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Regeneration Dynamics and Structural Recovery of South-Eastern Tropical Deciduous Forest in Gujarat, India

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Abstract
Tropical deciduous forests are ecologically important ecosystems, yet they remain highly vulnerable to escalating anthropogenic pressures. The current study appraises the tree regeneration status of tropical deciduous forests in the Narmada district of southeastern Gujarat, India. A total of seventy-two quadrats (0.1 ha each) and 288 regeneration subplots (3 × 3 m) were systematically sampled across an elevational gradient of 100–850 m. In total, 71 tree species belonging to 59 genera and 32 families were verified, with Fabaceae contributing the highest species richness. The regeneration assessment showed that 43 species were able to regenerate well, but 11 species like *Acacia catechu*, *Bombax ceiba*, and *Terminalia arjuna*, were not able to regenerate at all. This means that their populations could drop in the future. Generally, the forests exhibit healthy regeneration patterns and structural stability however, species with poor or absent recruitment demand immediate conservation concern. The results of this study offer a consistent baseline for biodiversity conservation planning and the development of sustainable forest management strategies in southeastern Gujarat.

Keywords: Floristic diversity; Stand structure; Regeneration; Species recruitment; Tropical deciduous forests

Introduction

Tropical deciduous forests establish one of the most extensive vegetation groups in India and are universally recognized for their ecological significance, high biodiversity, and vital role in supporting rural livelihoods (Murphy and Lugo, 1986; Ratnam et al., 2011) Characterized by distinct seasonality and prolonged dry periods, these forests are defined by strong environmental constraints, creating them predominantly sensitive to anthropogenic disturbances and climatic fluctuations (Sanchez-Azofeifa et al., 2005; Singh and Singh, 1992). In terms of their ecological status, tropical deciduous forests are amongst the most dishonoured ecosystems worldwide, with only a fraction of their original range remaining unbroken (Janzen, 1988; Miles et al., 2006). Human induced pressures such as fuel wood collection, grazing, agricultural infringement, and fires continue to change vegetation composition and regeneration processes. Tree diversity and stand structural abilities support as essential indicators of forest health and ecological functioning. Diversity gradients are repeatedly shaped by an organization of edaphic, climatic, and topographic factors that affect species spreading across landscapes (Condit et al., 2000; Phillips et al., 2010). Structural limits such as tree density, basal area, and size class distribution help explain successional patterns, competitive interactions, and the ecological roles of dominant and rare species (Lieberman et al., 1985; Poorter et al., 2006). Regeneration status, measured seedling and sapling abundance relative to mature trees, provides visions into the volume of species to maintain stable populations under changing environmental conditions (Saxena and Singh, 1984; Khumbongmayum et al., 2006). Species act non stop recruitment habitually display inverse J distributions, while those missing juveniles are at risk of upcoming decline (Peters, 1996). Tropical deciduous forests in India shows high spatial heterogeneity gripped by abnormalities in rainfall, soil fertility, elevation and disturbance history

(Kodandapani et al., 2008; Sagar and Singh, 2005). The forests of southeastern Gujarat, mostly within the Narmada district and the Shoolpaneshwar wildlife sanctuary landscape, indicate a limited piece of the deciduous biome. These forests host ecologically and economically vital species such as *Tectona grandis*, *Anogeissus latifolia*, *Terminalia crenulata*, and *Acacia catechu*, which pay meaningfully to the local economy and forest productivity (Patel et al., 2010; Joshi et al., 2015). Still, expanded anthropogenic activities counting illicit timber removal, shifting cultivation, grazing pressure, and human wildlife interactions have raised concerns about diminishing regeneration and altered forest structure in the region (Roy et al., 2013; Mehta and Shah, 2015; Yadav et al., 2015).

Climate deviation further strengthens the vulnerability of deciduous forests. Growing temperatures, unequal monsoon designs, and lengthy droughts directly affect seedling survival, species recruitment, and vegetation dynamics (Allen et al., 2015; IPCC 2019). Numerous studies have documented changes in species dominance, observed the recovery of moisture-sensitive species, and noted the spread of drought-tolerant taxa in response to increased climate stress (Devesh et al.,2024; Chaturvedi et al., 2011). Such variations not only alter biodiversity enterprises but also affect ecosystem procedures such as carbon sequestration, nutrient cycling, and habitat provision (Brown and Lugo, 1992; Lewis et al., 2009). Despite these apprehensions, systematic and measurable assessments of diversity, population structure, and regeneration dynamics in southeastern Gujarat remain limited. Most existing studies have focused on specific species groups or protected areas, leaving large portions of the landscape ecologically understudied (Reddy et al., 2011; Patel and Kumar, 2018). Inclusive field-based analyses are essential for recognizing regeneration bottlenecks, understanding species ecological strategies, and supporting forest restoration under climate-adaptive management frameworks (FAO, 2020). Such valuations can help conservation planners in prioritising species and habitats that require immediate attention and in designing evidence based management interferences. This outlines, the current study goals for detailed assessment of tree species diversity and regeneration status in the tropical deciduous forests of the Narmada district, Gujarat. By assimilating seedling, sapling, and adult population data with stand structural analyses, the study pursues to elucidate forest dynamics and species recruitment shapes across the landscape. The definitions contribute valuable ecological insights for guiding sustainable forest management, biodiversity conservation, and climate resilient restoration initiatives in southeastern Gujarat.

Materials and Methods

Study area

The District Narmada lies between 21.24° and 22° North (latitude) and 72.4° and 73.15° East (longitude) in the South Eastern Part of Gujarat as shown below in Fig.no.1. It has an area of around 2755 Square km which includes 1147.69 sq.km of forest cover representing 41.66% of the total area (Gujarat Forest Report, 2021-22) as shown in Fig. 1. The district shares its border with Surat in the South, Vadodra in the North, Bharuch in the West and State of Maharastra in the East (www.vibrantgujarat.com, (2014). The district has three well distinct zones Dry Summer (March-July), Monsoon (July-September) and winter (November-February). (Yadav et al., 2015). The maximum rainfall occurs in the month of June and lasts till first week of October. In the North Eastern part, lies the Shoolpaneshwar Wildlife Sanctuary (SWS) which was established in 1987 after the name of Shoolpaneshwar Temple. SWS has rich diversity in both aquatic and terrestrial life with dominant vegetation types of Slightly Moist Teak forests (3B/C1b), Southern Moist mixed deciduous forests (3B/C1c), dry deciduous scrubs (5/DS1), dry bamboo brakes (5/E9), and dry tropical riverine forests (5/1S1*)* according to Champion and Seth classification (1968) (Gupta. R and Sharma. L. K. 2020). SWS has around 600 plant species, among them *Tectona grandis* stands at the top with 127.221 density/ha. The other major floral species include *Wrightia tinctoria*, *Butea monosperma*, *Terminalia crenulata, Diospyros melanoxylon*, and *Anogeissus latifolia* (Kumar and Ramana, 2017). Among faunal species, SWS has 32 species of mammals, 198 species of birds and several species of reptiles and insects (https://forests.gujarat.gov.in/shoolpaneshwar-sanctuary.html).

Sampling Design

The present study was carried out in December 2023 which continued till February 2024. A total of 72 Quadrants of size of 0.1 ha ($31.62\,m \times 31.62m$) were laid down in the field for the phytosociological study. Within each quadrant, 4 sub-plots of size $3m \times 3m$ (288 quadrants) were laid down at each corner to study the seedling and sapling for forest regeneration potential. A random sampling technique was employed in the study area and quadrants were laid at different elevations from 100 meter above sea level (masl) to 850 m asl. The trees greater than 10cm in girth at breast height (gbh) were taken into consideration. Geographic coordinates along with elevation were recorded in the centre of each plot with the help of handheld GPS (Garmin, eTrex VISTA H). Moreover, at the sampling location and in the periphery of the plots, no. of trails, fire incidents, agricultural activities, deforestation and number of cutted stems etc. were recorded to check the forest disturbance. Tree species were identified with the help of forest department officials and local communities present in forest. At each sampling location, the local and common name of species was recorded. Moreover, voucher specimens of all the inventoried tree species were collected and later cross verified in the Forest Department Dediapada, District Narmada, Gujarat.

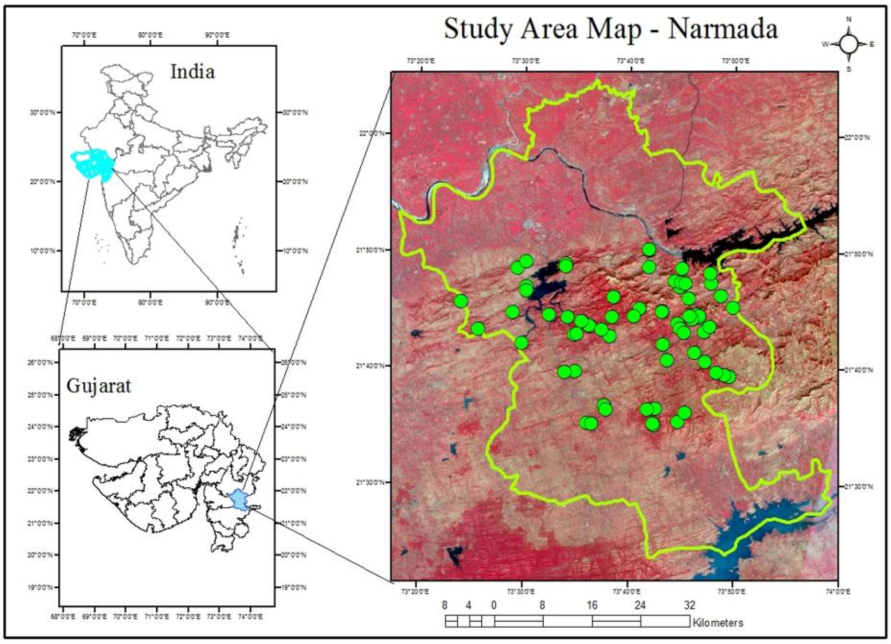

Fig. 1. Study area with Sampling Locations on False Colour Composite (FCC) Image.

Result

Forest structure and regeneration

The study area recorded a total of seventy-one species fitting to fifty-nine genera and thirty-two families, representing a temperately rich floristic composition as illustrated in Fig. 2. The examination of plant families suggested that Fabaceae was the main leading family, followed by Moraceae, Malvaceae and Combretaceae. *Tectona grandis* presented the maximum wealth in the forest, representing that it is the most numerically leading species in the stand. In contrast, species such as *Cordia dichotoma, Syzygium cumini, Acacia ferruginea*, and numerous other species occurred in low numbers. The number of species under fair regeneration status is around 8. The good regeneration status has the highest number of species, nearly 43. For no regeneration, the number of species is about 12. In the new regeneration category, there are around 3 species, although the poor regeneration status demonstrates the lowest number of species, approximately 2. Overall, most species fall under the good regeneration category, representing a healthy regeneration condition in the area.

Fig. 2. Regeneration status of recorded tree species in tropical dry forests.

Regeneration status by species recorded in the tropical deciduous forest.

The number of seedlings ranges from **0** at the lowest to 14194 at the highest. Sapling counts also vary widely, with the minimum being 0 and the maximum reaching 12611. Adult tree numbers show much lower variation, starting from a minimum of 0 and rising to a maximum of 1456. Regeneration status in the table spans categories from No, Poor, Fair, New, to Good, with Good being the most frequently represented status across the dataset as given in Table. 1.

Table 1. Regeneration status by species recorded in the tropical dry forest.

Species	Seedling	Sapling	Adult	Regeneration status
Acacia catechu (L.f.) Willd.	0	0	27	No
Acacia chundra (Roxb. ex Rottler) Willd.	111	56	5	Good
Acacia ferruginea DC.	28	0	1	Fair
Acacia senegal (L.) Willd.	0	56	10	Poor
Adina cordifolia (Roxb.) Brandis	3056	2000	128	Good
Aegle marmelos (L.) Corrêa	611	750	51	NA
Alangium salviifolium (L.f.) Wangerin	0	0	4	No
Albizia lebbeck (L.) Benth.	583	167	27	Good
Albizia procera (Roxb.) Benth.	278	111	2	Good
Annona squamosa L.	500	778	18	Good
Azadirachta indica A.Juss.	389	361	9	Good
Bauhinia racemosa Lam.	306	222	37	Good
Bombax ceiba L.	0	0	33	No
Boswellia serrata Roxb.	83	111	23	NA
Bridelia retusa (L.) A.Juss.	1083	1028	162	Good
Bridelia squamosa (Lam.) Gehrm.	278	56	50	Good
Butea monosperma (Lam.) Kuntze	5556	5028	566	Good
Careya arborea Roxb.	0	0	5	No
Carissa carandas L.	667	556	0	New
Casearia graveolens Dalzell	1222	1194	7	Good
Cassia fistula L.	972	806	99	Good
Commiphora wightii (Arn.) Bhandari	0	0	6	No
Cordia dichotoma G.Forst.	28	0	3	Fair
Cordia wallichii G.Don	389	611	46	NA
Dalbergia latifolia Roxb.	667	750	40	NA
Dalbergia paniculata Roxb.	56	250	98	NA
Dillenia pentagyna Roxb.	250	0	13	Fair
Diospyros melanoxylon Roxb.	9194	6333	221	Good
Dioscorea pentaphylla L.	28	28	0	New
Dolichandrone atrovirens (Roth) K.Schum.	139	139	15	NA
Emblica officinalis Gaertn.	0	0	8	No
Erythrina variegata L.	306	167	29	Good
Ficus amplissima Sm.	0	0	2	No
Ficus asperrima Roxb.	1472	1139	24	Good
Ficus hispida L.f.	3139	2000	38	Good
Ficus racemosa L.	889	500	29	Good
Ficus religiosa L.	0	0	7	No
Garuga pinnata Roxb.	611	500	210	Good
Gmelina arborea Roxb.	0	28	12	Poor
Grewia tiliifolia Vahl	2361	2750	126	NA
Helicteres isora L.	14194	10611	1	Good
Holarrhena antidysenterica Wall. ex A.DC.	6722	4611	124	Good
Holoptelea integrifolia (Roxb.) Planch.	583	444	22	Good
Kydia calycina Roxb.	1556	1861	239	NA
Lagerstroemia parviflora Roxb.	1861	1083	107	Good
Lannea coromandelica (Houtt.) Merr.	472	361	110	Good
Madhuca indica J.F.Gmel.	1722	694	24	Good
Miliusa tomentosa (Roxb.) Finet & Gagnep.	10194	7444	641	Good
Mitragyna parvifolia (Roxb.) Korth.	583	472	47	Good
Morinda tomentosa B.Heyne ex Roth	1167	500	74	Good
Ougeinia oojeinensis (Roxb.) Hochr.	278	222	27	Good
Piliostigma malabaricum (Roxb.) Benth.	111	28	20	Good
Pongamia pinnata (L.) Pierre	1722	1417	77	Good
Prosopis spicigera L.	639	389	35	Good
Pterocarpus marsupium Roxb.	389	56	15	Good
Sapindus mukorossi Gaertn.	1111	1028	25	Good
Schleichera oleosa (Lour.) Oken	472	361	21	Good
Soymida febrifuga (Roxb.) A.Juss.	0	56	23	Poor
Spondias pinnata (L.f.) Kurz	250	194	31	Good
Sterculia urens Roxb.	167	139	21	Good

Syzygium cumini (L.) Skeels	28	0	2	Fair
Tectona grandis L.f.	9111	7722	1456	Good
Terminalia anogeissiana Gere & Boatwr.	278	417	128	NA
Terminalia arjuna (Roxb. ex DC.) Wight & Arn.	0	0	12	No
Terminalia bellirica (Gaertn.) Roxb.	972	611	125	Good
Terminalia crenulata Roth	8028	7222	480	Good
Vitex negundo L.	28	0	20	Fair
Wrightia tinctoria var. typica Pichon	13333	12611	1085	Good
Wrightia tomentosa Roem. & Schult.	0	0	8	No
Woodfordia fruticosa (L.) Kurz	1472	1806	0	New
Xeromphis spinosa (Thunb.) Keay	0	0	4	No
Ziziphus mauritiana f. pendula V.V.Byalt & Korshunov	83	56	1	Good
Ziziphus nummularia (Burm.f.) Wight & Arn.	56	28	1	Good
Ziziphus xylopyrus (Retz.) Willd.	1861	1444	56	Good

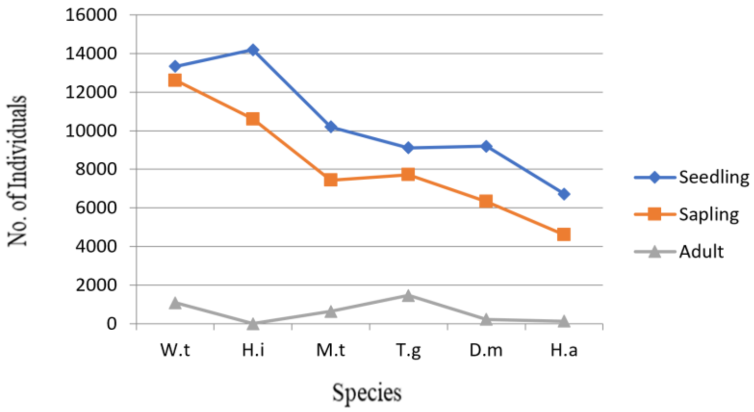

Fig. 3. Good Regeneration Status
W.t (*Wrightia tinctoria*), **H.i** (*Helicteres isora*), **M.t** (*Miliusa tomentosa*), **T.g** (*Tectona grandis*), **D.m** (*Diospyros melanoxylon*), and **H.a** (*Holarrhena antidysenterica*)

Good Regeneration Status

Numerous species presented dynamic regeneration, including *Wrightia tinctoria*, *Helicteres isora*, *Miliusa tomentosa*, *Tectona grandis*, *Diospyros melanoxylon*, and *Holarrhena antidysenterica* with good number of seedlings and saplings reflects strong recruitment. The occurrence of these species in all three life stages seedlings, saplings, and adults confirms positive and stable regeneration in the forest as shown in the Fig. 3. The regeneration pattern of the six studied tree species shows a clear deteriorating trend from seedling to adult stages. *Helicteres isora* recorded the uppermost seedling abundance (14,000 individuals), followed by *Wrightia tinctoria* and *Millusa tomentosa*, each showing strong early recruitment. Sapling populations were steadily lower than seedlings across all species, with values ranging from 12,500 in *Wrightia tinctoria* to less than 5,000 in *Holarrhena antidysenterica*, representing reduced survival during intermediate growth stages. Adult densities were extremely low for all species, with *Diospyros melanoxylon* showing the highest adult numbers (~1,800), while *Helicteres isora* and *Holarrhena antidysenterica* exhibited minimal adult representation.

New Regeneration Status

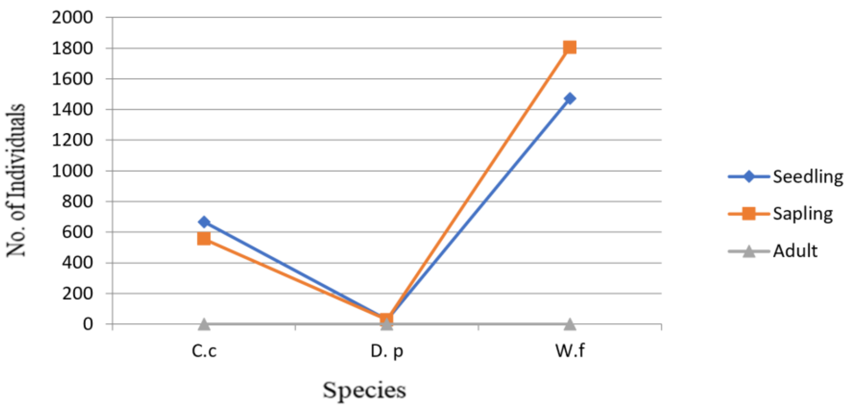

Fig. 4. New Regeneration Status
C.c (*Carissa carandas*), **W.f** (*Woodfordia fruticosa*), and **(D.p)** *Dioscorea pentaphylla*

Species characterized as new include *Carissa carandas, Woodfordia fruticosa and Dioscorea pentaphylla* as illustrated in Fig. 4. These species have seedling and sapling growth but lack fully-grown individuals, suggesting recent creation or colonization.

Poor Regeneration Status

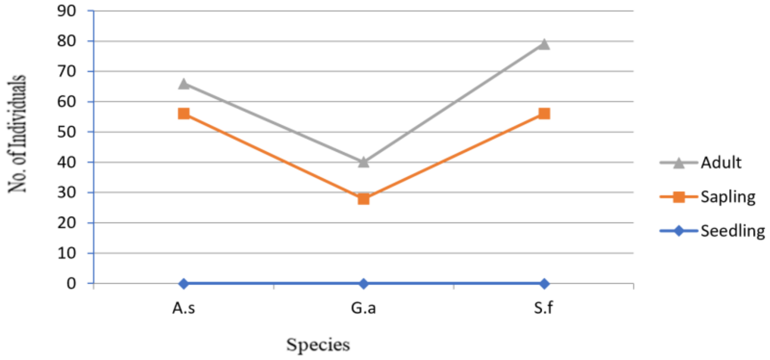

Fig. 5. Poor Regeneration Status
S.f (*Soymida febrifuga*), **A.s** *(Acacia senegal)* and **G.a** (*Gmelina arborea)*

Species with poor regeneration include *Soymida febrifuga*, *Acacia senegal* and *Gmelina arborea* as given in Fig. 5. These species have either low seedling numbers or an imbalance among regeneration stages, signifying weak or declining regeneration potential.

No Regeneration

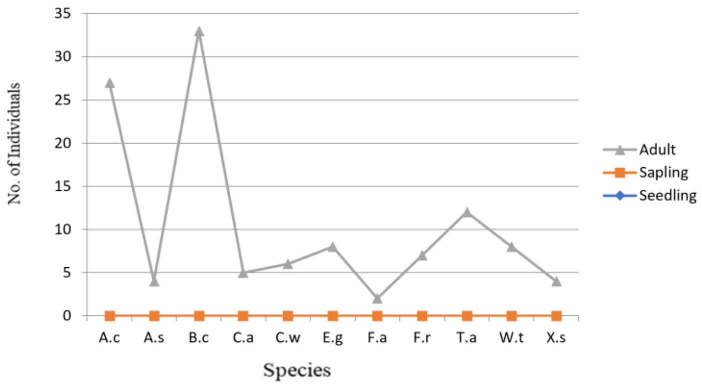

Fig. 6. No Regeneration
F.a (*Ficus amplissima*), **F.r** (*Ficus religiosa*), **T.a** (*Terminalia arjuna*), **W.t** (*Wrightia tomentosa*), **A.c** *(Acacia catechu)*, **A.s** (*Alangium salviifolium*), **B.c** (*Bombax ceiba), **C.a** (Careya arborea),* **C.w** (*Commiphora wightii*), **E.o** (*Emblica officinalis*) and **X.s** (*Xeromphis spinosa*)

Species showing no regeneration are *Ficus amplissima*, *Ficus religiosa*, *Terminalia arjuna*, *Wrightia tomentosa*, *Acacia catechu*, *Alangium salviifolium*, *Bombax ceiba*, *Careya arborea*, *Commiphora wightii*, *Emblica officinalis* and *Xeromphis spinosa* as shown in Fig. 6. These species lack seedlings and saplings despite the presence of adult trees, representing absence of regeneration in the study area.

Fair Regeneration Status

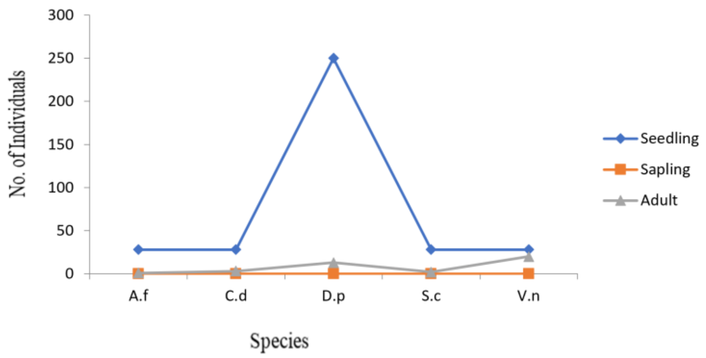

Fig. 7. Fair Regeneration Status
A.f (*Acacia ferruginea*), **C.d** (*Cordia dichotoma*), **D.p** (*Dillenia pentagyna*), **S.c** (*Syzygium cumini)* and **V.n** (*Vitex negundo)*

Fig. 7. Displays *Acacia ferruginea*, *Cordia dichotoma* , *Dillenia pentagyna*, *Syzygium cumini*, and *Vitex negundo* fall under the fair regeneration category, representing moderate regeneration with uneven seedling and sapling development.

Discussion

The current study offers a inclusive valuation of tree species diversity, forest structure, and regeneration dynamics in tropical deciduous forests, contribution critical insights into the complex interactions between ecological processes and anthropogenic pressures that figure community composition. The observed shapes of population structure, and regeneration reflect the mutual influence of climatic seasonality, soil characteristics, disturbance regimes, and resource availability recognized as basic drivers of vegetation dynamics in tropical deciduous forest ecosystems (Crausbay and Martin, 2016). Simultaneously, human activities such as fuelwood extraction, selective logging, grazing, and land-use modification play a significant role in determining regeneration success and stand structure (Zamorano and Rey-Benayas, 2014). The results are approximately reliable with classical ecological theories, counting successional dynamics, size-class distribution, niche differentiation, and regeneration niche concepts, which clarify species coexistence and perseverance along environmental and disturbance gradients (Unkule, 2022). The regeneration design across species is categorized by high seedling recruitment tracked by a distinct weakening toward sapling and adult stages, representing substantial mortality during later growth phases.

Species such as *Helicteres isora*, *Wrightia tinctoria*, and *Miliusa tomentosa* displayed exceptionally high seedling densities. However, their saplings and adult populations were excessively low. Similar designs have been reported from other tropical deciduous forests and are often credited to powerful biotic pressures and severe microclimatic conditions (Singh and Singh, 1992; Murali et al., 1996). These consequences propose that while early establishment conditions are auspicious, factors such as herbivory, interspecific competition, regular drought, and anthropogenic disturbances limit effective movement beyond the sapling stage (Tripathi and Khan, 2007; Sharma et al., 2016). Species including *Tectona grandis*, *Wrightia tinctoria*, *Miliusa tomentosa*, and *Terminalia crenulata* shown better adult illustration, indicating reasonably higher survival capacity, while still not comparative to their seedling input. The sharp decline from seedlings to adults reproduces regeneration bottlenecks commonly experiential in tropical deciduous forests, emphasizing the status of operative management interventions such as grazing regulation, habitat protection, and microsite improvement to enhance long-term forest sustainability (Pandey and Shukla, 2003; Rajput et al., 2020). The regeneration calculation uncovered that most species fall under the Good regeneration category, on behalf of robust recruitment potential at the landscape level. Species such as *Butea monosperma*, *Holarrhena antidysenterica*, *Diospyros melanoxylon*, *Ficus hispida*, and *Miliusa tomentosa* displayed high seedling and sapling densities, reproducing active population turnover and demographic reliability. In difference, numerous ecologically and economically important species, including *Careya arborea*, *Ficus religiosa*, *Acacia catechu*, *Bombax ceiba*, and *Terminalia arjuna*, showed no regeneration, indicating a complete absence of juvenile cohorts. Such deficiencies are commonly connected to overharvesting, low seed viability and grazing pressure, (Sahoo, 2021; Dar and Parthasarathy, 2022). Species categorized under Fair or Poor regeneration, such as *Dillenia pentagyna*, *Acacia ferruginea*, *Vitex negundo*, and *Gmelina arborea*, seem to be approaching regeneration dissatisfaction if existing disturbance regimes persevere. The occurrence of new regeneration species such as *Carissa carandas* and *Dioscorea pentaphylla* suggests recent recruitment, perhaps driven by localized changes in microclimatic conditions.

Generally, these results highlight that while the forest exhibts extensive ecological resilience and recovery potential, the rough regeneration among species signals emerging risks to long-term stability and biodiversity conservation. Consequently, accepting a landscape-scale and species-specific management framework that integrates ecological understanding with targeted conservation schemes is important for maintaining structural complexity, functional diversity, and long-term sustainability of tropical decidious forest ecosystems.

Conclusion

The tropical deciduous forests of the south-eastern part of Narmada district reflect high floristic abundance with 71 tree species in 59 genera and 32 families. According to the regeneration assessment, 43 species (Approx.60.6%) developed good regeneration with stable recruitment and community-level resilience. However, 12 species (Approx.16.9%) such *as Acacia catechu*, *Bombax ceiba*, and *Terminalia arjuna*, which are economically and ecologically important taxa, exhibited zero seedlings and saplings, suggesting a high risk of future population decline. The abundance of seedlings, saplings and adults fluctuated widely from 0–14,194, 0–12,611, and 0–1,456, which were indicative of high early recruitment and pronounced mortality at later stages. The main taxa, *Tectona grandis*, *Wrightia tinctoria*, *Miliusa tomentosa*, and *Diospyros melanoxylon* exhibited relatively constant populations that evolved in balanced structures, which could reflect the stability of the forest structure. There is considerable adaptability and recovery capacity of the forest ecosystem, but uneven re-establishment among species suggests that conservation issues are developing. Anthropogenic stresses, such as overburdened grazing, biomass extraction and land use conversion, are major issues for uneven new recruitment and long term survival of adult trees in the forest ecosystem. These results highlight the urgent need for integrated, site specific, and species focused conservation approaches in tropical deciduous forests of southeastern Gujarat to ensure their continued sustainability.

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MAS and RK conceived the concept, wrote and approved the manuscript.

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