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Phytosociological Structure and Regeneration Dynamics of Woody Tree Species Along an Altitudinal Gradient in the Riparian Forest of the Dikhu River, Nagaland, Northeast India

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ABSTRACT

This study examined the phytosociological structure and regeneration dynamics of woody tree species across an altitudinal gradient in the riparian forest of the Dikhu River, Nagaland, Northeast India. Vegetation sampling was conducted using 10 × 10 m quadrats along line transects across three altitudinal zones (Zone I: 697.12 m asl; Zone II: 758.4 m asl; Zone III: 810.13 m asl), comprising 30 main plots. Standard phytosociological parameters viz., density, frequency, abundance, basal area, and Importance Value Index (IVI)—were computed for the tree layer, and species diversity was assessed using Shannon–Wiener (H′) and Simpson's indices. Four dominant tree species were identified. Tectona grandis exhibited the highest IVI (107.12), followed by Terminalia chebula (52.96), Ficus religiosa (48.77) and Ficus hispida (44.18). Seedling density (~1,800–2,000 ind/ha) exceeded both tree (~610 ind/ha) and sapling (~200 ind/ha) densities, indicating a clear regeneration bottleneck at the seedling-to-sapling transition. T. grandis demonstrated consistent regeneration across all zones, whereas F. religiosa and T. chebula exhibited poor to absent regeneration. Diversity analysis revealed low to moderate species diversity across growth strata, with Shannon–Wiener values ranging from H′ = 0.000 in the seedling layer to H′ = 0.576 in the sapling layer, reflecting strong dominance at early regeneration stages. The results indicate that the riparian forest is undergoing structural imbalance, characterised by increasing dominance of T. grandis and reduced recruitment of subordinate species. These patterns highlight the influence of environmental variability and disturbance on regeneration dynamics. Targeted conservation strategies, including protection of regeneration niches and species-specific assisted regeneration, are recommended to enhance forest recovery and long-term ecosystem stability.

Keywords: *Riparian forest; Regeneration dynamics; Phytosociology; Altitudinal gradient; Species diversity; Importance Value Index (IVI); Dikhu River; Nagaland*

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Introduction

Riparian ecosystems occupy the transitional zone between terrestrial and aquatic environments and rank among the most ecologically dynamic and species-rich habitats on Earth. Positioned along riverbanks, stream margins, and wetland edges, these systems mediate the lateral exchange of energy, matter, and organisms between land and water [1]. Their ecological significance extends well beyond their relatively modest spatial extent: riparian forests regulate sediment transport, moderate flood regimes, stabilize stream channels against erosion, filter agricultural and industrial pollutants, and sustain aquatic productivity through organic matter inputs [2].

In addition to their hydrological functions, riparian forests serve as biodiversity reservoirs and wildlife movement corridors, supporting a disproportionately high number of plant and animal species relative to their areal coverage [3]. Nonetheless, these habitats are inherently fragile. Anthropogenic pressures: encompassing land conversion, unsustainable timber harvesting, livestock grazing, and altered flow regimes—can rapidly disrupt vegetation structure, impede natural regeneration, and precipitate long-term declines in biodiversity and ecosystem function.

Natural regeneration underpins the self-renewal capacity of forest ecosystems. The vertical and horizontal distribution of seedlings, saplings, and adult trees encodes critical information about forest health, species replacement dynamics, and long-term community trajectory [4]. Regeneration failure at any ontogenetic stage, whether due to inadequate seed supply, unfavorable germination conditions, herbivory, or interspecific competition—can fundamentally alter future forest composition [5]. In riparian contexts, these challenges are compounded by hydrological variability, periodic flooding, and substrate heterogeneity, which impose additional filters on seedling establishment and early survival.

Northeast India harbours some of the most diverse and least-studied riparian ecosystems in the Indo-Burma biodiversity hotspot. Despite this ecological significance, quantitative assessments of riparian forest structure and regeneration dynamics along environmental gradients remain sparse in the region. The Dikhu River, a Brahmaputra tributary originating in the Noto Hills of Zunheboto district, Nagaland, traverses a landscape subjected to intensifying anthropogenic disturbance, yet baseline phytosociological data for its riparian corridor are lacking. The present study addresses this gap by quantifying the phytosociological attributes and regeneration status of woody tree species along an altitudinal gradient in the Dikhu River riparian forest. Specific objectives were: (i) to characterize species composition and structural dominance using standard phytosociological indices; (ii) to assess regeneration patterns across tree, sapling, and seedling strata; (iii) to examine altitudinal variation in regeneration capacity; and (iv) to derive management implications for the long-term conservation of this ecologically sensitive landscape.

Materials and Methods

Study Area

Field investigations were conducted along the riparian corridor of the Dikhu River (26.2209°N, 94.5499°E) in Nagaland, Northeast India (Fig. 1). The Dikhu River rises in the Noto Hills, Zunheboto district, and flows northward through rugged, gorge-dissected terrain before entering the Assam plains as a Brahmaputra tributary. The riparian zone is characterised by heterogeneous vegetation cover, steep lateral slopes, and marked topographic relief. Three sampling zones were established along an altitudinal gradient, positioned approximately 500 m apart, to capture the range of ecological conditions encountered within the riparian landscape. Zone I was located at the lowest elevation (26.2476°N, 94.5468°E; 697.12 m asl), Zone II at an intermediate elevation (26.2444°N, 94.5348°E; 758.4 m asl), and Zone III at the highest elevation (26.2503°N, 94.5292°E; 810.13 m asl).

Fig. 1: Location map of Nagaland showing the Dikhu River study area and the three sampling zones along the altitudinal gradient

Sampling Design

A stratified sampling strategy was employed to select representative sites within each altitudinal zone. In each zone, 200 m line transects were established parallel to the riverbank, with 50 m spacing between adjacent transects. Along these transects, 10 × 10 m quadrats were laid systematically at 20 m intervals. A total of 30 main plots were established across the study area, with 10 plots in each altitudinal zone. Within each main plot, regeneration was assessed using four smaller corner subplots (2m x 2m), giving a total of 120 regeneration subplots. Plot boundaries were demarcated with corner pegs, and all woody species within each plot were identified, counted, and recorded. The 30 main plots were distributed equally across the three altitudinal zones as follows: 10 plots in Zone I (697.12 m asl), 10 plots in Zone II (758.4 m asl), and 10 plots in Zone III (810.13 m asl).

Data Collection and Growth Stage Classification

Vegetation surveys were carried out across multiple seasons to minimise phenological bias. Individual plants were assigned to one of three growth stages: (i) Trees (TR)—woody individuals with a girth at breast height (GBH) ≥ 10.5 cm, measured at 1.35 m above ground; (ii) Saplings (SP): woody individuals below the tree threshold but above early seedling stage; and (iii) Seedlings (SD): young recruits in the initial establishment phase. Voucher specimens were collected and identified using standard regional flora and taxonomic keys.

Phytosociological Analysis

The following parameters were calculated for the tree layer in each plot:

1. Density : $\frac{No\ of\ individuals\ of\ a\ spcecies}{Total\ no\ of\ quadrat\ studied}$

2. Relative Density : $\frac{No.of\ individuals\ of\ a\ species}{Total\ no.of\ individuals\ of\ all\ species} \times 100$

3. Frequency : $\frac{No\ of\ samplings\ units\ occur}{Total\ no\ of\ samplings\ unit}$ x100

4. Relative Frequency (%): $\frac{frequency\ of\ an\ individual\ species}{Frequency\ of\ all\ species}$ x 100

5 Abundance: $\frac{Total\ no\ of\ indivuals\ of\ a\ species}{Total\ no\ of\ qudrat\ studied}$ x 100

6. Relative Basal area (%): $\frac{Basal\ area\ of\ a\ species}{Basal\ area\ of\ all\ the\ species}$ x 100

7. Importance value index (IVI): R. F + R.D+ R.Dom.

Species Diversity Indices

Species diversity was quantified using two complementary indices. The Shannon–Wiener diversity index (H′) was computed as [6, 7]:

$H' = -\Sigma\,[p_i \times \ln(p_i)]$

where p_i is the proportional abundance of species i. The Simpson's diversity index (D) was calculated as [8]:

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

where n_i is the number of individuals of species i and N is the total number of individuals across all species.

Regeneration Status Classification

Regeneration status was determined by comparing the relative densities of trees, saplings, and seedlings for each species. Species were assigned to one of four regeneration categories: Good—seedlings and saplings both present in higher densities than mature trees; Fair—seedlings or saplings present, but at lower densities; Poor—seedlings or saplings present in very low numbers; None—no seedlings or saplings recorded.

Results and Discussion

Phytosociological Structure of the Tree Layer

Phytosociological analysis of the tree layer, based on 30 quadrats across three altitudinal zones (10 per zone), identified four dominant woody species throughout the study area (Table 1). Zone-wise analysis reveals that IVI values and structural dominance vary with altitude, with pooled IVI values ranging from 44.18 to 107.12, indicating a pronounced gradient in ecological dominance. *Tectona grandis* exhibited the highest IVI (107.12), primarily driven by its markedly high relative dominance (65.15%), reflecting substantial basal area contribution and clear structural prominence within the riparian stand. Its high frequency (90%) further indicates widespread distribution across the sampled plots. This pattern suggests strong competitive ability and effective site occupation, consistent with its known ecological adaptability to riparian conditions [9,10]. *Terminalia chebula* ranked second (IVI: 52.96), characterised by high frequency (80%) and broad distribution across the study area.

In contrast, *Ficus religiosa* (IVI: 48.77) and *Ficus hispida* (IVI: 44.18) occupied lower positions in the dominance hierarchy despite moderate frequency values (60–70%). Their comparatively low relative dominance suggests that, although widely distributed, their contribution to total stand basal area is limited. This disparity between frequency and dominance in the Ficus species indicates a structurally subordinate role, likely reflecting smaller individual sizes or reduced basal area contribution. Such patterns may reflect early to intermediate successional roles in disturbed riparian systems [11–13]. Overall, the IVI distribution highlights a community structure skewed toward a single dominant species across all altitudinal zones. Such patterns are commonly observed in anthropogenically influenced riparian forests and may result from disturbance history, regeneration dynamics, or past resource extraction. The zone-wise data reveal that this dominance pattern intensifies in Zone II (IVI: 126.17), where T. grandis achieved complete frequency (100%), before declining slightly at higher elevation in Zone III (IVI: 115.14).

Table 1: Phytosociological parameters of tree species in the Dikhu River riparian forest

Sl.	Species	Individuals	Frequency	RF (%)	Abundance	Density (trees m^{-2})	RD (%)	RDom (%)	IVI
Zone I (697.12 m asl)									
1	*Tectona grandis L.f.*	16	90	32.14	1.78	1.6	21.92	65.19	119.25
2	*Ficus hispida L.f.*	22	70	25.0	3.14	2.2	30.14	5.41	60.55
3	*Ficus religiosa L.*	15	50	17.86	3.0	1.5	20.55	16.97	55.38
4	*Terminalia chebula Retz.*	20	70	25.0	2.86	2.0	27.4	12.42	64.82
Zone II (758.4 m asl)									
1	*Tectona grandis L.f.*	22	100	31.25	2.2	2.2	27.5	67.42	126.17
2	*Ficus hispida L.f.*	20	70	21.88	2.86	2.0	25.0	5.06	51.94
3	*Ficus religiosa L.*	16	60	18.75	2.67	1.6	20.0	15.87	54.62
4	*Terminalia chebula Retz.*	22	90	28.12	2.44	2.2	27.5	11.64	67.26
Zone III (810.13 m asl)									
1	*Tectona grandis L.f.*	19	80	26.67	2.38	1.9	24.05	64.42	115.14
2	*Ficus hispida L.f.*	21	70	23.33	3.0	2.1	26.58	5.53	55.44
3	*Ficus religiosa L.*	20	70	23.33	2.86	2.0	25.32	17.35	66.0
4	*Terminalia chebula Retz.*	19	80	26.67	2.38	1.9	24.05	12.7	63.42
Pooled (All Zones, n=30)									
1	*Tectona grandis L.f.*	57	90	23.07	2.11	1.9	18.9	65.15	107.12
2	*Ficus hispida L.f.*	63	70	17.94	3.0	2.1	20.96	5.28	44.18
3	*Ficus religiosa L.*	51	60	15.38	2.83	1.7	16.83	16.56	48.77
4	*Terminalia chebula Retz.*	61	80	20.54	2.54	2.03	20.29	12.13	52.96
	Total	**232**		**76.93**		**7.73**	**77.02**	**99.12**	**253.03**

RF = Relative Frequency; RD = Relative Density; RDom = Relative Dominance; IVI = Importance Value Index.

Spatial Distribution Patterns

The spatial arrangement of tree species across the study plots exhibited a predominance of clumped distribution (Table 2), with species showing varying degrees of clumped (40–76%), random (14–28%), and regular (10–36%) distribution patterns. Clumped distribution was most pronounced in *T. grandis* and *T. chebula* (both 90%), reflecting their tendency to occupy favourable microsites within the riparian environment. Clumped distribution in forest communities is typically associated with resource heterogeneity, seed dispersal limitations, or vegetative propagation, all of which are plausible mechanisms in this system [14]. The co-occurrence of random and regular distribution patterns among species suggests that suitable microsites for establishment are not uniformly distributed, and that inter-individual competition may increasingly influence spatial structure as stands develop [15]. Overall, these distribution patterns indicate a spatially heterogeneous environment, where variability in microsite conditions plays a key role in shaping species establishment and persistence within the Dikhu riparian zone.

Table 3. Spatial distribution patterns of tree species in the Dikhu River riparian forest

Species	Clumped (%)	Random (%)	Regular (%)	Predominant Pattern
Tectona grandis L.f.	76	14	10	Clumped
Ficus hispida L.f.	44	20	36	Clumped
Ficus religiosa L.	40	28	32	Clumped
Terminalia chebula Retz.	76	14	10	Clumped

Regeneration Status Across Growth Strata

The density profiles across growth stages revealed a non-uniform population structure (Table 3). Total seedling density (~1,800–2,000 ind/ha) was substantially higher than sapling density (~200 ind/ha) and mature tree density (~610 ind/ha), indicating a clear imbalance in population structure. This corresponds to approximately three times higher seedling density than tree density and nearly nine times higher than sapling density.

This inverse relationship between seedling abundance and sapling recruitment constitutes a classic regeneration bottleneck, wherein abundant seedling production is not translated into successful sapling establishment [16]. Such bottlenecks are frequently attributed to post-germination mortality factors including canopy shading, soil moisture deficits, fungal pathogens, herbivory, and interspecific competition [17,18]. In riparian environments, periodic hydrological disturbances may further exacerbate seedling mortality through uprooting, sediment burial, and flood-induced stress. The reduced representation of saplings suggests that the transition from early establishment to sub-canopy growth is constrained. *T. grandis* was the only species classified as exhibiting good regeneration, with seedling (1,800 ind/ha) and sapling (160 ind/ha) densities substantially exceeding those of other species. Its ecological plasticity, tolerance to seasonal waterlogging, and prolific seed production likely contribute to its higher recruitment success [19]. *F. hispida* exhibited fair regeneration, characterised by moderate sapling presence. In contrast, *F. religiosa* showed poor regeneration, with only five saplings recorded and no seedlings or mature individuals observed in the sampled plots. *T. chebula*, despite ranking second in IVI, showed no regeneration across any growth stage. The absence of recruits in *T. chebula* suggests constraints in recruitment, potentially driven by seed limitation, predation, or post-establishment mortality under prevailing micro environmental conditions.

Table 3: Population density (ind/ha) and regeneration status of recorded species

Species	Trees (ind/ha)	Saplings (ind/ha)	Seedlings (ind/ha)	Regeneration Status
Tectona grandis L.f.	560	160	1800	Good
Ficus hispida L.f.	50	35	—	Fair
Ficus religiosa L.	—	5	—	Poor
Terminalia chebula Retz.	—	—	—	None

TR = Trees; SP = Saplings; SD = Seedlings; — = not recorded.

Zonal Variation in Regeneration Capacity

Stratification of regeneration data across the three altitudinal zones revealed appreciable spatial heterogeneity (Table 4). Zone I, Zone II, and Zone III together span an elevational range of approximately 113 m, representing a modest altitudinal gradient along the riparian corridor. *T. grandis* maintained good regeneration across all zones, with consistent representation in tree, sapling, and seedling strata. Seedling density peaked in Zone II (800 ind/ha), suggesting that mid-elevation conditions may be relatively more favourable for early-stage recruitment. However, variation in sapling densities across zones indicates that the transition from seedling to sapling stage is not uniform. *F. hispida* exhibited a variable response, qualifying as fair across all three zones (Zones I, II, and III), as no seedlings were recorded in any zone despite moderate sapling presence. The reduced sapling density in Zone II further weakens its regeneration score in that zone. This pattern suggests sensitivity to site-specific environmental conditions influencing establishment and survival. *F. religiosa* was absent from Zones I and II, with no individuals recorded in any growth stage. In Zone III, the species was represented only by five saplings and was therefore classified as exhibiting poor regeneration, indicating limited recruitment success under the prevailing conditions. *T. chebula* recorded no individuals in any growth stage across all zones, suggesting a decline in its current representation within the sampled plots despite its structural importance in the overall community. The observed zonal variation supports the view that even modest altitudinal differences can influence regeneration patterns through associated changes in microsite conditions and disturbance regimes [14, 20–22]. Species with narrower ecological tolerances may therefore be disproportionately affected by such environmental variability [23].

Table 4: Altitudinal variation in population density (ind/ha) and regeneration status across three zones

Species	Zone I				Zone II				Zone III			
	TR	SP	SD	Status	TR	SP	SD	Status	TR	SP	SD	Status
Tectona grandis L.f.	180	50	550	Good	220	60	800	Good	160	50	450	Good
Ficus hispida L.f.	15	12	—	Fair	10	5	—	Fair	25	18	—	Fair
Ficus religiosa L.	—	—	—	None	—	—	—	None	—	5	—	Poor
Terminalia chebula Retz.	—	—	—	None	—	—	—	None	—	—	—	None

TR = Trees; SP = Saplings; SD = Seedlings; — = not recorded.

Species Diversity Across Growth Strata

Species diversity varied across growth strata, with the sapling layer exhibiting the highest diversity and the seedling layer the lowest (Table 5). Shannon–Wiener values ranged from H′ = 0.000 in the seedling stratum to H′ = 0.576 in the sapling stratum, while the tree stratum showed a comparatively low value of H′ = 0.284. These values indicate extremely low diversity in the seedling layer due to the complete dominance of *T. grandis*, resulting in pronounced evenness inequality. In contrast, the sapling stratum retained relatively greater species representation, suggesting partial relaxation of competitive dominance. Simpson's index further supported this pattern, with diversity (1 − D) increasing from 0.000 in seedlings to 0.329 in saplings, before declining again in the tree stratum (0.150). The higher diversity observed at the sapling stage, relative to seedlings, suggests that density-dependent thinning and differential survival act as ecological filters between growth stages, reducing the numerical dominance of *T. grandis* while allowing limited persistence of less-abundant species [17,18]. Overall, these diversity patterns indicate that species co-existence is weakest at the earliest regeneration stage, where competitive exclusion is most pronounced, and somewhat improved at the sapling stage, although overall diversity remains low. This reflects a regeneration system strongly dominated by a single species, with implications for long-term community composition and stability [24].

Table 5. Shannon–Wiener and Simpson's diversity indices for tree, sapling, and seedling strata in the Dikhu River riparian forest

Growth stratum	Shannon–Wiener index (H′)	Simpson's dominance (D)	Simpson's diversity (1 − D)
Tree	0.284	0.850	0.150
Sapling	0.576	0.671	0.329
Seedling	0.000	1.000	0.000

Ecological Interpretation and Forest Condition

Taken together, the phytosociological and regeneration data indicate that the riparian forest is undergoing structural transition. The high seedling density demonstrates that reproductive inputs remain substantial, particularly for dominant species; however, the marked reduction in recruitment at the sapling stage suggests that this potential is not being effectively translated into canopy replenishment for most species [25]. This regeneration bottleneck, if persistent, may progressively erode the structural and compositional complexity of the stand. The dominance of *T. grandis*—both in structural terms (IVI: 107.12, RDom: 65.15%) and regeneration performance—indicates a strong competitive advantage that may drive a gradual shift in community composition. This dominance pattern appears more pronounced at lower and mid elevations (Zones I and II), where species such as *F. religiosa* are absent from the regeneration pool. These patterns suggest that environmental variation along the altitudinal gradient may be influencing species distribution and recruitment, contributing to compositional simplification in certain zones. Such simplification of species composition may reduce functional redundancy within the ecosystem, potentially lowering its resilience to future disturbances. The absence of regeneration in *T. chebula*, despite its current representation in the canopy, is an early indication of possible compositional change that warrants attention.

Ecological Implications and Management Recommendations

The findings of this study have direct implications for the conservation and management of the Dikhu River riparian forest. The regeneration bottleneck identified at the seedling-to-sapling transition represents a key vulnerability in the forest's renewal pathway. The results suggest that post-establishment mortality, rather than seed limitation, is the primary constraint on recruitment, which has important implications for management strategies. Five management priorities emerge from the analysis. First, protection of high-density seedling patches through the exclusion of livestock and limitation of ground-disturbing activities may enhance survival during early establishment. Second, canopy management to maintain appropriate light conditions could improve seedling-to-sapling transition, particularly where shading by dominant species is excessive. Third, species-specific assisted regeneration, including enrichment planting of *F. religiosa* and *T. chebula*, may help restore declining components of the community. Fourth, long-term monitoring of population structure across growth strata is necessary to track compositional shifts and evaluate management effectiveness. Finally, protection of riparian buffer zones through erosion control measures and regulated land use may reduce physical disturbances that currently limit successful recruitment.

Conclusion

This study provides a quantitative assessment of phytosociological structure and regeneration dynamics in the riparian forest of the Dikhu River, Nagaland. Four dominant tree species were recorded, with *T. grandis* occupying the highest structural position (IVI: 107.12). Despite substantial seedling recruitment, the forest exhibits a pronounced regeneration bottleneck at the seedling-to-sapling transition, reflected in reduced sapling representation for most species and the complete absence of regeneration in *T. chebula*. Altitudinal stratification revealed clear spatial heterogeneity in regeneration patterns, with mid-elevation zones favouring *T. grandis* recruitment and upper-elevation conditions permitting limited establishment of *F. religiosa*. Diversity analysis indicated low to moderate species diversity across growth strata, with the seedling layer showing extremely low diversity due to the numerical dominance of a single species. Collectively, these findings indicate a structurally imbalanced system with increasing dominance by *T. grandis* and declining representation of other canopy species. If this pattern persists, it may lead to further compositional simplification and reduced ecological resilience. Targeted management interventions—including protection of seedling cohorts, canopy regulation, enrichment planting of underrepresented species, and long-term monitoring—are recommended to restore regeneration balance and maintain the ecological integrity of this riparian forest.

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