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RESEARCH ARTICLE

Regeneration dynamics and ecological assessment in Purna Wildlife Sanctuary, Northern Western Ghats, Gujarat, India

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Abstract

Tree species diversity and regeneration dynamics are vital for maintaining ecosystem health, particularly in biodiversity-rich regions such as the Western Ghats. This study investigates the tree species diversity and regeneration patterns across five forest ranges (Ahwa West, Baripada, Bheskatri, Kalibel and Singhana) of the Purna Wildlife Sanctuary in Gujarat, India. The sanctuary, located in the northern section of the Western Ghats, hosts a mix of moist and dry deciduous forests. Data were collected using transects and quadrats to assess tree density, basal cover, species richness and regeneration success. The study highlights significant spatial variations in tree density, species composition and regeneration patterns across the sanctuary's diverse habitat types. Among the different forest ranges, the Singhana range showed the highest species density, richness, diversity index and evenness index, while it recorded the lowest Simpson index compared to the other ranges of Purna Wildlife Sanctuary. *Tectona grandis* was found to be the dominant species, with varying dominance across ranges. The regeneration status showed a mixture of good, fair and poor regeneration across species, with some areas showing higher sapling and seedling densities. The study emphasizes the importance of understanding tree diversity and regeneration dynamics for effective forest management and conservation efforts in Purna Wildlife Sanctuary.

Keywords: Purna Wildlife Sanctuary; regeneration status; vegetation analysis; Western Ghats

Introduction

Tree species diversity is a fundamental component of biodiversity in many ecosystems, as trees act as ecosystem engineers, providing resources and habitats for nearly all other forest organisms. Globally, forest diversity varies based on geography, soil conditions, climate and anthropogenic pressures (1, 2). Spatial heterogeneity (uneven distribution) in tree diversity may result from underlying patterns such as environmental heterogeneity, biotic interactions and abiotic-biotic coupling (3). In natural forests, tree diversity largely depends on a site's regeneration potential, which ensures species composition, stocking after disturbances and long-term forest sustainability. The regenerative potential of tree species is influenced by factors such as the availability of mother trees, seed dispersal mechanisms, germination capacity and vigor and the ability of seedlings and saplings to survive and grow (4). New recruitment is often constrained by limited and uncertain seed supply, as well as challenges in establishment. Additionally, the availability of suitable microsites and factors affecting early seedling growth and mortality further limit recruitment. Micro-environmental conditions fluctuate with seasonal changes, influencing different tree growth stages-including seedlings, saplings, coppice and young trees-which play a crucial role in maintaining population structure (1, 5). Understanding tree regeneration and species diversity is vital for foresters to assess forest complexity and resource availability in each ecosystem.

The Indian subcontinent boasts one of the world's most diverse floras, with over 17000 species of flowering plants. The tropical regions of the country contribute 22 % of their forest and tree cover. The Western Ghats, a recognized biodiversity hotspot and the focus of this study, is a mountainous region in peninsular India that spans 1600 km^2, with an average elevation of 1500 m above mean sea level, extending from the Tapti River in the north to Kanyakumari in the south (1, 6). A key characteristic of the Western Ghats is the decrease in annual precipitation and the increase in the length of the dry period from south to north. The region is generally classified into three sub-regions: the Northern, Central and Southern Western Ghats (7). Compared to the other two, the northern region experiences a shorter rainy season, with only 4 months of

rainfall followed by an eight-month dry period. Although it has a lower elevation, it features a unique mosaic of forested and open landscapes, with hills adorned by laterite and basaltic outcrops, creating a seasonal environment that sustains a diverse endemic herbaceous flora (8, 9). These open habitats are interspersed with patches of forest located in valleys, ravines and plains. However, these forests are highly fragmented due to various anthropogenic activities (10). The novelty of this study lies in its focused analysis of regeneration potential and diversity patterns within the lesser-studied northern Western Ghats, specifically in the fragmented forests of Purna Wildlife Sanctuary-an area facing increasing anthropogenic pressure but lacking comprehensive ecological assessment. An intensive study was conducted across five ranges of Purna Wildlife Sanctuary: Ahwa West, Baripada, Bheskatri, Kalibel and Singhana. Purna Wildlife Sanctuary is one of Gujarat's most significant wildlife reserves, serving as the northernmost extension of the ecologically rich Western Ghats. This study aims to generate essential data to inform effective management strategies, particularly to advocate for the site's designation as a Protected Area, thereby enhancing ecosystem conservation efforts. Against this backdrop, we examined tree species diversity and regeneration patterns in a section of the Purna Wildlife Sanctuary.

Materials and Methods

Study area

The Purna forest is a highly dynamic ecosystem influenced by both climatic and cultural factors. The sanctuary derives its name from the Purna River, which flows through it, shaping its drainage system. The Purna River originates from the Salher Hills of Maharashtra and traverses the sanctuary. Geographically, the sanctuary is located between 20°51′N, 73°32′E and 21°31′N, 73°48′E in the Dangs district, covering an area of 160.84 km^2. It comprises five distinct teak forest types, ranging from very moist teak forests to very dry teak forests, along with southern moist deciduous and southern dry deciduous forests (11). The region receives an average annual rainfall of approximately 2100 mm. The terrain is undulating, with an altitude range of 130-1100 m (Fig. 1).

Methodology

Vegetation analysis

The transect line of 2 km and quadrat methods were conducted using the assessment of tree diversity, a widely accepted technique for vegetation analysis. Within this approach, quadrats were utilized to assess floral diversity, ensuring systematic data collection and minimizing sampling bias. The selection of quadrat size and number was guided by the species-effort curve, a method used to determine the optimal sampling intensity for capturing species richness (12). Based on the species-effort curve, sample plots (quadrats) measuring 20 × 20 m were systematically established across the study area to ensure comprehensive coverage of tree species diversity. A sampling intensity of 2 % was used for assessment which includes 43 transects and 200 plots were laid out in the study area during the monsoon period (June-October), 2024. Each quadrat was carefully surveyed for tree species, with parameters such as species composition, abundance, density, basal area and regeneration potential recorded. This standardized approach enabled a comparative analysis of tree diversity across different habitat types within the Purna Wildlife Sanctuary. In addition to tree species, the presence of seedlings and saplings was documented to evaluate natural regeneration patterns. Key quantitative parameters, including

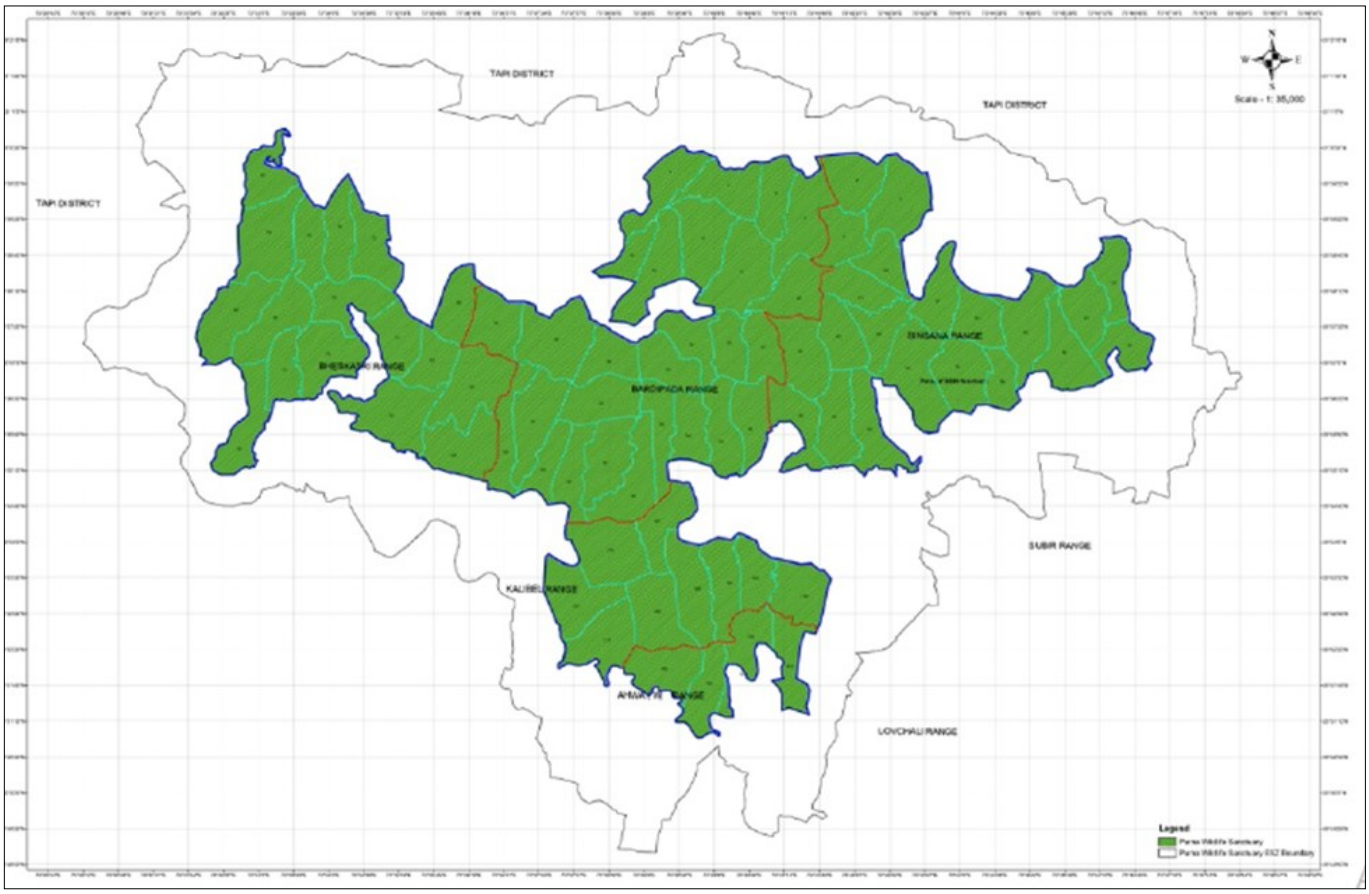

Fig. 1. Location map of Purna Wildlife Sanctuary.

density, frequency, abundance, relative density, relative frequency, relative dominance and the Importance Value Index (IVI) of trees, were determined following the methodology (17). The vegetation analysis was assessed using the Shannon-Wiener Index (13), while species dominance was analyzed using the Simpson's Index (14). Species richness was determined using the Margalef Richness Index (15) and Pielou's evenness index was also calculated (16) and the formulas were given below.

Shannon-Wiener Index (H'): The Shannon-Wiener Index is a widely used diversity metric that accounts for both species' richness (the number of species) and evenness (the relative abundance of species). It measures the uncertainty in predicting the species identity of an individual randomly selected from a dataset. The formula is:

$$H = -\sum (pi * \ln(pi))$$

Where H′ is the species diversity index, s is the number of species and pi is the proportion of individuals of each species belonging to the ith species of the total number of individuals. Higher H′ values indicate greater diversity, reflecting both a higher number of species and more equitable distribution among them.

Simpson's Index (D): Simpson's Index measures the probability that two individuals randomly selected from a sample will belong to the same species. It places more weight on dominant species. The formula is

$$D = \sum[n_i(n_i-1)/N(N-1)]$$

Where n_i is the number of individuals of a particular species and N is the total number of individuals of all species.

Margalef's Richness Index (d): Margalef's Index is used to quantify species richness while accounting for sample size. The formula is:

$$d = (S-1)/\ln N$$

Where, S = total number of species and N = total number of individuals in the sample.

Pielou's Evenness Index (J'): Pielou's Index measures how evenly individuals are distributed among the species present. It is derived from the Shannon Index and is calculated as:

$$J' = H/\ln S$$

Where, H = Shannon-Wiener diversity index and S = total number of species in the sample. A value of J' close to 1 indicates a more even distribution of individuals among species.

Population dynamics

Population dynamics and regeneration structure were assessed using the quadrat method. A quadrat size of 20 × 20 m was used to evaluate tree regeneration status. Species were identified and categorized based on growth parameters, considering the girth and density of individuals at different life stages. The following size classifications were used: seedlings (<20 cm in height), saplings (<30 cm collar circumference and >20 cm in height) and trees (≥30 cm DBH). Regeneration status was determined based on the population size of seedlings and saplings following the criteria (18):

i. Good regeneration: Seedlings > saplings > adults.

ii. Fair regeneration: Seedlings ≥ or ≤ saplings ≤ adults.

iii. Poor regeneration: Species persist only in the sapling stage, with no seedlings (saplings may be <, >, or = adults).

iv. No regeneration: Species are present only in the adult stage.

v. New regeneration: Species are represented only by seedlings or saplings, with no adults present.

This classification helps assess the ecological health of tree populations and their potential for natural regeneration within the study area.

Statistical analysis

Analysis of Variance (ANOVA) was conducted using the Statistical Package for the Social Sciences (SPSS) software to determine the statistical significance of differences among the different community compositions of Purna Wildlife Sanctuary.

Results

Community composition

The forest area under study is a significant wildlife sanctuary in Gujarat, marking the beginning of the rich biodiversity of the Western Ghats, particularly the northern section. It comprises various broad-leaved tree species, ranging from moist deciduous to dry deciduous forest types. At the same time the forest area is facing significant anthropogenic pressure such as forest fire, firewood collection, grazing, lopping and collection of NTFPs and the invasive species abundance (Table 1). *Tectona*

Table 1. Vegetation and anthropogenic disturbance in Purna Wildlife Sanctuary

Sr. No.	Range	Major vegetation[a]	Anthropogenic disturbance
1.	Ahwa West	***Tectona grandis***, *Mitragyna parvifolia*, *Aegle marmelos*, *Terminalia anogeissiana*, *Terminalia elliptica*, *Albizia procera*, *Lannea coromandelica* and *Heterophragma quadriloculare*	Heavy grazing, low forest fire, low tree lopping and high firewood collection
2.	Baripada	***Tectona grandis***, *Wrightia tinctoria*, *Holoptelea integrifolia*, *Garuga pinnata*, *Lannea coromandelica*, *Dalbergia paniculata* and *Senegalia catechu*	High forest fire, heavy grazing and low tree lopping
3.	Singhana	***Tectona grandis***, *Wrightia tinctoria*, *Desmodium oojeinense*, *Terminalia elliptica*, *Adina cordifolia*, *Lagerstroemia parviflora*, *Terminalia anogeissiana*, *Bridelia retusa* and *Holoptelea integrifolia*	Moderate forest fire, heavy grazing, collection of NTFPs and low tree lopping
4.	Bheskatri	***Tectona grandis***, *Terminalia elliptica*, *Wrightia tinctoria*, *Lannea coromandelica*, *Senegalia catechu*, *Adina cordifolia*, *Dalbergia latifolia*, *Mitragyna parvifolia* and *Ficus hispida*	Moderate forest fire, heavy grazing, collection of NTFPs and medium tree lopping
5.	Kalibel	***Tectona grandis***, *Wrightia tinctoria*, *Garuga pinnata*, *Adina cordifolia*, *Lannea coromandelica*, *Grewia tiliifolia*, *Trewia nudiflora* and *Lagerstroemia parviflora*	Heavy grazing, low forest fire, low tree lopping, collection of NTFPs and high firewood collection

[a]Species in **highlights** show the dominant tree species of a particular range.

grandis emerged as a dominant tree species present across all five forest ranges-Ahwa West, Baripada, Singhana, Bheskatri and Kalibel-of Purna Wildlife Sanctuary. Its widespread occurrence indicates a consistent ecological presence and potential management preference or regeneration success across varied habitat types within the sanctuary.

Tree density varied considerably among the forest ranges of Purna Wildlife Sanctuary, reflecting notable differences in tree population abundance. The results indicated that tree density ranged from a minimum of 5.85 ± 1.89 ha^{-1} in Singhana to a maximum of 13.74 ± 0.09 ha^{-1} in Bheskatri, highlighting significant spatial variation in population distribution across the landscape. Total Basal Cover (TBC), an indicator of tree dominance and girth, also showed substantial variation among the ranges. The highest TBC was recorded in Kalibel (59.93 ± 0.69 m^2 ha^{-1}), suggesting a prevalence of larger and possibly older trees, while Ahwa West exhibited the lowest value (10.74 ± 0.08 m^2 ha^{-1}), indicating a sparser or younger stand structure. In terms of species diversity, Bheskatri supported the highest species richness (68.82 ± 0.49), pointing to a more heterogeneous and floristically rich habitat. In contrast, Ahwa West had the lowest richness (14.63 ± 0.21), suggesting a more limited tree flora. The Shannon diversity index (H), which accounts for both species abundance and evenness, was highest in Singhana (3.26) and lowest in Ahwa West (2.65). This indicates that Singhana harbors a more balanced and equitably distributed tree community, despite its lower species richness. Similarly, Simpson's index (D), which inversely reflects diversity, was lowest in Singhana (0.04) and highest in Kalibel (0.17). These values further underscore the higher diversity and lower dominance of single species in Singhana. Pielou's evenness index (J) ranged from 1.26 in Bheskatri to 1.68 in Singhana, reinforcing the observation that Singhana exhibits a relatively balanced and evenly distributed tree population (Table 2).

Important Value Index (IVI)

The analysis of the IVI revealed notable variation in the dominance of tree species across the five forest ranges of Purna Wildlife Sanctuary. *Tectona grandis* emerged as the most dominant species in Bheskatri (55.97 %), followed by Baripada (54.28 %), Ahwa (41.66 %), Singhana (38.58 %) and Kalibel (27.66 %), indicating its strong ecological significance in these ranges. *Wrightia tinctoria* also demonstrated wide distribution and dominance, particularly in Bheskatri (29.78 %) and Baripada (23.51 %), reflecting their adaptive success across varied ecological conditions. *Terminalia elliptica* was most prominent in Singhana (30.43 %) and Ahwa West (27.85 %), while *Mitrogyna parvifolia* recorded the second highest IVI in Ahwa West (44.35 %) and substantial values in Singhana (19.70 %) and Kalibel (9.49 %), though it was absent in Bheskatri. *Ficus rumphii* was highly dominant in Bheskatri (49.54 %) but was not recorded in the other ranges, suggesting a localized distribution. Similarly, *Aegle marmelos* showed strong representation only in Ahwa West (30.38 %). Other species such as *Adina cordifolia*, *Terminalia anogeissiana*, *Lannea coromandelica* and *Holoptelea integrifolia* showed moderate IVI values across multiple ranges and species like *Butea monosperma*, *Bauhinia racemosa*, *Bridelia retusa* and *Albizia procera* had lower IVI values (<20 %), with distribution restricted to specific ranges (Table 3). These values reflect their comparatively limited dominance but continued ecological presence.

Raunkiaer's frequency classification

The distribution of tree species across the five ranges of Purna Wildlife Sanctuary revealed significant variation in their frequency classes according to Raunkiaer's classification. Many species in all ranges fell into the rarest frequency class (Class A: 1-20 %), suggesting that the sanctuary's flora is predominantly made up of low-frequency species. Bheskatri had the highest number of species in Class A (33 species), followed by Kalibel (31 species), Singhana (30 species), Baripada (29 species) and

Table 2. The structural and compositional parameters of tree communities in Purna Wildlife Sanctuary

S. No.	Ranges	Density (ha^{-1})	TBC (m^2 ha^{-1})	SR	H	D	J
1.	Ahwa West	9.10 ± 4.23	10.74 ± 0.08	14.63 ± 0.21	2.65	0.10	1.30
2.	Baripada	9.58 ± 2.41	28.78 ± 0.11	38.42 ± 0.41	2.68	0.14	1.43
3.	Singhana	5.85 ± 1.89	27.88 ± 0.11	16.59 ± 0.10	3.26	0.04	1.68
4.	Bheskatri	13.74 ± 0.09	26.41 ± 0.10	68.82 ± 0.49	2.82	0.10	1.26
5.	Kalibel	11.19 ± 2.44	59.93 ± 0.69	43.89 ± 0.48	2.56	0.17	1.35

*TBC: Tree Basal Cover; SR: Species Richness; H: Shannon Diversity Index; D: Simpson Diversity Index; J: Species Evenness.

Table 3. Important value index of major species of different forest ranges of Purna Wildlife Sanctuary

S. No.	Species	Ahwa West	Baripada	Singhana	Bheskatri	Kalibel
1.	*Tectona grandis*	41.66	54.28	38.58	55.97	27.66
2.	*Wrightia tinctoria*	6.34	23.51	26.70	29.78	20.75
3.	*Terminalia elliptica*	27.85	6.13	30.43	8.89	15.34
4.	*Mitrogyna parvifolia*	44.35	5.52	19.70	-	9.49
5.	*Holoptelea integrifolia*	-	15.30	1.89	2.56	18.08
6.	*Ficus rumphii*	-	-	-	49.54	-
7.	*Adina cordifolia*	10.35	1.77	16.70	18.33	15.30
8.	*Aegle marmelos*	30.38	-	2.82	1.35	-
9.	*Terminalia anogeissiana*	20.49	9.19	3.61	3.09	11.00
10.	*Lannea coromandelica*	21.47	15.30	18.45	9.56	8.19
11.	*Garuga pinnata*	-	15.12	5.05	11.40	4.19
12.	*Butea monosperma*	-	15.48	2.71	-	4.19
13.	*Bauhinia racemosa*	16.37	8.60	-	2.59	2.47
14.	*Bridelia retusa*	14.88	8.60	2.24	-	11.10
15.	*Albizia procera*	21.58	9.56	1.19	-	-

Ahwa West (20 species), indicating that these species are spread sparsely across the landscape. The intermediate frequency classes (B: 21-40 % and C: 41-60 %) had fewer species, with Class B ranging from 3 species in Ahwa West to 6 in Bheskatri, while Class C had minimal species, with only one species each in Bheskatri, Baripada, Kalibel and Singhana and none in Ahwa West. The higher frequency classes (D: 61-80 % and E: 81-100 %) showed minimal representation, indicating a lack of dominant species within the sanctuary. Ahwa West exhibited slightly more species in Class E (2 species), while Bheskatri had the highest number in Class D (2 species). Singhana had no species in Class E, further reflecting its lack of dominant species. The *Tectona grandis*, *Terminalia elliptica*, *Wrightia tinctoria* and *Mitragyna parvifolia* found throughout the sanctuary (Fig. 2). The overall distribution of species confirms Raunkiaer's "normal" biological spectrum, where most species are rare and only a few exhibits widespread or dominant distribution. This indicates a diverse forest structure dominated by a large number of less frequent species, with very few that are more widespread or dominant across the ranges of the sanctuary.

Saplings and seedlings community composition

The structural and diversity attributes of sapling and seedling layers showed notable spatial variation across the five forest ranges of Purna Wildlife Sanctuary. Sapling density ranged from a maximum of 16.3 ± 0.09 ha^{-1} in Singhana to a minimum of 5.58 ± 0.09 ha^{-1} in Kalibel, indicating variability in regeneration success across the landscape. Singhana not only had the highest sapling density but also maintained a high TBC (1.31 ± 0.001 m^2 ha^{-1}), reflecting both abundance and the presence of moderately sized young individuals. In contrast, Ahwa West had a moderate density (13.9 ± 0.09 ha^{-1}) but the lowest TBC (0.98 ± 0.002 m^2 ha^{-1}), indicating a greater proportion of smaller saplings. In terms of species richness (SR), Baripada (52.16 ± 0.43) and Singhana (51.67 ± 0.33) stood out, highlighting their contribution to species-level regeneration. The Shannon diversity index (H) was also highest in Singhana (3.06), followed by Baripada (2.94) and Ahwa West (2.85), reflecting a more diverse and stable sapling community in these ranges. The Simpson's index (D), which inversely indicates diversity, was highest in Kalibel (0.16) and Bheskatri (0.12), suggesting a relatively lower diversity with potential species dominance. Notably, Bheskatri exhibited the highest Pielou's evenness (1.27), indicating a more uniform distribution

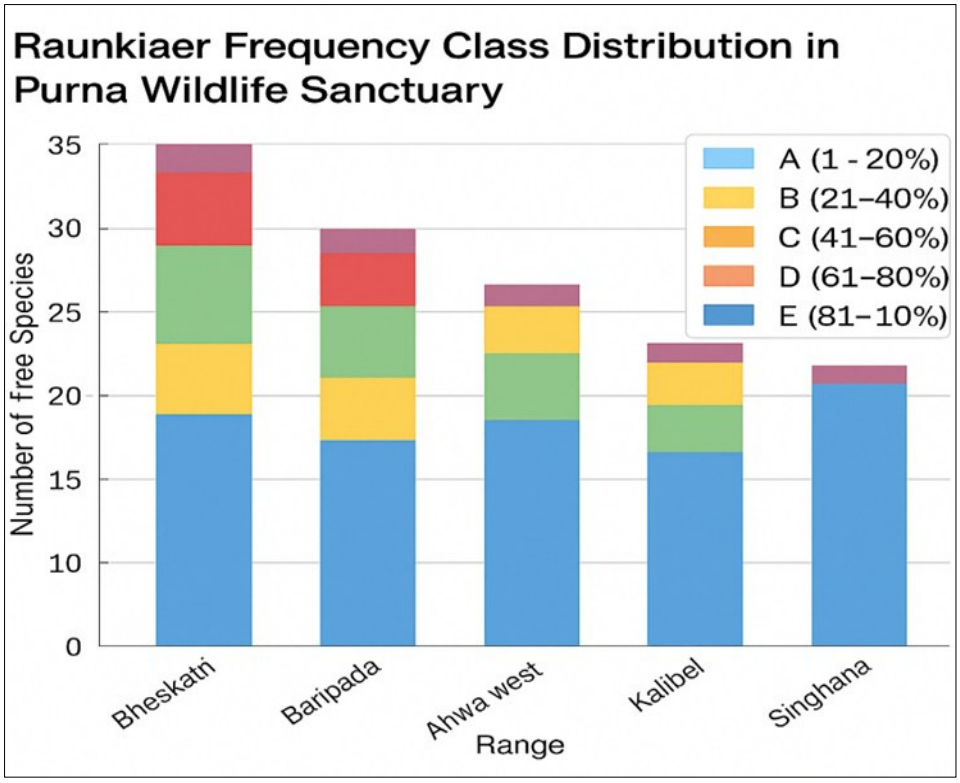

Fig. 2. Raunkiaer's frequency class distribution in Purna Wildlife Sanctuary.

Table 4. The structural and compositional parameters of saplings and seedlings communities in Purna Wildlife Sanctuary

S. No.	Ranges	Density (ha^{-1})	TBC (m^2 ha^{-1})	SR	H	D	J
			Saplings				
1.	Ahwa West	13.9 ± 0.09	0.98 ± 0.002	24.12 ± 0.17	2.85	0.06	0.97
2.	Baripada	12.6 ± 0.09	1.20 ± 0.002	52.16 ± 0.43	2.94	0.07	0.93
3.	Singhana	16.3 ± 0.09	1.31 ± 0.001	51.67 ± 0.33	3.06	0.06	0.95
4.	Bheskatri	6.03 ± 0.07	1.32 ± 0.002	34.00 ± 0.46	2.62	0.12	1.27
5.	Kalibel	5.58 ± 0.09	1.01 ± 0.001	24.92 ± 0.48	2.23	0.16	0.98
			Seedlings				
6.	Ahwa West	15.3 ± 0.09	0.87 ± 0.002	27.04 ± 0.19	2.74	0.06	0.85
7.	Baripada	12.0 ± 0.11	0.41 ± 0.001	50.47 ± 0.49	2.81	0.08	0.90
8.	Singhana	10.4 ± 0.05	0.31 ± 0.001	33.19 ± 0.20	3.09	0.05	1.13
9.	Bheskatri	7.30 ± 0.08	0.38 ± 0.001	40.63 ± 0.47	2.71	0.10	1.13
10.	Kalibel	20.8 ± 0.13	0.43 ± 0.001	79.47 ± 0.52	2.87	0.08	1.06

of individuals across species despite having a lower overall richness (34.00 ± 0.46) (Table 4).

In the seedling layer, the highest density was recorded in Kalibel (20.77 ± 0.13 ha^{-1}), followed by Ahwa West (15.3 ± 0.09 ha^{-1}), reflecting a strong regenerative capacity in these ranges. However, Kalibel's high seedling density was also accompanied by the greatest species richness (79.47 ± 0.52), indicating diverse and dense early-stage growth. Singhana, despite a moderate seedling density (10.35 ± 0.05 ha^{-1}), showed the highest Shannon diversity index (3.09) and evenness (1.13), suggesting that regeneration in this range is not only diverse but also well distributed across species. Bheskatri also recorded high evenness (1.13) and relatively high richness (40.63 ± 0.47) but had lower density than other ranges. The TBC of seedlings was relatively low across all ranges, as expected in early growth stages. The highest TBC was observed in Ahwa West (0.87 ± 0.002 m^2 ha^{-1}) and the lowest in Singhana (0.31 ± 0.001 m^2 ha^{-1}), possibly indicating size variation among seedling populations (Table 4).

Regeneration status

The regeneration status of tree species in the five forest ranges of Purna Wildlife Sanctuary, based on the density of trees, saplings and seedlings, reveals distinct patterns. Ahwa West shows good regeneration, as the density follows the trend of seedlings > saplings > trees, indicating a healthy and sustainable population structure. Baripada and Singhana both exhibit fair regeneration, where the densities of seedlings and saplings are either slightly lower or higher than tree density, suggesting moderately stable regeneration with potential for improvement.

In Bheskatri, the sapling and seedling densities are lower than the adult tree density, pointing toward poor to fair regeneration, meaning the species may be persisting but are not regenerating vigorously. Kalibel presents a unique case of new regeneration, with the highest seedling density among all ranges but relatively low densities of saplings and trees. This suggests recent recruitment of species that may not yet have matured, reflecting positive but early-stage regeneration (Fig. 3).

Discussion

Community composition

A forest's richness is determined by its constituent species' regenerative potential across both spatial and temporal scales (19). The structural and compositional attributes of tree communities in the five forest ranges of Purna Wildlife Sanctuary reveal pronounced ecological heterogeneity, shaped by both natural and anthropogenic factors. The observed variation in tree density and TBC reflects differences in forest stand structure, species composition and possibly site-specific regeneration dynamics. The highest tree density in Bheskatri suggests favorable ecological conditions or effective regeneration, potentially linked to the presence of a wide array of tree species, as supported by its high species richness. In contrast, the lower density in Singhana may be attributed to anthropogenic pressures such as grazing and non-timber forest product (NTFP) collection, which can suppress seedling recruitment and sapling survival. A similar analysis was conducted in various forest areas of Kedarnath Wildlife Sanctuary by Malik and Bhatt (4), who reported the highest tree density (505 ± 21 trees/ha) and TBC (42.92 ± 2.57 m^2/ha) in Triyuginarayan Forest 2 (TN2). The woody species diversity in different parts of Chandoli National Park, recording the highest tree density (657 trees/ha) and basal area (57.16 m^2/ha) in the Male forest area, while the lowest values were observed in the Gave forest area (149 trees/ha and 10.22 m^2/ha) was studied (20). In the previous study of Mahal forest area of Purna Wildlife Sanctuary, the tree density values ranging from 0.1 to 4.1 trees/ha and basal area values between 0.01 and 3.48 m^2/ha was recorded (21). Additionally, a tree density of 613.34 trees/ha and a basal cover of 20.3 m^2/ha were reported in the Mankulam Forest Division of the Western Ghats (22).

TBC, being an indicator of tree maturity and dominance, peaked in Kalibel, where fewer but larger trees dominate the stand. This suggests that Kalibel may harbor older, well-established individuals, potentially due to lower rates of tree felling or historical protection. In contrast, the lowest TBC in Ahwa West may reflect a younger stand structure or degradation due to disturbances such as firewood collection and grazing, both of which are noted in the area. The variation in species richness (SR) is especially telling: Bheskatri's exceptionally high richness points to a diverse and heterogeneous habitat, possibly benefiting from a mosaic of microhabitats and relatively less intensive anthropogenic impact. On the other hand, Ahwa West, with the lowest richness and diversity indices, appears to be the most ecologically simplified, likely due to higher disturbance levels such as grazing pressure and firewood collection, as noted in field observations. Interestingly, Singhana, despite its lower

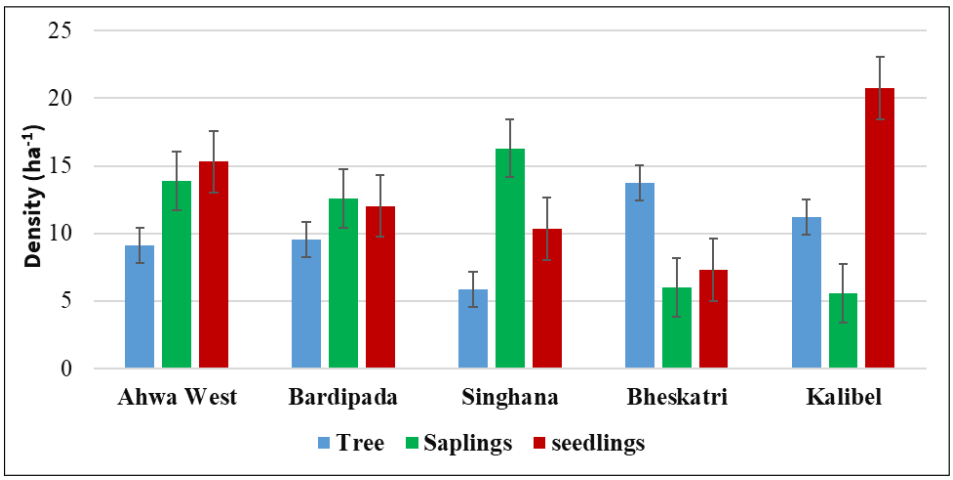

Fig. 3. Regeneration status of different forest ranges of Purna Wildlife Sanctuary.

species richness, recorded the highest Shannon index (3.26) and lowest Simpson's index (0.04), indicating a well-balanced species composition with minimal dominance. This pattern underscores the importance of evenness in determining community structure -wherein the species are more equitably distributed rather than concentrated in a few dominant taxa. Pielou's evenness index (J) further supports this interpretation, with Singhana showing the highest evenness (1.68), suggesting that species are more uniformly represented compared to Bheskatri, where dominance by certain species may be more pronounced (1.26). These findings highlight that species richness alone does not equate to ecological balance-distribution and relative abundance are equally critical. The species diversity in different forest patches of North Sulawesi, Indonesia and reported Shannon diversity index values ranging from 3.3720 to 1.6990 and evenness index values between 0.9524 and 0.7099 was studied (23). In the tropical moist deciduous forest of the Veerakal forest area, Coimbatore Forest Division, a species diversity value of 2.79, evenness index of 2.18, species richness of 4.25 and dominance value of 0.14 were recorded (24). Additionally, species diversity values ranging from 0.026 to 0.321 and Simpson index values between 0.000 and 0.039 in the Mahal forest area of Purna Wildlife Sanctuary have been reported (21). The varying intensities of anthropogenic disturbance documented in each location can explain the contrasting patterns across ranges. For instance, heavy grazing and firewood collection in Ahwa West and Kalibel likely suppress regeneration and alter stand structure. Conversely, ranges like Singhana, while not free from human pressure, may experience a more diffused or moderate disturbance regime that maintains diversity without allowing specific species to dominate.

The variation in IVI across the five ranges of Purna Wildlife Sanctuary highlights the spatial heterogeneity and ecological dominance of certain tree species. The IVI analysis revealed that *Tectona grandis* is the most dominant species in several ranges of Purna Wildlife Sanctuary, especially in Bheskatri, Baripada and Singhana, indicating its wide adaptability and ecological importance. Other species like *Wrightia tinctoria* and *Terminalia elliptica* also showed significant dominance in specific ranges, while *Mitragyna parvifolia* was notably dominant in Ahwa West and selectively present in other areas. Some species, such as *Ficus rumphii* and *Aegle marmelos*, exhibited localized dominance, suggesting site-specific habitat preferences. Species with lower IVI values, including *Butea monosperma* and *Bridelia retusa*, had limited distribution but remained ecologically relevant. These IVI patterns collectively reflect the structural complexity and ecological interactions shaping the forest communities within the sanctuary. Understanding such species -level dominance and distribution is crucial for prioritizing conservation actions, especially for maintaining the ecological balance and ensuring the resilience of both dominant and lesser-represented tree species in Purna Wildlife Sanctuary. The Mahal forest area of Purna Wildlife Sanctuary identified *Tectona grandis*, *Terminalia elliptica*, *Sterculia urens*, *Ficus racemosa* and *Diospyros melanoxylon* as the species with the highest IVI reported in previous study (21). Similarly, *Memecylon umbellatum*, *Syzygium cumini*, *Olea dioica*, *Terminalia elliptica* and *Gnidia glauca* as the most dominant species in the semi-evergreen forests of Chandoli National Park in the northern Western Ghats were reported (20).

Raunkiaer's frequency

The distribution of tree species across the five forest ranges of Purna Wildlife Sanctuary reveals interesting patterns when analyzed using Raunkiaer's frequency classification. Many species in all the ranges fall into Class A (1-20%), suggesting that the sanctuary's flora is dominated by rare species, with many species occurring sparsely across the landscape. Notably, *Tectona grandis*, *Terminalia elliptica*, *Wrightia tinctoria* and *Mitragyna parvifolia* are the major dominant species across all the ranges. These species have a wide distribution and significant frequency, especially *Tectona grandis*, which is prominent in most ranges. The prevalence of these species reinforces the idea of a diverse forest structure, with many less frequent species scattered across the landscape and very few exhibiting dominances across the sanctuary. The distribution of species follows Raunkiaer's 'normal' biological spectrum, where most species are rare and only a few are widely distributed or dominant and the forest area was homogeneity in nature. This pattern points to a healthy, diverse forest structure in Purna Wildlife Sanctuary, dominated by many less frequent species and a few dominant, widespread species. A similar study conducted in the Saputara Forest Area and Purna Wildlife Sanctuary by Kumar et al. (2022) (25) documented high frequency values for *Tectona grandis*, *Terminalia elliptica*, *T. chebula*, *T. bellerica* and *Madhuca indica*. A similar homogeneous forest community was reported (26) in various forest habitats of the Chapredi Reserve Forest, Bhuj-Kachchh, Gujarat, based on Raunkiaer's frequency values.

Saplings and seedlings community composition

The sapling and seedling layers across the five ranges of Purna Wildlife Sanctuary reveal important patterns in forest regeneration, structural composition and species diversity. The significant variation in sapling density, basal cover and diversity indices across ranges indicate that localized environmental conditions and ecological processes highly influence regeneration. Singhana displayed the highest sapling density and Shannon diversity index, suggesting it supports a structurally rich and taxonomically diverse sapling community. Its high basal cover further indicates the presence of moderately mature saplings, reflecting successful recruitment and establishment. In contrast, Kalibel exhibited the lowest sapling density and diversity, along with the highest Simpson's index, pointing to possible dominance by a few species and limited regeneration success at this stage. Interestingly, Bheskatri, despite lower species richness, had the highest evenness (1.27) in the sapling layer, indicating a balanced representation of individuals among the species present. This suggests that while species richness may be modest, competition among species is low, potentially allowing for more stable coexistence.

In the seedling layer, Kalibel recorded the highest density and species richness, reflecting strong regeneration potential and active recruitment. However, Singhana once again showed the highest diversity (3.09) and evenness, indicating that seedlings there are not only diverse but also more uniformly distributed. This balanced distribution of individuals across species in both the sapling and seedling layers points to long-term regeneration stability in Singhana. Ahwa West, while moderate in diversity, had the highest seedling basal cover, suggesting the presence of relatively larger individuals at early growth stages. On the other hand, Singhana had the lowest seedling basal cover, possibly

indicating a dominance of smaller individuals despite high diversity, which may reflect recent recruitment or slow growth rates. A similar study by Malik and Bhatt (2016) (4) in Kedarnath Wildlife Sanctuary reported the highest sapling density (5690 individuals/ha) and seedling density (7485 individuals/ha) in the Jamu forest area, while the lowest densities were recorded in Patheli (1850 saplings/ha and 1670 seedlings/ha). The species richness ranged from 2.02 to 3.71 for saplings and 0.86 to 2.48 for seedlings. The Shannon diversity index varied between 2.07-3.59 (saplings) and 1.91-3.32 (seedlings), while Simpson dominance values ranged between 0.07-0.24 for saplings and 0.11-0.37 for seedlings, indicating moderate to high diversity and variability across forest areas.

Overall, the contrasting patterns in density, richness and diversity indices across sapling and seedling layers highlight the regeneration dynamics and ecological variability across the sanctuary. Singhana and Baripada emerge as critical areas for diverse and balanced regeneration, while Kalibel shows promising early-stage recruitment. These insights are crucial for guiding site-specific conservation and forest management strategies aimed at sustaining long-term forest structure and biodiversity in Purna Wildlife Sanctuary.

Regeneration status

The regeneration patterns observed across the five forest ranges of Purna Wildlife Sanctuary indicate varying stages of ecological recovery and forest sustainability. The classification of regeneration status, derived from the relative densities of trees, saplings and seedlings, provides key insights into the recruitment dynamics and future composition of the forest stands. Ahwa West demonstrates good regeneration with a healthy structure of seedlings > saplings > trees, indicating stable recruitment. Such trends typically reflect favorable environmental conditions, effective seed dispersal and minimal disturbance, which support continuous forest renewal. Baripada and Singhana show fair regeneration, suggesting moderately stable but improvable regeneration potential. This implies that regeneration is ongoing but may be influenced by factors such as grazing, competition, or site-specific disturbances that could limit seedling establishment or transition into mature trees. Bheskatri exhibits poor to fair regeneration, as lower sapling and seedling densities compared to tree density indicate limited recruitment. This suggests that while mature individuals are present, the lack of younger cohorts may result in future population decline if natural regeneration is not supported through improved management practices or habitat restoration efforts. Kalibel shows signs of new regeneration, with high seedling density but few saplings and trees, reflecting early-stage recovery. This pattern demonstrates early-stage recruitment, possibly driven by recent disturbance recovery or favorable seasonal conditions. However, the long-term success of regeneration in Kalibel will depend on the survival and development of these seedlings into saplings and ultimately mature individuals. The different forest areas of Kedarnath Wildlife Sanctuary, where they reported good regeneration in the Barmadi, Kukrani Band, Jamu and Triyuginarayan forest areas, while poor regeneration was found in the Pathali forest area similar study was conducted (4). The tree regeneration potential of tropical forests in the Western Ghats and observed that most forest types showed poor regeneration, including tropical lowland broad-leaved semi-deciduous seasonal forests, tropical broad-leaved evergreen/montane forests, tropical broad-leaved evergreen forests and tropical lowland broad-leaved seasonal evergreen forests was investigated (1). In contrast, good regeneration was found in human undisturbed areas of tropical broad-leaved drought deciduous forests and tropical broad-leaved drought deciduous woodlands. Overall, the regeneration status across the sanctuary ranges from well-established to early-stage or limited regeneration, underscoring the importance of range-specific conservation interventions. Continuous monitoring and adaptive management will be essential to support natural regeneration and maintain the ecological integrity of Purna Wildlife Sanctuary.

Conclusion

This study comprehensively examined the forest structure and regeneration dynamics across five ranges of Purna Wildlife Sanctuary using a suite of ecological parameters: tree density, basal cover, species richness, Shannon-Wiener and Simpson's diversity indices, Pielou's evenness index, IVI, Raunkiaer's frequency classification and regeneration status based on seedlings and saplings. The results revealed significant spatial heterogeneity in species composition and forest stand characteristics. *Tectona grandis* emerged as the ecologically dominant species across all ranges, while diversity and evenness were highest in Singhana, suggesting a balanced community structure. Kalibel had the highest basal cover, indicating mature tree stands, whereas Bheskatri supported the richest species pool. The frequency classification showed that most species belonged to the rarest class (Class A), reflecting a diverse but sparsely distributed flora. The IVI analysis highlighted the localized dominance of species such as *Wrightia tinctoria*, *Ficus rumphii* and *Terminalia elliptica* in specific ranges.

Regeneration status varied: Ahwa West showed good regeneration, Baripada and Singhana had fair regeneration, Bheskatri indicated poor to fair regeneration and Kalibel showed signs of new regeneration with high seedling density. Sapling and seedling diversity metrics further supported these findings, revealing range-specific regeneration dynamics. Altogether, this research provides crucial ecological insights that can inform conservation strategies. Targeted management interventions-such as reducing anthropogenic pressures, enhancing the regeneration of key species, controlling invasive plants and protecting rare species-are essential for maintaining the biodiversity and ecological integrity of Purna Wildlife Sanctuary.

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Authors' contributions

MRS conducted the field surveys, collected ecological data and drafted the manuscript. KS, BK and GTG assisted with data analysis and preparation of species frequency tables. KP

contributed to GIS mapping and interpretation of results. FP provided support in data validation and literature review. BK, GTG and KS conceived the study, coordinated with the Gujarat Forest Department and supervised the overall research process. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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