Research Article

Assessing Ecosystem Service Potential of Trees Outside Forests (TOF) Along Altitudinal Gradients in the Eastern Himalayas

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Teak forestry plantations are a critical TOF system that provides numerous ecosystem services. In this study, 30 teak forestry plantations in the foothills of the Indian Eastern Himalayas were examined to understand the ecosystem services provided by trees through direct observation, farmer interviews, and secondary validation using published literature and ethnobotanical databases. A total of 26 tree species were identified from the plantations. Species richness was higher at low altitudes, followed by mid and high altitudes. The study documented 81 provisioning services, 22 regulating services, 64 cultural services, and 56 supporting services. Species such as *Albizzia lebbeck*, *A. procera*, *Melia azedarach*, *Acacia auriculiformis*, *Neolamarckia cadamba*, and *Alstonia scholaris* contributed the highest number of services. The extent of ecosystem services provided by teak plantations varies with altitude. The highest number of provisioning services was observed in teak plantations at low altitudes, followed by those at mid and high altitudes. Conversely, the highest number of cultural services was reported from high-altitude plantations, with fewer at low and mid altitudes. These findings highlight the varied roles of trees across different altitudinal zones and the importance of multifunctional tree-based land management systems in delivering ecosystem services. Further research is needed to accurately quantify the economic value of these ecosystem services.

Keywords: TOFs, ecosystem services, farm forestry plantations

Introduction

Trees Outside Forests (TOFs) are vital ecosystems that maintain ecological health and support human well-being across different landscapes. They provide numerous ecosystem services, such as improving land productivity, conserving biodiversity, protecting soils, sequestering carbon, and regulating microclimates, which benefit both rural and urban communities worldwide. TOFs form an integral component of green infrastructure, connecting the ecological and socio-economic spectrum between forests and agricultural lands (Brandt et al., 2024; Islam et al., 2022; Peros et al., 2022; Tamang et al., 2018).

Globally, tropical regions cover about 1.35 billion hectares of land with tree plantations, of which around 336 million hectares are actual tree cover. The distribution of TOFs in tropical regions is influenced by a combination of anthropogenic and environmental factors such as land use, population density, farming intensity, water supply, and soil quality (Crowther et al., 2015; Kelley et al., 2024). These TOF systems act as refuges for biodiversity, help to sequester carbon (Montagnini, 2017), and play a crucial role in areas where deforestation and land degradation have destroyed natural forest ecosystems.

In India, trees growing outside the Recorded Forest Area (RFA) are formally classified as TOFs (Duraisami et al., 2022; Ghosh & Sinha, 2018). TOFs appear in diverse formations, including small woodlots, block plantations, farm forests, homesteads, and linear plantations along roads, canals, and field boundaries. In addition, they serve as a major source of timber, fuelwood, fodder, and non-timber products, and possess important cultural and social significance.

Teak (*Tectona grandis*)-based agroforestry plantations are a significant component of Trees Outside Forests (TOFs) systems in the foothills of the Indian Eastern Himalayas. In the region, farmers usually plant teak on their farms, typically spanning 0.5 to 5 hectares close to their crops. These agroforestry mosaics act as biodiversity hotspots, providing a range of ecological and economic advantages. Incorporating trees into farming reflects a wider global trend of agroforestation, which is increasingly recognised for its role in meeting domestic industrial wood needs, improving agricultural yields, diversifying rural livelihoods, and reducing environmental degradation (Roshetko, 2013; Brandt et al., 2024).

Ecosystem services from TOFs include a range of tangible and intangible benefits that humans obtain, such as provisioning, regulating, supporting, and cultural services. These multispecies and multifunctional systems offer services such as soil improvement, pollination, microclimate regulation, and carbon storage (Bieng et al., 2022; Mobarak et al., 2025; Raveloaritiana et al., 2023). Despite their importance, a comprehensive understanding of ecosystem services from farm forestry plantations remains limited (Peros et al., 2022). A thorough assessment of potential ecosystem services from such TOF systems is crucial to improve knowledge of the status, dynamics, and multifunctionality of tree resources across human-altered landscapes. Therefore, the present study aims to address two primary research questions: (a) what are the major ecosystem services provided by various tree species in teak farm forestry plantations? and (b) do the ecosystem services received from these systems vary with altitude?

Materials and Methods

Study area

The current study was carried out in the sub-humid region of West Bengal, situated in the foothills of the Indian Eastern Himalayas, where *Tectona grandis* L.f. (teak)-based farm forests are commonly established. To assess the ecosystem services of teak farm forests across different altitudes, the study sites were divided into three elevation categories: low (0–200 m a.s.l.), mid (200–500 m a.s.l.), and high (>500 m a.s.l.). The low-altitude teak farm forests were selected from the Cooch Behar district

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(26°19′–26°32′ N; 89°54′–89°57′ E). The region experiences a humid tropical climate with a mean annual rainfall of approximately 320 cm. The soils are moderately fertile and rich in organic matter.

The mid-altitude systems were selected from the Alipurduar district (26°15′–26°50′ N; 89°00′–89°55′ E), representing a transitional zone between the plains and the Himalayan foothills, which receives more than 350 cm of annual precipitation, with sandy loam to clay loam soils. The high-altitude farm forests were studied in the Darjeeling district (26°31′–27°13′ N; 87°59′–88°53′ E), located in the hilly terrain of the sub-Himalayan range, characterised by a subtropical climate and acidic soils rich in organic carbon.

A reconnaissance survey was conducted during 2023–24 to select teak farm forestry plantations. A total of 30 farm forests were selected from the entire study area, with 10 representative plantations from each altitudinal zone, based on accessibility, farmer cooperation, and management conditions. The average size of selected teak farm forests ranged between 0.5 and 5 ha per holding.

Quantification of ecosystem services

In each selected plantation, plot-based enumeration was conducted to record tree species in teak plantations. Data on ecosystem services were then compiled through (i) direct field observation of plant use and functions, (ii) structured interviews with farmers and local communities, and (iii) secondary validation using published literature and ethnobotanical databases. The documented species were then analysed for four major ecosystem service types, following the Millennium Ecosystem Assessment (MEA, 2005) and IPBES (2019) frameworks (Table 2). The contribution of species in different altitudinal classes was analysed using Microsoft Excel.

Results

In the present study, 26 tree species were found in the teak forestry plantations. The maximum number of tree species was recorded in the low-altitude plantations (20). The mid- and high-altitude plantations reported an equal number of species (17 each) (Fig. 1). Table 1 indicates the ecosystem services offered by various tree species in the teak forestry plantations within the study area.

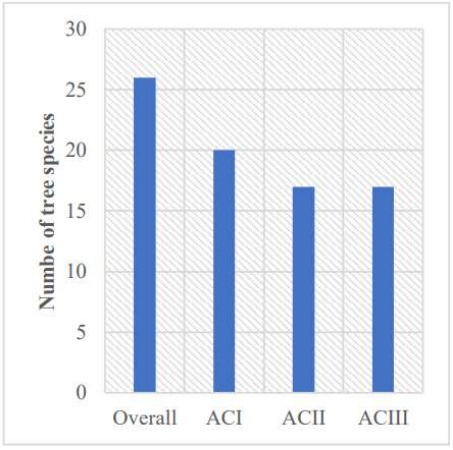

Figure 1: Number of tree species found in teak forestry plantations (ACI-low, ACI-Imid and ACIII-high)

In this study, the tree species that provided the most ecosystem services were *Albizzia lebbeck* (15), *A. procera* (13), *Melia azedarach* (13), *Acacia auriculiformis* (12), *Neolamarckia cadamba* (11), and *Alstonia scholaris* (11). In low-altitude teak plantations, *Neolamarckia cadamba* (13), *Acacia auriculiformis* (12), and *Alstonia scholaris* (11) contributed the most services. Mid-altitude teak plantations showed *Albizzia lebbeck* (15), *Melia azedarach* (13), and *Acacia auriculiformis* (12) providing the highest number of services. In high-altitude plantations, *Melia azedarach* (15), *Albizzia procera* (13), and *Neolamarckia cadamba* (13) delivered the greatest number of services.

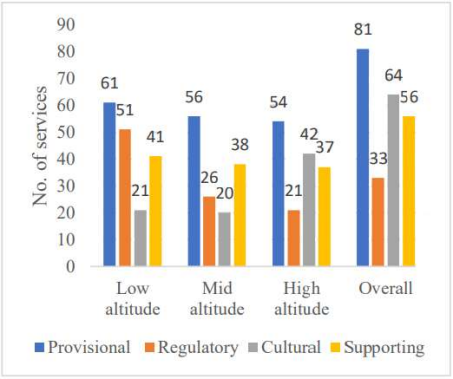

Figure 2: Number of ecosystem services provided by tree species in the teak plantations

The study documented 81 provisioning services, 22 regulating services, 64 cultural services, and 56 supporting services from trees present in the teak farm forestry plantations. The highest number of provisioning services was observed in teak plantations at low altitudes, followed by those at mid and high altitudes. Conversely, the highest number of cultural services was reported from high-altitude teak plantations, with fewer at low and mid altitudes. The greater number of provisioning services in low-altitude plantations is likely due to their higher species richness. This finding aligns with research showing a positive correlation between the diversity of woody plant species and ecosystem service diversity in different land-use types (Gamfeldt et al., 2013; Brockerhoff et al., 2017; Shumi et al., 2020). Meanwhile, the higher cultural services in high-altitude teak plantations indicate a stronger cultural reliance on trees among high-altitude communities for various cultural and indigenous practices (Mobarak et al., 2025).

Discussion

In the case of provisioning services, the trees were mainly analysed in terms of food, fodder, fuelwood, timber, medicinal uses, and non-timber forest products (NTFPs) (Table 2). The study revealed that 30.86% of the trees found in the teak farm forestry plantations in the Eastern Himalayan foothills served as medicinal sources. Furthermore, 22.22% of species provided timber, while 12.35% provided food and fodder each; 11.11% supplied fuelwood and NTFPs, respectively.

In the low-altitude farm forests, 32.79%, 22.95%, 11.48%, 11.48%, 11.48%, and 9.84% of species provided medicine, timber, food, fodder, NTFPs, and fuelwood, respectively. Similarly, at mid-altitude, 28.57%, 19.64%, 16.07%, 14.29%, 10.71%, and 10.71% of species offered medicine, timber, fodder, NTFPs, food, and fuelwood, respectively. At high altitude, 31.48% of species provided medicine; 22.22% supplied timber; 16.67% provided fodder; 11.11% each contributed to NTFPs and fuelwood; and 7.41% offered food.

The major regulating services provided by the trees in the study included microclimate regulation, carbon and climate regulation, air quality regulation, pest control, and pollination. Across the entire study area, the most significant regulating service offered by the trees was air quality regulation (26.56%), while pest control was the least represented (9.38%). Similar results were observed in both low- and high-altitude plantations, with 31.37% and 23.81% of species reported for air quality

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regulation, respectively. Conversely, in mid-altitude teak plantations, the highest percentage of species was reported for pest control.

Table 1: Documented ecosystem services

Category	Description
Provisioning	Food, fodder, fuelwood, timber, and medicinal plants.
Regulating	Microclimate, carbon, and pollination.
Cultural	Aesthetic, spiritual, and handicraft values.
Supporting	Nutrient cycling and soil fertility.

Cultural services were largely categorised under ethnobotany, aesthetic and ornamental values, handicrafts, and spiritual and religious categories. Across the entire study area, 33.33% of species contributed to ethnobotanical and spiritual and religious services. Handicraft-related services were the least explored by farmers in the study area, with 0%, 5%, and 9.52% of species used for manufacturing handicrafts in low-, mid-, and high-altitude farm forestry plantations, respectively.

Supporting services were analysed in terms of nutrient cycling, soil fertility, erosion control, habitat provision, and biodiversity support. In low-, mid-, and high-altitude farm forests, 36.59%, 36.84%, and 37.84% of species were reported to contribute to nutrient cycling and soil fertility, respectively. Regarding erosion control, 29.27%, 31.58%, and 32.43% of species in farm forests were noted for their role in erosion control. Similarly, 34.15%, 31.58%, and 29.73% of tree species were reported to provide habitat and support biodiversity in low-, mid-, and high-altitude teak plantations.

These findings emphasise the varied roles of trees across different altitudinal zones and the significance of multifunctional tree-based land management systems in providing ecosystem services. Comparative research supports these conclusions. Tamang et al. (2018) identified 95 woody species that supply food, ethnomedicine, fuelwood, and fodder outside forests in West Bengal. Similarly, Yarnvudhi et al. (2021) found that provisioning services have the highest economic value in Bangkok's urban parks. In addition to offering tangible goods, trees deliver crucial regulating and supporting services vital for ecosystem health and human well-being (Naudiyal & Schmerbeck, 2021). For example, Scholz et al. (2018)

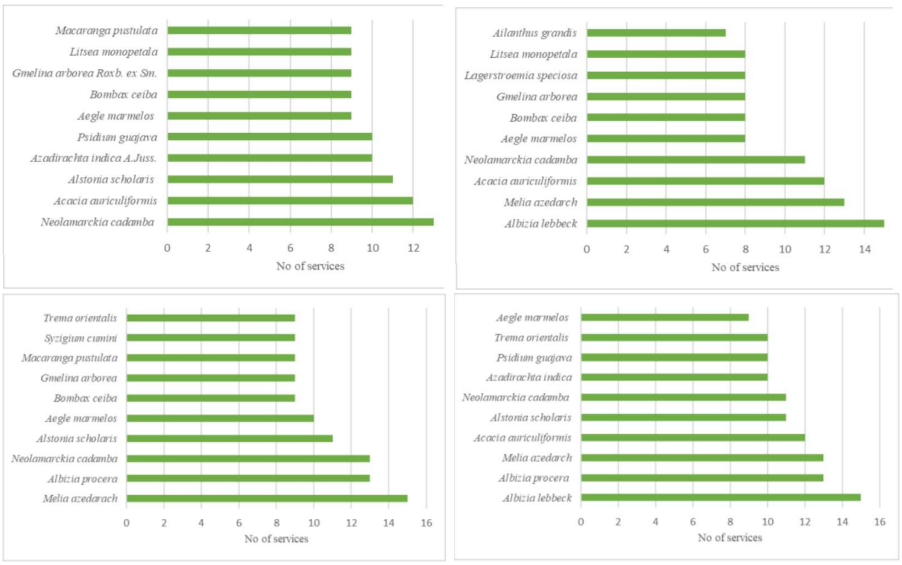

Figure 3: Number of services provided by the top ten tree species present in teak farm forests in (a) low-, (b) mid-, (c) high-altitude plantations, and (d) overall study area.

discovered that urban trees can remove up to 16% of particulate matter emissions. Their role in climate regulation and improving air quality is also well established (Thorsen et al., 2014; Endreny, 2018). The social and aesthetic value of trees was further highlighted by Tamang et al. (2018), who noted that 46 tree species were used for ornamental and avenue planting in institutional landscapes.

Conclusion

The present study systematically examined the ecosystem services provided by teak farm forestry plantations in the foothills of the Eastern Himalayas along an altitudinal gradient. These plantations are crucial centres of ecosystem functions that offer considerable ecological, economic, and cultural advantages. These tree-based land-use systems encompass not only the primary tree species but also a diverse array of associated species, reflecting high biodiversity and species richness.

Albizzia lebbeck, *Albizza procera*, *Melia azedarach*, *Acacia auriculiformis*, *Neolamarckia cadamba*, and *Alstonia scholaris* were identified as the key species delivering the highest number of ecosystem services. The extent of ecosystem services provided by teak plantations varies with altitude. Increased species diversity at lower elevations, alongside greater cultural reliance by communities at higher elevations, were the primary factors influencing this variability. Further research is necessary to precisely quantify the economic value of these ecosystem services. Such assessments will enable policymakers to incorporate these considerations into policy frameworks and support rural livelihoods, thereby encouraging the adoption and sustainability of tree-based land-use systems.

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Table 2: Tree species and documented ecosystem services in teak farm forestry plantations

Scientific name	Family	Documented services
Abroma augusta L.	Malvaceae	Medicine, pollination, nutrient cycling
Acacia auriculiformis A. Cunn. ex Benth.	Fabaceae	Fuelwood, timber, medicine, NTFP, landscaping, shade regulation, carbon sequestration, air quality improvement, pollination, nutrient cycling, erosion control, habitat provision
Aegle marmelos (L.) Correa	Rutaceae	Food, fodder, fuelwood, medicine, spiritual, air quality regulation, pollination, nutrient cycling, erosion control
Ailanthus grandis Prain	Simaroubaceae	Fodder, timber, medicine, air quality regulation, nutrient cycling, erosion control
Albizia lebbeck (L.) Benth.	Fabaceae	Food, fodder, fuelwood, timber, medicine, NTFP, landscaping, shade regulation, carbon sequestration, air quality regulation, pest regulation, nutrient cycling, erosion control, habitat provision
Albizia procera (Roxb.) Benth.	Fabaceae	Fodder, fuelwood, timber, medicine, NTFP, handicraft, shade regulation, carbon sequestration, pest regulation, nutrient cycling, erosion control, habitat provision
Alstonia scholaris (L.) R.Br.	Apocynaceae	Timber, medicine, landscape, spiritual, shade regulation, carbon sequestration, air quality regulation, pest control, pollination, nutrient cycling, habitat provision
Azadirachta indica A. Juss.	Meliaceae	Food, timber, medicine, spiritual, shade regulation, air quality improvement, pest control, nutrient cycling, erosion control
Bombax ceiba L.	Malvaceae	Timber, medicine, NTFP, spiritual, shade regulation, air quality improvement, nutrient cycling, erosion control, habitat provision
Chukrasia tabularis A. Juss.	Meliaceae	Fuelwood, timber, medicine, shade regulation, carbon sequestration, air quality regulation, pollination, erosion control
Elaeocarpus floribundus Blume	Elaeocarpaceae	Food, medicine, erosion control, habitat provision
Erythrina indica Lam.	Fabaceae	Fodder, medicine, NTFP, spiritual, air quality regulation, pollination, nutrient cycling, habitat provision
Gmelina arborea Roxb. ex Sm.	Lamiaceae	Fodder, timber, medicine, shade regulation, carbon storage, nutrient cycling, erosion control, habitat provision
Lagerstroemia speciosa (L.) Martyn	Lythraceae	Timber, medicine, landscape, shade regulation, air quality improvement, pollination, erosion control, habitat provision
Litsea monopetala (Roxb.) Pers.	Lauraceae	Food, timber, medicine, NTFP, spiritual, shade regulation, air quality improvement, erosion control, habitat provision
Macaranga pustulata King ex Hook.f.	Euphorbiaceae	Fuelwood, timber, medicine, landscape, shade regulation, carbon storage, air quality improvement, nutrient cycling, habitat provision
Melia azedarach L.	Meliaceae	Food, fodder, fuelwood, landscape, handicrafts, shade regulation, carbon storage, air quality improvement, pest control, nutrient cycling, erosion control, habitat provision
Moringa oleifera Lam.	Moringaceae	Food, fodder, medicine, air quality improvement, pollination, nutrient cycling, erosion control
Neolamarckia cadamba (Roxb.) Bosser	Rubiaceae	Food, fodder, timber, medicine, NTFP, landscape, spiritual, carbon storage, pest control, nutrient cycling, habitat provision
Psidium guajava L.	Myrtaceae	Food, fuelwood, timber, medicine, spiritual, shade regulation, carbon storage, air quality improvement, nutrient cycling, habitat provision
Sterculia villosa Roxb. ex Sm.	Malvaceae	Medicine, NTFP, spiritual, shade regulation, air quality improvement, nutrient cycling, erosion control, habitat provision
Swietenia macrophylla King	Meliaceae	Timber, medicine, aesthetic, shade regulation, carbon storage, air quality improvement, habitat provision
Syzygium cumini (L.) Skeels	Myrtaceae	Food, timber, medicine, aesthetic, spiritual, pollination, erosion control, habitat provision
Tectona grandis L.f.	Lamiaceae	Timber, medicine, spiritual, shade regulation, carbon storage, nutrient cycling
Trema orientalis (L.) Blume	Ulmaceae	Fodder, fuelwood, medicine, NTFP, carbon storage, pollination, nutrient cycling, erosion control, habitat provision

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