of mid-sized trees, with fewer saplings and older trees. Across all five study sites, the bole class (B) consistently had the highest tree density, while the oldest girth class (F) showed the lowest density, reflecting a limited presence of mature, old-growth trees (Table S3).

The basal area distribution across different girth classes reveals distinct structural patterns within each study site (Fig. 5). Overall, girth class C (post-bole) consistently shows the highest basal area values across all sites, emphasizing the significant biomass contribution of mid-sized, established trees to forest structure. In BFR and KFR, the highest basal area is observed in girth class C, with the order C > B > D > E > A > F, indicating a modest presence of saplings and few old-growth trees. In BEFR, the basal area trend follows C > B > D > E > F > A, highlighting the dominance of mid-sized trees with limited old-growth individuals. For BRFR, the order is C > B > D > A > F > E, suggesting a small presence of both young saplings and large, old trees. In JFR, the basal area pattern is arranged as C > B > D > A > E > F, indicating a strong presence of mid-sized trees along with a notable number of young saplings.

Biomass and carbon stock

Biomass and carbon stock measurements showed notable variation across the study sites (Table 3), likely influenced by differences in tree age, species composition, density, and size. Estimates of above-ground biomass (AGB) varied, with values recorded at 98.73 Mg/ha for BFR, 102.88 Mg/ha for BEFR, 74.20 Mg/ha for BRFR, 68.83 Mg/ha for JFR, and 83.09 Mg/ha for KFR. Similarly, below-ground biomass (BGB) was calculated as 25.67 Mg/ha for BFR, 26.75 Mg/ha for BEFR, 19.29 Mg/ha for BRFR, 17.90 Mg/ha for JFR, and 21.60 Mg/ha for KFR. Combined total biomass (AGB + BGB) across the sites showed a range from 86.73 Mg/ha in JFR to 129.63 Mg/ha in BEFR, indicating substantial site-specific differences in biomass accumulation potential (Fig. 6). There was a significant difference observed in biomass among the five ranges (KWT: $H = 10.36$, $df = 4$, $p = 0.03$).

The carbon stock estimations followed IPCC guidelines, applying a conversion factor of 47% for above-ground biomass carbon (AGBC) and 27% for below-ground biomass carbon (BGBC). These conversion factors were used to calculate total biomass carbon (TBC) for each site by

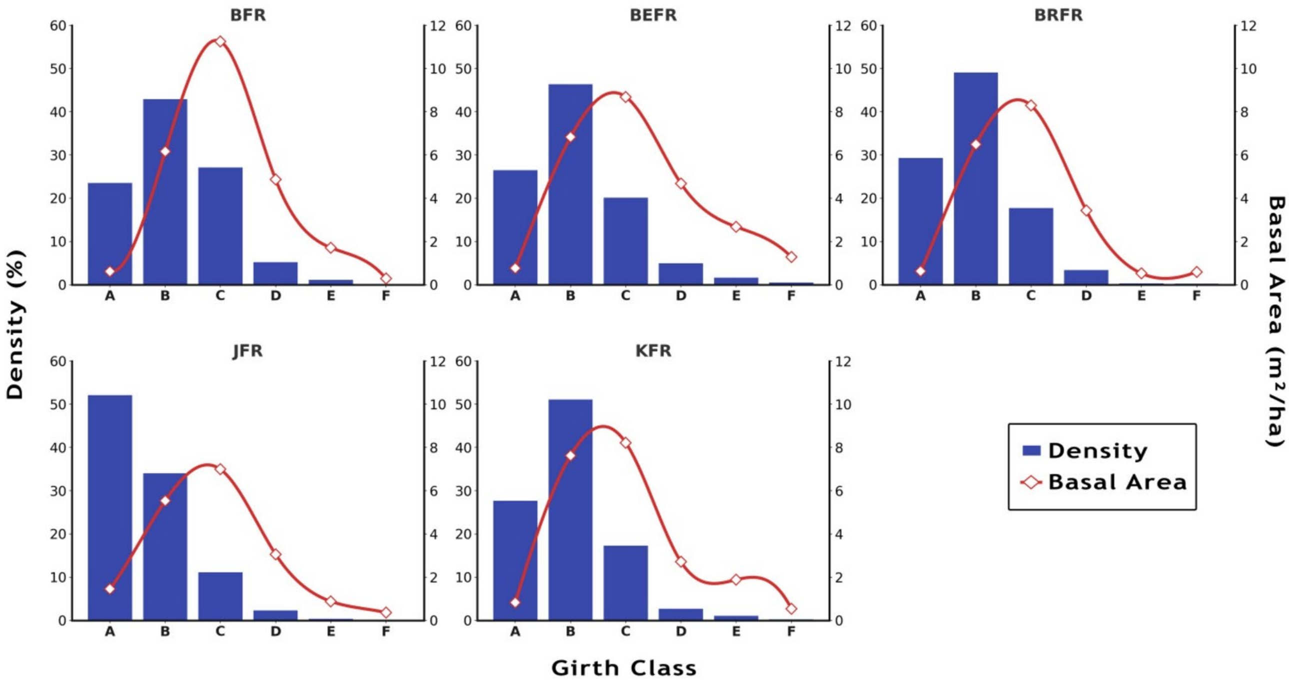

Fig. 5 Comparative distribution of tree density and basal area across girth classes at each study site

Table 3 Distribution of biomass and carbon stocks in the study sites

Parameters	BFR	BEFR	BRFR	JFR	KFR
AGB (Mg/ha)	98.73	102.88	74.20	68.83	83.09
BGB (Mg/ha)	25.67	26.75	19.29	17.90	21.60
TB (Mg/ha)	124.40	129.63	93.50	86.73	104.70
AGBC (MgC/ha)	46.41	48.35	34.88	32.35	39.05
BGBC (MgC/ha)	12.07	12.57	9.07	8.41	10.15
TBC (MgC/ha)	58.47	60.93	43.94	40.76	49.21

summing the AGBC and BGBC values. TBC varied notably across sites, with the highest carbon stock observed in BEFR (60.93 MgC/ha), followed by BFR (58.47 MgC/ha), KFR (49.21 MgC/ha), BRFR (43.94 MgC/ha), and the lowest in JFR (40.76 MgC/ha). These differences underscore the varying capacities for carbon storage across the distinct forest reserves, influenced by each site's ecological and structural characteristics.

The biomass also varied in different girth classes within the sites (Fig. 6). The smallest girth class A contains relatively low biomass across all sites, indicating that smaller trees contribute modestly to total AGB. Notably, JFR has the highest biomass (2.41 Mg/ha) in this range, while other sites such as KFR (1.56 Mg/ha), BEFR (1.36 Mg/ha), BRFR (1.01 Mg/ha), and BFR (0.96 Mg/ha) show comparatively lower values. Trees in the girth class B contribute substantially to the total AGB, especially in KFR (22.33 Mg/ha) and BEFR (19.80 Mg/ha). This range captures a significant proportion of the forest biomass, suggesting a high density of mid-sized trees in these regions. Biomass contribution peaks in the girth class C across most sites, with the highest values in BFR (44.79 Mg/ha), followed by BEFR (33.99 Mg/ha), KFR (32.22 Mg/ha), BRFR (32 Mg/ha), and JFR (27.46 Mg/ha). This class represents a considerable portion of the total AGB, reflecting a dominance of larger post boles in the study site. Biomass values in the girth class D shows a decline across sites, with BFR having 24.63 Mg/ha leading, while KFR records the lowest at 13.82 Mg/ha. This reduction suggests that very large trees are less common, though they still contribute to the overall biomass. In the class E reflects a notable decrease in biomass contribution, with moderate values in BEFR (15.49 Mg/ha) and KFR (10.48 Mg/ha), while BRFR shows the lowest (3.02 Mg/ha). These lower values indicate fewer trees in this size class. The largest girth class (F) has the smallest biomass contribution across most sites, with BEFR (8.66 Mg/ha) exhibiting the highest value in this class, suggesting occasional presence of very large trees, while BFR (1.8 Mg/ha) shows relatively low biomass in this range. Overall, the total AGB varies by site, with BEFR showing the highest total biomass (102.88 Mg/ha) and JFR the lowest (68.83 Mg/ha). These variations reflect differences in forest structure, density, and species composition across the sites, with middle-sized trees (CBH 32–101 cm) playing a dominant role in overall biomass accumulation (Fig. 6).

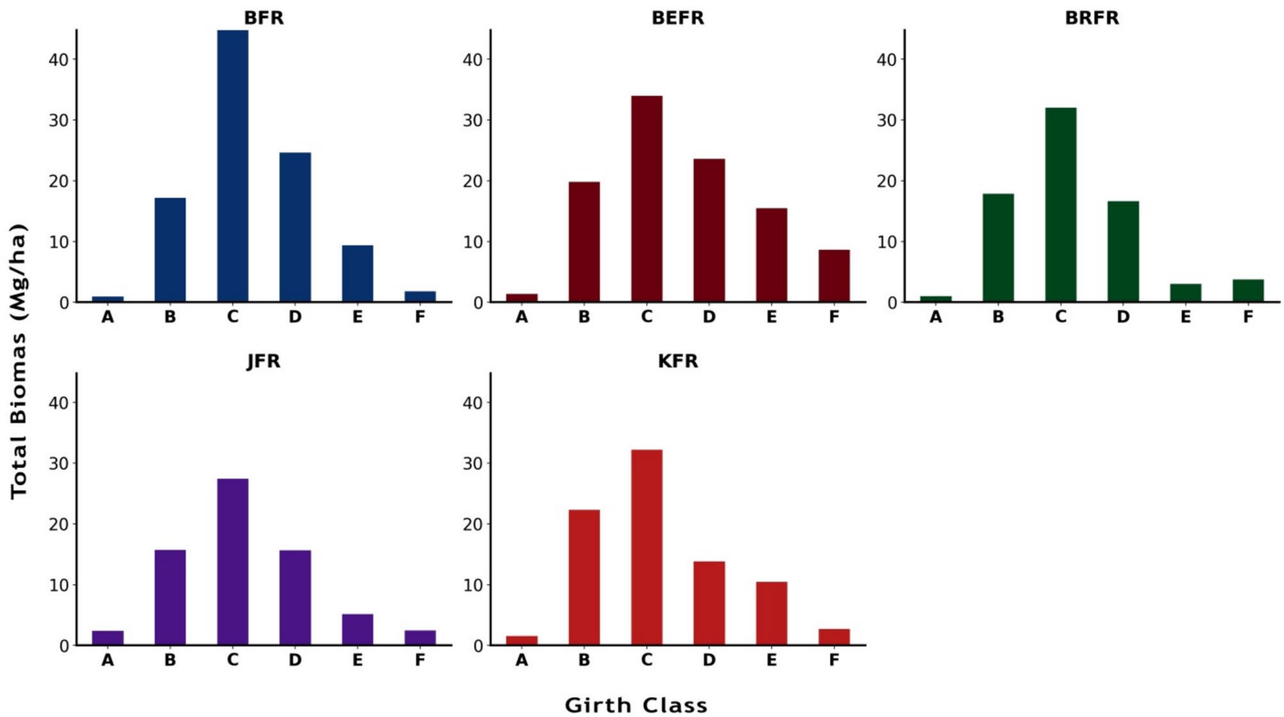

Fig. 6 Distribution of site-specific biomass across different girth classes

Discussion

The study highlights striking variations in tree diversity, population structure, and biomass carbon stock across five forest ranges in the Jharsuguda Forest Division. While each site shows some differences in species composition, these differences are not statistically significant only in the case of tree diversity. This suggests that the regional ecological characteristics play a key role in promoting a similar distribution of species, with *Shorea robusta* (Sal tree) standing out as the dominant species. The presence of these forest ranges within a shared agro-climatic zone likely explains this uniformity, as such regions tend to shape species composition and maintain regional distinctiveness [71]. Interestingly, the diversity and structural characteristics observed in this study differ from findings in several earlier studies conducted in recent years. To provide a meaningful comparison, we focused on research conducted in Indian settings over the past five years (Table 4). This approach provides a modern perspective since structural features are constantly changing over time.

The vegetation analysis of the five forest ranges in Jharsuguda indicated a lower tree species richness compared to studies conducted in other parts of India, particularly the Eastern and Western Ghats. This difference may be attributed to geographic variations and habitat disturbances resulting from rapid industrialization in the region. Conversely, the stand density in our study was higher than that observed in most Indian forest types. These values align with those reported for Western Odisha and the Mahendragiri range of the Eastern Ghats [43, 82], suggesting that tropical dry deciduous forests can exhibit higher densities. The basal area values in our study were comparatively lower than those reported in other studies. This finding is consistent with the observations of Pradhan et al. [43] in Western Odisha, indicating that tropical dry forests in this ecoregion tend to have lower basal area compared to other forest types.

The combination of high tree density and low basal area indicates a population dominated by younger or mid-sized trees, as reflected in the forest stand structure. This suggests that these forests are secondary and in a state of regeneration, consistent with findings from other studies [43]. The reduced stand density in larger girth classes may be attributed to factors such as selective logging, natural mortality, or anthropogenic pressures, a common trend observed in tropical dry forests [43, 86]. A comparison of tree density and basal area across the study sites suggests that JFR, with the lowest basal area and highest density of younger trees, may be more disturbed than BEFR and BFR, which exhibit lower density but higher basal area. This observation aligns with findings from other regions, where forests with younger trees often exhibit denser populations but lower basal area, potentially due to selective logging or natural disturbances [87].

The species diversity indices, including the Shannon diversity index, provide valuable insights into the diversity and abundance of tree species within an ecosystem.

Table 4 Structural attributes and biomass distribution of tree species across various forest types in India

Sl. No.	Author	Location of work	Density (trees/ha)	BA (m^2/ha)	Family (Nos.)	$\bar{H}$	EI	Cd	Biomass (Mg/ha)
1	Deb et al. [72]	Tripura	145–199		22–25	2.17–2.74	0.704–0.852	0.085–0.09	79.81–367.7
2	Gogoi et al. [73]	Assam	952–1045	32.6–37.4	54–57	2.52–2.9	0.87–0.88	0.09–0.13	299.86–358.3
3	Joshi et al. [74]	Central Himalaya	153–1500						145-634.20
4	Joshi et al. [75]	Uttarakhand Himalaya	652–884	33.42–51.58		1.1–2.31	0.46–0.9	0.24–0.66	
5	Kaushal et al. [76]	Uttarakhand, Central Himalayas	153–457	37.4-94.75	29	0.77–2.63	0.48–0.86	0.09–0.62	
6	Sahoo et al. [46]	Northeast India	344–840	11.43–30.63		0.20–2.40	0.55–0.99	0.09–0.83	2.53-259.77
7	Sharma et al. [77]	Manipur	359–383	24.2–28.2					46.5-212.6
8	Thakur et al. [26]	Central India	467.5-652.5	9.26–34.12	11–29	0.67–2.34	0.25–0.67	0.09–0.75	83.74-111.21
9	Raha et al. [78]	Madhya Pradesh	519.4-859.4	20.5–29.5	25	1.14–2.08	0.22–0.39	0.19–0.46	160.7-223.3
10	Joshi & Dhyani, [79]	Madhya Pradesh	489–1671	15.43–71.76	29–54	0.69–3.22	0.81	0.06	103.32-453.54
11	Naidu et al. [21]	Eastern Ghats, Visakhapatnam	328–718	2.2-34.91	38–79	3.26–4.12		0.95–0.98	
12	Srinivas & Sundarapandian, [80]	Andhra Pradesh	510–649	14.35–57.50	81–96				73.12-464.17
13	Sahoo et al. [81]	Eastern Ghats, Odisha	185.25–744	12.54–36.95	62–101	3.20–3.44	0.74–0.79	0.09–0.12	
14	Pradhan et al. [43]	Western Odisha	1008–1662	23.61–24.35	42–60	3.06–3.21	0.78–0.82	0.07	281.60-310.95
15	Khadanga and Jayakumar, [82]	Mahendragiri, Eastern Ghats	1238.83			3.39		0.09	129.05-255.87
16	Jaiswal & Jayakumar, [83]	Tamil Nadu	399.44	27.28	188	4.13–4.52	0.92–0.94	0.97–0.986	
17	Saha et al. [84]	Western Ghats Karnataka	316–716						253.4-634.2
18	Subashree et al. [85]	Western Ghats, Tamil Nadu	370–900	24.23–75.34	24–151	1.99–2.93	0.23–0.67	0.09–0.30	
19	Present study	Jharsuguda, Odisha	804–1332	18.28–24.92	31–52	3.0-3.45	0.86–0.88	0.05–0.08	86.73-129.63

Higher values of these indices indicate greater species richness and evenness [88]. In this study, the Shannon diversity index for tree species ranged from 3.00 in JFR to 3.45 in KFR. This range is notably higher than values reported in studies from Northern, North-Eastern, and Central India (Table 4). While the site-specific differences in species diversity were not statistically significant, our findings align well with other studies conducted in the Eastern Ghats of Odisha and Andhra Pradesh. However, the study by Jaiswal & Jayakumar [83] reported higher diversity, likely due to the observed higher species richness in their study area. The concentration of dominance (Cd) values in our study (0.05–0.08) was relatively low compared to most other studies. Although Sal is a dominant species in these forests, as commonly observed [89], the lower Cd values suggest a more balanced species distribution compared to other, potentially more monospecific forest types. The evenness index, which measures the equitable distribution of species abundance, was also found to be relatively high in our study (0.86–0.88). This indicates a more balanced distribution of individuals among species, contributing to the overall high diversity observed.

Structural attributes, such as tree density and basal area, provide valuable insights into the ecological variations among the study sites. These attributes directly influence ecosystem functioning and carbon storage potential. Biomass and carbon stock estimates highlight the significant carbon sequestration potential of these forest ranges. BEFR, with the highest total biomass value (129.63 Mg/ha), emerges as a substantial carbon sink. In contrast, JFR, characterized by a dominance of younger trees and a smaller basal area, exhibits lower total biomass (86.73 Mg/ha), indicating limited carbon sequestration capacity [37, 90, 91]. Statistically significant variations in woody biomass were observed among the sites. The high total biomass carbon (TBC) in BFR, primarily driven by mature tree populations, underscores the ecological importance of conserving these carbon-rich forests (Patra et al., 2020; Rai et al., 2023). These results align with the range of biomass values reported in various regions of India (Table 4). However, regions like the Central Himalayas [76] and Western Ghats [85] exhibit even higher biomass values (~634.2 Mg/ha), highlighting the substantial role of Indian forests in mitigating climate change [90, 91].

These findings underscore the importance of conserving and sustainably managing tropical dry forests like those in Jharsuguda, not only for their biodiversity but also for their significant carbon storage potential. Forests such as BEFR and BFR, with their high TBC values, are particularly valuable for climate mitigation efforts and should be prioritized in conservation and carbon offset initiatives [9, 43]. Sustainable forest management practices, including minimizing human disturbance, protecting mature trees, and promoting structural diversity, are vital for preserving the resilience of these ecosystems and enhancing their carbon sink capacity. Global research on tropical dry forests supports the effectiveness of these practices [92–94]. Given the urgent need for climate adaptation strategies, the conservation of tropical dry forests in India and worldwide holds immense potential for both biodiversity conservation and climate stabilization [95, 96].

Given the rapid industrial growth in Jharsuguda, which poses potential risks to regional biodiversity, the government should implement strict regulations instructing industries to thoroughly assess biodiversity and the ecological hazards linked to their operations. This includes conducting baseline biodiversity surveys and regular monitoring to identify any alterations in species composition. Biodiversity offset programs should be enhanced through robust No Net Loss (NNL) strategies and comprehensive Environmental Impact Assessments (EIAs) incorporating cumulative effect analyses. Employing geospatial technology and remote sensing can help pinpoint biodiversity hotspots and accurately predict industrial impacts. Moreover, industries must adopt sustainable practices such as green belt development, ecological restoration, and zero-discharge policies. By integrating these strategies, industries in Jharsuguda can effectively mitigate environmental risks and support long-term sustainable growth.

Conclusion

This study provides valuable insights into the ecological characteristics of tropical dry deciduous forests in the Jharsuguda Forest Division. The findings reveal a relatively uniform species composition across the study sites, dominated by *Shorea robusta*. The forest structure exhibited a high density of younger trees in diameter classes A and B, indicating active and ongoing regeneration processes, even though species diversity remained similar across the study locations. However, in four out of the five sites studied, the density of the youngest class (class A) was lower compared to the bole class (class B). This trend suggests that these four locations are gradually transitioning towards a secondary successional state, characterized by relatively higher densities in the bole class compared to the sapling class. In contrast, the site JFR distinctly represented a regenerating forest, showing the highest density within the sapling class. Additionally, the comparatively smaller basal area observed at this site likely reflects residual impacts from past disturbances. This research has important implications for forest management and conservation strategies, especially given the global emphasis on climate change mitigation and biodiversity conservation. The identification of site-specific differences in tree diversity, density, and biomass carbon stock emphasizes the need for targeted management approaches that prioritize the conservation of high-biodiversity, high-carbon forests like BFR and KFR. Effective forest conservation practices should include strategies to protect mature tree populations, foster species diversity, and mitigate anthropogenic impacts, all of which are essential for maintaining the resilience and ecological integrity of these forest ecosystems. Furthermore, the study highlights the importance of ongoing monitoring of forest structure and biomass changes to assess the impacts of environmental and human-driven disturbances on carbon storage and biodiversity. Conservation strategies should include flexible management plans that focus on restoring forests, making them more resilient, and involving local communities. Linking scientific research to climate policy helps create better forest management plans that protect biodiversity and ensure forests continue to provide valuable services for future generations. The insights gained from this research contribute to a broader understanding of how tropical dry forests function as critical carbon sinks and biodiversity pools, providing a foundation for policies that integrate biodiversity conservation with carbon management. This approach will not only support regional conservation priorities but also contribute to national and global efforts to meet climate goals and sustain ecosystem services.

Supplementary Information

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Supplementary Material 1

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Author contributions

Abinash Mansingh: Conceptualization, methodology, data collection, data curation, map and graph preparation, writing the original draft. Antaryami Pradhan: Played a key role in the development of research ideas and contributed to reviewing and editing the manuscript. Satya Ranjan Sahoo: Assisted in field work, data typing and managing the formatting of the references. Sujeet Sameer Cherwa: Supported in the field data collection process and data typing. Bibhuprasad Mishra: Assisted in field work, data typing and species-specific check list preparation. Laxmi Prasad Rath: Assisted in field work and did the statistical analysis in R studio. Nirius Jenan Ekka: Conceptualization, supervision, logistics support, provided overall supervision and contributed critical input in finalizing the manuscript. Bibhu Prasad Panda:

Data interpretation, map preparation, writing supervision and editing. All authors read and approved the final manuscript.

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Data availability
Data is provided within the manuscript or supplementary information files.

Declarations

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Not applicable.

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Competing interests
The authors declare no competing interests.

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