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Ecological energetics and phytosociological analysis of forest ecosystems in Jamtara: A study on biomass accumulation and energy flow

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ABSTRACT

The forest ecosystems of Jamtara district in Jharkhand represent a unique ecological interface between Chotanagpur plateau and Gangetic plains, yet their functional dynamics remain poorly understood. This comprehensive study investigated the phytosociological characteristics, biomass accumulation patterns, and energy flow dynamics across three distinct forest types Sal dominated, mixed deciduous, and riverine forests using systematic quadrat sampling and allometric equations. Results revealed significant variation in community structure, with Sal dominated forests exhibiting maximum tree density (485 individuals ha^{-1}) and basal area (32.6 m^2 ha^{-1}), while mixed deciduous forests showed highest species diversity (H'=3.42). Total biomass accumulation ranged from 259.8 to 329.8 t ha^{-1}, corresponding to carbon stocks of 121.9-154.8 t C ha^{-1} across forest types. Net primary productivity varied between 17.8-18.7 t ha^{-1} yr^{-1}, with energy fixation rates reaching 3.35×10^8 kJ ha^{-1} yr^{-1} in Sal forests. Litter decomposition rates were maximum in mixed deciduous forests (k=0.82 yr^{-1}), facilitating faster nutrient turnover. Soil organic carbon was highest under mixed deciduous vegetation (2.12%), indicating better soil fertility. The total ecosystem carbon sequestration potential ranged from 3.9-4.2 t C ha^{-1} yr^{-1}, highlighting these forests' significant climate change mitigation service. This research provides crucial baseline data for understanding forest functional ecology and developing science-based conservation strategies for tropical dry deciduous forests of Jharkhand.

Key Words - Phytosociology, biomass accumulation, net primary productivity, carbon sequestration, tropical dry deciduous forest, Jamtara, ecosystem energetics

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INTRODUCTION

Tropical dry deciduous forests (TDFs) constitute one of the most widespread yet ecologically vulnerable forest biomes in the tropics, occurring in regions marked by pronounced seasonality, 5–6 dry months annually, and relatively low precipitation (Murphy & Lugo, 1986). These climatic constraints impose strong selective pressures that have shaped distinctive adaptive strategies in plant communities. Seasonal leaf shedding (deciduousness) represents a key physiological adaptation, enabling dominant tree species to reduce transpirational water loss and survive extended drought periods (Singh & Singh, 1991). Despite their broad distribution across South Asia, Africa, and Latin America, TDFs have historically received less scientific attention than humid tropical forests, resulting in limited understanding of their structural organization, biomass dynamics, and ecosystem functioning (Miles *et al.,* 2006).

In India, tropical dry deciduous forests represent a major vegetation type, extending across central and peninsular regions. The Chotanagpur Plateau, particularly the Santhal Pargana division of Jharkhand, forms a biogeographically transitional zone where peninsular floristic elements intersect with those of the Gangetic plains (Champion & Seth, 1968). The forests of Jamtara district, dominated by *Shorea robusta* (Sal), exemplify this ecological interface. However, increasing anthropogenic pressures including mining expansion, shifting cultivation, fuelwood extraction, and land-use change have led to fragmentation and degradation of forest cover in the broader Rajmahal Hills landscape (FSI, 2021). Although these forests sustain tribal communities through provisioning ecosystem services such as non-timber forest products and fuelwood, comprehensive ecological assessments integrating structural and functional dimensions remain scarce.

Forest ecosystem functioning is governed by three interrelated processes: phytosociological organization, biomass accumulation, and energy flow dynamics (Odum, 1971). Phytosociological attributes species composition, density, basal area, and importance value index (IVI) define the structural framework of forest communities (Curtis & McIntosh, 1951). These structural parameters directly influence biomass storage and carbon sequestration potential, which are critical in the context of global climate change mitigation (Pan *et al.,* 2011). Studies from comparable Indian forest ecosystems have demonstrated substantial carbon storage capacities; for example, natural and planted forests in northeastern India have reported ecosystem carbon stocks exceeding 160 Mg C ha^{-1} (Nath *et al.,* 2019). Yet, equivalent empirical data for the dry deciduous forests of Jharkhand remain largely unavailable.

Energy flow represents the functional dimension of forest ecosystems, encompassing solar energy capture, biomass production, and nutrient cycling. Net Primary Productivity (NPP): the net carbon gain after autotrophic respiration serves as a master variable integrating photosynthetic efficiency, biomass allocation, and turnover rates (Whittaker, 1975). Productivity in dry deciduous forests is closely linked to rainfall variability, species composition, and stand structure (Roy & Joshi, 2002). Although satellite-derived estimates such as MODIS-based Gross Primary Productivity (GPP) provide landscape-scale insights, they cannot adequately capture species-level contributions, belowground biomass allocation, or stand structural complexity (Running *et al.,* 2004). Ground-based ecological studies are therefore essential to validate and complement remote sensing assessments.

The forests of Jamtara district offer a natural gradient for examining relationships between community structure and ecosystem energetics. Preliminary observations identify three major forest types: Sal-dominated stands, mixed deciduous forests, and riverine formations. Each differs in floristic heterogeneity, disturbance intensity, and microclimatic conditions. Such variation provides an opportunity to test ecological hypotheses linking biodiversity with ecosystem function. The niche complementarity hypothesis posits that higher species diversity enhances productivity through more efficient resource partitioning (Tilman *et al.,* 1997). Empirical evidence increasingly supports positive diversity–productivity relationships in forest ecosystems (Cardinale *et al.,* 2012), yet such relationships remain unexplored for Jharkhand's dry deciduous forests.

Significant knowledge gaps thus persist. Baseline phytosociological data are insufficient for long-term monitoring; biomass and carbon stock assessments are absent from regional inventories; and component-wise productivity measurements, including litterfall and belowground allocation, have not been systematically documented. Moreover, the linkage between soil physico-chemical properties and vegetation parameters remains poorly understood. Addressing these gaps is crucial for incorporating Jharkhand's forests into regional carbon accounting frameworks and for informing sustainable management strategies.

Accordingly, the present study aims to: (i) characterize phytosociological attributes across major forest types; (ii) quantify above- and belowground biomass pools using allometric approaches; (iii) estimate ecosystem carbon stocks and sequestration potential; (iv) determine net primary productivity and energy fixation rates; and (v) examine relationships among biodiversity, soil properties, and ecosystem function. By integrating structural and energetic dimensions, this research provides the first comprehensive ecological assessment of Jamtara's tropical dry deciduous forests, contributing both to tropical forest ecology and to evidence-based conservation planning.

LITERATURE REVIEW

Tropical dry deciduous forests (TDFs) represent a structurally distinct and climatically constrained biome whose ecological processes differ fundamentally from humid tropical systems. Early syntheses by Murphy and Lugo (1986) emphasized that seasonally dry forests exhibit lower canopy height, reduced basal area, and pronounced phenological synchrony compared to evergreen forests. Subsequent global assessments confirmed that TDFs are characterized by moderate biomass stocks but high functional sensitivity to rainfall variability (Miles *et al.,* 2006). In the Indian context, Champion and Seth (1968) classified tropical dry deciduous forests as one of the dominant vegetation formations, yet systematic quantitative analyses of their structure and energetics have remained limited relative to moist deciduous and evergreen systems.

Floristic diversity forms the foundation of ecosystem structure and resilience. Gentry (1988) demonstrated that species richness in tropical forests is strongly influenced by climatic gradients and edaphic heterogeneity. In Indian dry forests, Singh and Singh (1991) observed that species composition is shaped by monsoonal seasonality and anthropogenic disturbances, often leading to dominance by drought-tolerant taxa such as *Shorea robusta*. Recent regional studies have reported that eastern Indian dry forests exhibit moderate species richness but significant dominance–diversity skewness, reflecting competitive exclusion under resource-limited conditions (Sagar *et al.,* 2003). Despite these insights, floristic inventories in Jharkhand remain fragmentary, with limited integration of diversity indices such as the Shannon–Wiener index into functional analyses.

Phytosociological investigations provide critical understanding of forest stand dynamics. The foundational work of Curtis and McIntosh (1951) introduced the Importance Value Index (IVI) as a composite measure of species dominance, density, and frequency. In central Indian dry deciduous forests, Jha and Singh (1990) documented strong correlations between basal area and disturbance gradients, demonstrating that anthropogenic pressure reduces structural complexity and shifts community composition toward secondary species. Similar findings have been reported in eastern plateau regions, where Sal-dominated stands exhibit high IVI values but reduced understorey heterogeneity under intensive extraction regimes (Sahu *et al.,* 2012). However, few studies have simultaneously examined phytosociological parameters alongside biomass quantification and productivity estimation within the same landscape unit.

Biomass accumulation and carbon storage represent central themes in contemporary forest ecology due to their relevance for climate mitigation. Whittaker and Likens (1973) provided early global biomass estimates, while more recent analyses have refined carbon accounting frameworks using allometric equations and ecosystem-level assessments (Pan *et al.,* 2011). In Indian dry forests, aboveground biomass typically ranges between 120–220 Mg ha^{-1} depending on stand age and disturbance intensity (Chhabra *et al.,* 2002). Nath et al. (2019) reported ecosystem carbon stocks exceeding 160 Mg C ha^{-1} in northeastern plantations, underscoring the sequestration potential of managed systems. Nevertheless, dry deciduous formations in Jharkhand have not been comprehensively incorporated into regional carbon inventories, resulting in underrepresentation in national climate mitigation assessments.

Net Primary Productivity (NPP) integrates structural and functional attributes of forest ecosystems. Roy and Joshi, (2002) highlighted that NPP in Indian forests varies with rainfall, soil fertility, and stand density, with dry deciduous systems exhibiting moderate productivity relative to moist forests. Remote sensing approaches, including MODIS-derived Gross Primary Productivity (GPP), have expanded large-scale monitoring capabilities (Running *et al.,* 2004), yet such methods cannot resolve species-level contributions or belowground allocation patterns. Ground-based measurements of litterfall, biomass increment, and root allocation remain indispensable for accurate energy flow analysis.

An emerging theme in forest ecology is the diversity–productivity relationship. Experimental and observational studies suggest that increased species richness enhances productivity through niche complementarity and facilitation mechanisms (Tilman *et al.,* 1997; Cardinale *et al.,* 2012). While this relationship has been widely examined in temperate and moist tropical systems, empirical evidence from Indian dry deciduous forests remains sparse.

Collectively, the literature underscores substantial progress in understanding tropical forest ecology, yet reveals critical gaps for Jharkhand's dry deciduous landscapes. Integrative studies combining phytosociological organization, biomass partitioning, productivity dynamics, and diversity–function relationships are lacking. Addressing these gaps is essential for advancing regional carbon accounting, biodiversity conservation, and sustainable forest management frameworks.

MATERIALS & METHODS

Study Area Description

The present investigation was conducted in the forest ecosystems of Jamtara district, located in the Santhal Pargana division of Jharkhand, India (23°45' to 24°15' N latitude and 86°45' to 87°15' E longitude). The study area encompasses approximately 1,802 km² and represents a transitional biogeographic zone between the Chotanagpur plateau and the lower Gangetic plains. The region experiences a tropical monsoon climate with three distinct seasons: summer (March-June), rainy (July-October), and winter (November-February). The average annual rainfall ranges between 1,200-1,400 mm, received primarily from the southwest monsoon. Temperature varies considerably, with summer maxima reaching 42°C and winter minima dropping to 8°C. The relative humidity ranges from 35% during summer to 85% during monsoon months. The topography is undulating with elevations ranging from 150-300 meters above mean sea level. The predominant soil types are red lateritic and sandy loam soils derived from Archaean rocks and granite-gneiss complexes. Based on preliminary reconnaissance surveys and forest department records, three distinct forest types were identified for detailed ecological investigation: (i) Sal dominated forests, (ii) Mixed deciduous forests, and (iii) Riverine forests.

Research Period and Sampling Design

The field study was conducted over two consecutive years from January 2024 to December 2025, covering all three seasonal periods (summer, monsoon, and winter) to capture temporal variations in ecological parameters. A stratified random sampling design was employed to ensure representative coverage of each forest type. Within each forest type, ten permanent sample plots of 0.1 ha each (31.62 m × 31.62 m) were randomly established following standard phytosociological protocols. The total sampling area comprised 30 plots covering 3.0 hectares across the three forest types. Geographical coordinates of each plot were recorded using a handheld GPS (Garmin eTrex 30) for precise location mapping and future monitoring.

Phytosociological Analysis

Vegetation analysis was conducted using standard quadrat methods following the protocols established by Misra (1968) and Mueller-Dombois and Ellenberg (1974). Within each 0.1 ha main plot, all tree species (≥ 10 cm diameter at breast height, DBH at 1.37 m) were measured for circumference using a measuring tape, and their DBH was calculated. Tree density (individuals ha^{-1}) and basal area (m^2 ha^{-1}) were determined for each species. For shrubs and saplings (individuals <10 cm DBH but >1 m height), five 5 m × 5 m sub-plots were established within each main plot. For herbs and seedlings, ten 1 m × 1 m quadrats were randomly placed within each main plot. The Importance Value Index (IVI) for each tree species was calculated as the sum of relative density, relative frequency, and relative dominance. Species diversity was computed using the Shannon-Wiener diversity index ($H' = -\Sigma\, pi \ln pi$), where pi represents the proportion of individuals of the i^{th} species. Simpson's dominance index was calculated as $D = \Sigma\,(ni/N)^2$, where *ni* is the number of individuals of species *i* and *N* is the total number of individuals. Species richness was recorded as the total number of species present in each forest type.

Biomass Estimation

Biomass accumulation was quantified using non-destructive methods employing species-specific allometric equations. For tree biomass estimation, DBH measurements of all individuals within the sample plots were utilized. Above-ground biomass (AGB) of trees was calculated using the allometric equation developed by Chave *et al.,* (2005) for tropical forests: $AGB = \rho \times \exp(-1.499 + 2.148 \ln(DBH) + 0.207 (\ln(DBH))^2 - 0.0281 (\ln(DBH))^3)$, where ρ is wood density ($g\ cm^{-3}$). Species-specific wood density values were obtained from the Global Wood Density Database and published literature. For species without published wood density values, the mean wood density of the genus or family was used. Below-ground biomass (BGB) of trees was estimated using the root-to-shoot ratio method following IPCC guidelines, with a factor of 0.26 for tropical dry forests. Shrub biomass was determined by harvest method in 5 m × 5 m sub-plots, drying collected samples at 80°C until constant weight. Herbaceous biomass was estimated by harvest method in 1 m × 1 m quadrats during peak growing season. Litter biomass was collected from five 50 cm × 50 cm litter traps installed in each plot and collected monthly.

Net Primary Productivity and Energy Flow

Net primary productivity (NPP) was estimated through component-wise assessment following standard methodologies. Tree productivity was partitioned into bole wood, branch and twig, foliage, and reproductive parts. Increment in bole biomass was determined using DBH growth measurements obtained from permanently marked trees over the two-year study period. Diameter increment was measured using dendrometer bands installed on 30 representative trees per forest type. Biomass increment was calculated by applying allometric equations to initial and final DBH measurements. Foliage productivity was estimated from litterfall collection, assuming that leaf litter represents current year's foliage production. Branch and twig productivity was derived from litterfall data and allometric relationships. Reproductive parts productivity was quantified through litterfall collection of flowers, fruits, and seeds. Understory productivity (shrubs and herbs) was determined by harvesting peak season biomass in protected sub-plots at quarterly intervals. Root productivity was estimated using the ingrowth core method, with 20 nylon mesh bags (15 cm diameter, 30 cm depth) filled with root-free soil installed in each forest type and harvested after 12 months.

Gross primary production (GPP) was calculated as the sum of NPP and ecosystem respiration (Re). Ecosystem respiration was estimated using the closed chamber method with infrared gas analysis. Monthly respiration measurements were conducted using portable CO, analyzer (LI-COR LI-840A) with custom-made cylindrical chambers (30 cm diameter, 30 cm height) inserted 5 cm into the soil. Ten chambers were randomly installed in each forest type, and measurements were taken during morning hours (9:00-11:00 AM) to minimize diurnal variation. Energy fixation rate was calculated by multiplying total NPP by the calorific value of plant material (18.7 $kJ\ g^{-1}$ for tropical dry forest species). Photosynthetic efficiency was determined as the ratio of energy fixed through NPP to the incident photosynthetically active radiation (PAR), which was measured using quantum sensors (LI-COR LI-190R) installed above the canopy.

Litter Production and Decomposition

Litter production was quantified using circular litter traps (50 cm diameter, 1 mm mesh size) installed 30 cm above ground level. Twenty litter traps were randomly placed in each forest type, and collections were made monthly from January 2024 to December 2025. Collected litter was separated into leaf, twig, bark, and reproductive parts, oven-dried at 80°C to constant weight, and weighed. Annual litterfall was calculated by summing monthly values. Decomposition dynamics were studied using the litter bag technique. Freshly senesced leaves of dominant species were collected, air-dried, and 10 g samples were placed in 20 cm × 20 cm nylon litter bags with 2 mm mesh size. Two hundred litter bags (50 per forest type for four collection intervals) were placed on the forest floor in December 2024 and retrieved at 3, 6, 9, and 12-month intervals. Retrieved samples were cleaned of soil particles, oven-dried, and weighed to determine mass loss. Decomposition constant (k) was calculated using the negative exponential decay model: $X/X_o = e^{-kt}$, where X_o is initial mass, X is mass at time t. Half-life (t_{so}) was calculated as ln 2/k, and turnover time as 1/k.

Nutrient Analysis

Litter samples collected monthly and from decomposition bags were analyzed for nutrient concentrations. Composite litter samples were ground using a Wiley mill and passed through a 0.5 mm sieve. Total nitrogen was determined by the micro-Kjeldahl digestion and distillation method. Phosphorus was analyzed using the vanadomolybdophosphoric acid method with UV-VIS spectrophotometer. Potassium, calcium, and magnesium were determined by atomic absorption spectrophotometry after tri-acid digestion ($HNO_3 : H_2SO_4 : HClO_4$ in 10:1:4 ratio). Nutrient return was calculated by multiplying litterfall mass by respective nutrient concentrations.

Soil Sampling and Analysis

Soil samples were collected from two depths (0-15 cm and 15-30 cm) at ten randomly selected points within each forest type during three seasons. Samples from each depth within a plot were composited to form a representative sample. Bulk density was determined by the core method using stainless steel cores of known volume (5 cm diameter, 5 cm height). Soil moisture was determined gravimetrically by drying samples at 105°C for 24 hours. Water holding capacity was measured using Keen's box method. Soil pH was determined in 1:2.5 soil-water suspension using digital pH meter. Soil organic carbon was analyzed by Walkley-Black rapid titration method. Total nitrogen was determined by the micro-Kjeldahl method. Available phosphorus was extracted using Olsen's reagent and estimated by molybdenum blue method using spectrophotometer. Available potassium was extracted with neutral normal ammonium acetate and determined by flame photometer. Cation exchange capacity was determined by sodium saturation method. Soil carbon stock was calculated as: Soil carbon stock ($t\ ha^{-1}$) = SOC (%) × bulk density ($g\ cm^{-3}$) × depth (cm). Total ecosystem carbon was computed as the sum of vegetation carbon (above-ground + below-ground) and soil carbon.

Carbon Sequestration Potential

Annual carbon sequestration rate was determined by multiplying the carbon concentration in different plant parts (assumed as 47% of biomass for tropical species) with the annual biomass increment. Carbon dioxide equivalent was calculated by multiplying carbon stock by 3.67 (molecular weight ratio of CO_2 to C). Carbon mitigation potential was expressed as $t\ CO_2\ ha^{-1}\ yr^{-1}$.

Statistical Analysis

All data were compiled and analyzed using Microsoft Excel 2019 and SPSS version 26.0. Results were expressed as mean ± standard deviation. One-way analysis of variance (ANOVA) followed by Tukey's post-hoc test was employed to compare parameters among forest types. Differences were considered statistically significant at $p < 0.05$. Correlation and regression analyses were performed to establish relationships between phytosociological parameters and biomass accumulation patterns.

RESULTS & DISCUSSION

Phytosociological Characteristics and Community Structure

The phytosociological analysis revealed distinct structural variations across the three forest types investigated in Jamtara (Table 1). Sal dominated forests exhibited the highest tree density (485 ± 32.5 individuals ha^{-1}), followed by riverine forests (412 ± 30.2 individuals ha^{-1}) and mixed deciduous forests (356 ± 28.7 individuals ha^{-1}). The basal area followed a similar pattern, with maximum values recorded in Sal dominated forests (32.6 ± 2.8 m^2 ha^{-1}), indicating mature stand development with larger diameter trees. Riverine forests maintained intermediate basal area (28.7 ± 2.4 m^2 ha^{-1}), while mixed deciduous forests showed the lowest values (24.3 ± 2.1 m^2 ha^{-1}).

The Importance Value Index (IVI) analysis demonstrated clear dominance patterns across forest types. *Shorea robusta* emerged as the overwhelmingly dominant species in Sal forests with an IVI of 98.4 ± 6.2, reflecting its ecological amplitude as the climax species. In mixed deciduous forests, *Terminalia tomentosa* attained the highest IVI (56.8 ± 4.2), followed by *Diospyros melanoxylon* (38.5 ± 3.1), indicating a more equitable distribution of dominance among co-dominant species. Riverine forests showed reduced IVI values for all major species, with *Shorea robusta* (28.6 ± 2.5), *Terminalia tomentosa* (18.9 ± 1.8), and *Diospyros melanoxylon* (15.2 ± 1.4) contributing more moderately to community structure.

Table 1: Phytosociological Characteristics and Community Structure

Parameter	Sal Dominated Forest	Mixed Deciduous Forest	Riverine Forest	Units
Tree Density	485 ± 32.5	356 ± 28.7	412 ± 30.2	individuals/ha
Basal Area	32.6 ± 2.8	24.3 ± 2.1	28.7 ± 2.4	m²/ha
Importance Value Index (IVI) - *Shorea robusta*	98.4 ± 6.2	42.3 ± 3.8	28.6 ± 2.5	-
Importance Value Index (IVI) - *Terminalia tomentosa*	32.7 ± 2.9	56.8 ± 4.2	18.9 ± 1.8	-
Importance Value Index (IVI) - *Diospyros melanoxylon*	28.4 ± 2.6	38.5 ± 3.1	15.2 ± 1.4	-
Shannon-Wiener Diversity Index (H')	2.86 ± 0.21	3.42 ± 0.28	2.94 ± 0.23	-
Simpson's Dominance Index (D)	0.18 ± 0.02	0.12 ± 0.01	0.15 ± 0.02	-
Species Richness	24	38	29	number
Density of Seedlings	1250 ± 98	890 ± 72	1120 ± 86	individuals/ha
Density of Saplings	420 ± 35	310 ± 28	385 ± 32	individuals/ha

Species diversity, as measured by the Shannon-Wiener index (H'), was highest in mixed deciduous forests (3.42 ± 0.28), substantially exceeding values recorded in riverine forests (2.94 ± 0.23) and Sal dominated forests (2.86 ± 0.21). This pattern inversely corresponded to Simpson's dominance index, which was lowest in mixed deciduous forests (0.12 ± 0.01) and highest in Sal dominated forests (0.18 ± 0.02), confirming that species richness and evenness were maximized where single-species dominance was minimized. Species richness followed identical trends, with mixed deciduous forests harboring 38 species, riverine forests 29 species, and Sal dominated forests 24 species.

Regeneration potential, assessed through seedling and sapling densities, revealed interesting patterns. Despite having the lowest overall species richness, Sal dominated forests exhibited the highest seedling density (1250 ± 98 individuals ha^{-1}) and sapling density (420 ± 35 individuals ha^{-1}), indicating robust regeneration of the dominant species. Riverine forests maintained intermediate regeneration levels (seedlings: 1120 ± 86 individuals ha^{-1}; saplings: 385 ± 32 individuals ha^{-1}), while mixed deciduous forests showed comparatively lower regeneration densities despite their higher species richness.

Biomass Accumulation and Carbon Stock Distribution

Biomass accumulation patterns across forest types are presented in Table 2. Total biomass varied considerably, ranging from 259.8 ± 21.0 t ha^{-1} in mixed deciduous forests to 329.8 ± 26.2 t ha^{-1} in Sal dominated forests, with riverine forests exhibiting intermediate values (288.1±23.4 t ha^{-1}). Above-ground biomass (AGB) constituted the dominant fraction of total biomass across all forest types, contributing 80.2%, 80.2%, and 80.1% in Sal dominated, mixed deciduous, and riverine forests, respectively.

Table 2: Biomass Accumulation and Carbon Stock Distribution

Component	Sal Dominated Forest	Mixed Deciduous Forest	Riverine Forest	Units
Above Ground Biomass (AGB)				
Tree Biomass	248.6 ± 18.4	186.4 ± 14.2	212.8 ± 16.5	t/ha
Shrub Biomass	8.4 ± 0.8	12.6 ± 1.1	9.8 ± 0.9	t/ha
Herb Biomass	2.6 ± 0.3	3.8 ± 0.4	3.2 ± 0.3	t/ha
Litter Biomass	4.8 ± 0.5	5.6 ± 0.6	5.2 ± 0.5	t/ha
Total AGB	264.4 ± 20.0	208.4 ± 16.3	231.0 ± 18.2	t/ha

Tree biomass represented the major AGB component, with Sal dominated forests accumulating 248.6 ± 18.4 t ha^{-1}, significantly higher ($p < 0.05$) than mixed deciduous forests (186.4 ± 14.2 t ha^{-1}) and riverine forests (212.8 ± 16.5 t ha^{-1}). Shrub biomass showed an inverse pattern, with maximum accumulation in mixed deciduous forests (12.6 ± 1.1 t ha^{-1}), where greater light penetration beneath the more open canopy facilitated understory development. Herb biomass followed similar trends, peaking in mixed deciduous forests (3.8 ± 0.4 t ha^{-1}). Litter biomass, representing the detrital pool, was highest in mixed deciduous forests (5.6 ± 0.6 t ha^{-1}), consistent with their greater litter production rates.

Below-ground biomass (BGB) ranged from 51.4 ± 4.7 t ha^{-1} in mixed deciduous forests to 65.4 ± 6.2 t ha^{-1} in Sal dominated forests. Root-to-shoot ratios calculated from these data (0.20-0.25) fell within the expected range for tropical dry forests and were consistent across forest types, indicating similar carbon allocation patterns below-ground. Total carbon stocks, derived from biomass carbon content (assumed 47% of biomass), ranged from 121.9 ± 9.8 t C ha^{-1} in mixed deciduous forests to 154.8 ± 12.3 t C ha^{-1} in Sal dominated forests. When converted to carbon dioxide equivalents (CO_2e), these stocks represented substantial carbon storage, with Sal dominated forests sequestering 568.1 ± 45.2 t CO_2e ha^{-1}, riverine forests 496.2 ± 40.1 t CO_2e ha^{-1}, and mixed deciduous forests 447.4 ± 36.1 t CO_2e ha^{-1}. These values underscore the significant climate change mitigation service provided by these forest ecosystems.

Net Primary Productivity and Energy Flow Dynamics

Net primary productivity (NPP) and associated energy parameters are summarized in Table 3. Total NPP showed remarkable consistency across forest types, ranging from 17.8 ± 1.7 t ha^{-1} yr^{-1} in mixed deciduous forests to 18.7 ± 1.7 t ha^{-1} yr^{-1} in Sal dominated forests, with riverine forests exhibiting intermediate productivity (18.0 ± 1.6 t ha^{-1} yr^{-1}). Despite comparable total NPP, allocation patterns among components varied significantly between forest types.

Table 3: Net Primary Productivity (NPP) and Energy Flow Dynamics

Parameter	Sal Dominated Forest	Mixed Deciduous Forest	Riverine Forest	Units
Net Primary Productivity				
Tree Component				
- Bole Wood	6.8 ± 0.6	5.2 ± 0.5	5.9 ± 0.5	t/ha/yr
- Branch & Twig	2.4 ± 0.2	1.9 ± 0.2	2.1 ± 0.2	t/ha/yr
- Foliage	3.6 ± 0.3	4.2 ± 0.4	3.9 ± 0.3	t/ha/yr
- Reproductive Parts	0.8 ± 0.1	1.1 ± 0.1	0.9 ± 0.1	t/ha/yr
Understory Productivity	1.9 ± 0.2	2.8 ± 0.3	2.3 ± 0.2	t/ha/yr
Root Productivity	3.2 ± 0.3	2.6 ± 0.2	2.9 ± 0.3	t/ha/yr
Total NPP	18.7 ± 1.7	17.8 ± 1.7	18.0 ± 1.6	t/ha/yr

Tree component productivity was partitioned into bole wood, branch and twig, foliage, and reproductive parts. Bole wood productivity, representing stem increment, was highest in Sal dominated forests (6.8 ± 0.6 t ha^{-1} yr^{-1}), reflecting active diameter growth of the dominant *Shorea robusta* individuals. Branch and twig productivity followed similar patterns, with maximum values in Sal forests (2.4 ± 0.2 t ha^{-1} yr^{-1}). Notably, foliage productivity peaked in mixed deciduous forests (4.2 ± 0.4 t ha^{-1} yr^{-1}), where the more diverse species assemblage and deciduous nature contributed to greater leaf turnover. Reproductive parts productivity was also maximized in mixed deciduous forests (1.1 ± 0.1 t ha^{-1} yr^{-1}), indicating higher allocation to flowering and fruiting in these communities.

Understory productivity contributed 1.9 ± 0.2 t ha^{-1} yr^{-1} in Sal forests, 2.8 ± 0.3 t ha^{-1} yr^{-1} in mixed deciduous forests, and 2.3 ± 0.2 t ha^{-1} yr^{-1} in riverine forests. The elevated understory productivity in mixed deciduous forests corresponds to greater light availability beneath the more open canopy, facilitating shrub and herb growth. Root productivity, estimated through ingrowth core methods, ranged from 2.6 ± 0.2 t ha^{-1} yr^{-1} in mixed deciduous forests to 3.2 ± 0.3 t ha^{-1} yr^{-1} in Sal forests, representing 14.6-17.1% of total NPP across forest types.

Energy flow parameters revealed the efficiency of solar energy capture and transformation in these ecosystems. Gross primary production (GPP), representing total carbon fixed through photosynthesis, ranged from 38.6 ± 3.4 t ha^{-1} yr^{-1} in mixed deciduous forests to 42.5 ± 3.8 t ha^{-1} yr^{-1} in Sal dominated forests. Ecosystem respiration (Re), comprising autotrophic and heterotrophic respiration, accounted for 53.9-56.0% of GPP across forest types, resulting in net ecosystem exchange (NEE) values equivalent to NPP. Energy fixation rates, calculated by multiplying NPP by calorific values (18.7 kJ g^{-1}), were substantial: 3.35× 10x kJ ha^{-1} yr^{-1} in Sal forests, 3.22 × 10x kJ ha^{-1} yr^{-1} in riverine forests, and 3.19 × 10 x kJ ha^{-1} yr^{-1} in mixed deciduous forests. Photosynthetic efficiency, expressing the proportion of incident photo synthetically active radiation (PAR) converted to chemical energy through NPP, ranged from 1.73% in mixed deciduous forests to 1.82% in Sal dominated forests, values consistent with global averages for tropical dry forests.

Litter Production, Decomposition and Nutrient Cycling

Litter production dynamics and nutrient return patterns are presented in Table 4. Total annual litterfall varied significantly among forest types, with mixed deciduous forests producing the highest litter mass (7.6 ± 0.7 t ha^{-1} yr^{-1}), followed by riverine forests (7.1 ± 0.7 t ha^{-1} yr^{-1}) and Sal dominated forests (6.8 ± 0.7 t ha^{-1} yr^{-1}). Leaf litter constituted the dominant fraction across all forest types, contributing 61.8%, 63.2%, and 63.4% of total litterfall in Sal dominated, mixed deciduous, and riverine forests, respectively. Twig litter represented the second largest component, ranging from 1.2 ± 0.1 to 1.4 ± 0.1 t ha^{-1} yr^{-1}. Bark litter and reproductive parts contributed smaller proportions, though reproductive litter was notably higher in mixed deciduous forests (0.9 ± 0.1 t ha^{-1} yr^{-1}), consistent with their greater allocation to flowering and fruiting observed in productivity estimates.

Decomposition dynamics, assessed through litter bag experiments, revealed significant differences in decay rates among forest types. The decomposition constant (k) was highest in mixed deciduous forests (0.82 ± 0.08 yr^{-1}), indicating more

Table 4: Litter Production, Decomposition and Nutrient Cycling

Parameter	Sal Dominated Forest	Mixed Deciduous Forest	Riverine Forest	Units
Litter Production				
Leaf Litter	4.2 ± 0.4	4.8 ± 0.4	4.5 ± 0.4	t/ha/yr
Twig Litter	1.2 ± 0.1	1.4 ± 0.1	1.3 ± 0.1	t/ha/yr
Bark Litter	0.6 ± 0.1	0.5 ± 0.05	0.5 ± 0.05	t/ha/yr
Reproductive Parts	0.8 ± 0.1	0.9 ± 0.1	0.8 ± 0.1	t/ha/yr
Total Litterfall	6.8 ± 0.7	7.6 ± 0.7	7.1 ± 0.7	t/ha/yr

rapid breakdown of organic matter, followed by riverine forests (0.74 ± 0.07 yr^{-1}) and Sal dominated forests (0.68 ± 0.06 yr^{-1}). These differences in decomposition rates translated into corresponding variations in half-life (t_{50}), the time required for 50% mass loss. Mixed deciduous forests exhibited the shortest half-life (0.85 years), while Sal dominated forests required 1.02 years for 50% decomposition. Turnover time, representing the mean residence time of litter on the forest floor, followed the same pattern, ranging from 1.22 years in mixed deciduous forests to 1.47 years in Sal dominated forests.

Nutrient return through litterfall showed pronounced variation among forest types, reflecting differences in both litter mass and tissue nutrient concentrations. Nitrogen return was highest in mixed deciduous forests (68.4 ± 5.9 kg ha^{-1} yr^{-1}), substantially exceeding values in riverine forests (58.2 ± 5.1 kg ha^{-1} yr^{-1}) and Sal dominated forests (52.6 ± 4.8 kg ha^{-1} yr^{-1}). Phosphorus return followed identical trends, with mixed deciduous forests returning 5.8 ± 0.5 kg ha^{-1} yr^{-1}, compared to 4.9 ± 0.4 kg ha^{-1} yr^{-1} in riverine forests and 4.2 ± 0.4 kg ha^{-1} yr^{-1} in Sal forests. Potassium return was similarly maximized in mixed deciduous forests (36.2 ± 3.2 kg ha^{-1} yr^{-1}). Calcium showed a different pattern, with Sal dominated forests returning 42.8 ± 3.9 kg ha^{-1} yr^{-1}, exceeding values in mixed deciduous forests (38.6 ± 3.4 kg ha^{-1} yr^{-1}), reflecting the calcium-rich nature of *Shorea robusta* litter. Magnesium returns followed patterns similar to nitrogen and phosphorus, peaking in mixed deciduous forests (14.8 ± 1.3 kg ha^{-1} yr^{-1}).

The combined patterns of litter production and nutrient return indicate that mixed deciduous forests, despite having lower standing biomass, maintain faster nutrient cycling rates through higher litter quality (lower C:N ratios) and more rapid decomposition, facilitating greater nutrient availability for plant uptake.

Soil Physico-chemical Properties and Carbon Sequestration Potential

Soil physico-chemical characteristics and carbon sequestration parameters are detailed in Table 5. Physical properties showed distinct depth-related gradients across forest types. Bulk density increased with depth in all forests, ranging from 1.28-1.32 g cm^{-3} in surface layers (0-15 cm) to 1.38-1.42 g cm^{-3} in deeper layers (15-30 cm). Mixed deciduous forests exhibited the lowest bulk density (1.28 ± 0.07 g cm^{-3} in surface soil), indicating better soil structure and higher organic matter content. Soil moisture content varied significantly with season and forest type, with riverine forests maintaining highest moisture levels (24.8 ± 2.1% in surface soil during sampling periods), followed by mixed deciduous forests (22.4 ± 1.9%) and Sal dominated forests (18.6 ± 1.5%). Water holding capacity followed similar patterns, ranging from 48.2 ± 3.6% in Sal forests to 54.8 ± 4.3% in riverine forests, reflecting differences in organic matter content and textural composition.

Chemical properties revealed pronounced differences in soil fertility status among forest types. Soil organic carbon (SOC) in surface layers was highest in mixed deciduous forests (2.12 ± 0.18%), significantly exceeding values in riverine forests (1.98 ± 0.16%) and Sal dominated forests (1.86 ± 0.15%). SOC decreased with depth across all forest types, with 15-30 cm layers containing 66.7%, 69.8%, and 68.7% of surface SOC in Sal dominated, mixed deciduous, and riverine forests, respectively. Total nitrogen followed identical patterns, with mixed deciduous forests exhibiting the highest surface nitrogen concentrations (0.192 ± 0.016%) and Sal forests the lowest (0.168 ±

Table 5: Soil Physico-chemical Properties and Carbon Sequestration Potential

Parameter	Soil Depth	Sal Dominated Forest	Mixed Deciduous Forest	Riverine Forest	Units
Physical Properties					
Bulk Density	0-15 cm	1.32 ± 0.08	1.28 ± 0.07	1.30 ± 0.08	g/cm³
	15-30 cm	1.42 ± 0.09	1.38 ± 0.08	1.40 ± 0.09	g/cm³
Soil Moisture	0-15 cm	18.6 ± 1.5	22.4 ± 1.9	24.8 ± 2.1	%
	15-30 cm	16.2 ± 1.4	19.8 ± 1.7	22.3 ± 1.9	%
Water Holding Capacity	0-15 cm	48.2 ± 3.6	52.6 ± 4.1	54.8 ± 4.3	%

0.014%). The C:N ratio, calculated from these values, ranged from 11.0-11.1 across forest types, indicating similar organic matter quality despite differences in absolute carbon and nitrogen contents.

Available phosphorus showed considerable variation, with mixed deciduous forests containing 10.2 ± 0.9 kg ha^{-1}, significantly higher than riverine forests (9.4 ± 0.8 kg ha^{-1}) and Sal dominated forests (8.6 ± 0.7 kg ha^{-1}). Available potassium followed parallel trends, ranging from 186.4 ± 14.2 kg ha^{-1} in Sal forests to 212.6 ± 18.4 kg ha^{-1} in mixed deciduous forests. Soil pH was moderately acidic across all forest types, with values ranging from 5.8 ± 0.3 in Sal forests to 6.4 ± 0.4 in riverine forests. Cation exchange capacity (CEC), reflecting the soil's nutrient retention capacity, was highest in mixed deciduous forests (16.8 ± 1.4 meq 100g^{-1}), intermediate in riverine forests (15.9 ± 1.3 meq 100g^{-1}), and lowest in Sal dominated forests (14.6 ± 1.2 meq 100g^{-1}).

Soil carbon stock in the upper 30 cm, calculated from SOC concentrations and bulk density, ranged from 42.8 ± 3.6 t C ha^{-1} in Sal dominated forests to 48.2 ± 4.1 t C ha^{-1} in mixed deciduous forests. When combined with vegetation carbon, total ecosystem carbon stocks reached 197.6 ± 15.9 t C ha^{-1} in Sal dominated forests, 180.8 ± 14.8 t C ha^{-1} in riverine forests, and 170.1 ± 13.9 t C ha^{-1} in mixed deciduous forests. These values demonstrate that while Sal forests store more carbon in vegetation, mixed deciduous forests compensate partially through greater soil carbon accumulation.

Annual carbon sequestration rates, representing current carbon uptake, ranged from 3.9 ± 0.3 t C ha^{-1} yr^{-1} in mixed deciduous forests to 4.2 ± 0.4 t C ha^{-1} yr^{-1} in Sal dominated forests. These rates translate to carbon mitigation potentials of 14.3-15.4 t CO_2 ha^{-1} yr^{-1}, indicating that all three forest types are actively sequestering atmospheric carbon and contributing to climate change mitigation, with Sal dominated forests showing the highest current sequestration capacity.

SUMMARY

The integrated analysis of phytosociological parameters, biomass accumulation, productivity, nutrient cycling, and soil properties reveals distinct functional signatures for each forest type. Sal dominated forests function as biomass accumulators, storing maximum carbon in vegetation with moderate diversity but lower nutrient cycling rates. Mixed deciduous forests operate as nutrient cyclers, maintaining highest species diversity, rapid decomposition, and greatest soil fertility despite lower standing biomass. Riverine forests occupy an intermediate position, benefiting from greater moisture availability but showing moderate values for most parameters. These complementary functional strategies contribute to landscape-level ecosystem resilience and highlight the importance of conserving all three forest types for maintaining regional ecological integrity.

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