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RESEARCH ARTICLE

Assessment of forest structure, carbon stock and regeneration dynamics in the Raipur Range of Mussoorie Forest Division, Uttarakhand, India

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Abstract

Present study is a comprehensive assessment of the carbon stock in various tree species, the structure of the forests, and the regeneration status within the Raipur Range of the Mussoorie Forest Division, located in the Dehradun district of the Garhwal Himalaya. The Raipur Range is situated in a unique geographical area between 30°14'40" and 30°25'20" North latitude, and 78°01'80" to 78°18'00" East longitude, encompassing a total area of approximately 9,624.10 ha. The study was conducted in the between November 2022 - March 2024. To gather data, 30 sample plots (0.1 ha) were established randomly throughout the range, allowing for a representative analysis of the forest ecosystems. The investigation revealed three distinct types of forests along the altitudinal gradient of the region. Among these, the *Shorea robusta* forest was identified as the most dominant, characterizing the landscape and contributing significantly to the overall biomass of the area. The results indicated that the maximum total biomass was recorded at altitudes between 1,000 and 1,200 m, reaching an impressive 163.65 Mg ha^{-1}. Conversely, the study documented a minimum biomass of 128.71 Mg ha^{-1} at elevations ranging from 800 to 1,000 m, highlighting the variations in forest productivity across different altitudinal zones. In terms of regeneration status, the overall findings suggested that forest regeneration was poor across most types, except the *Pinus roxburghii* forest, which demonstrated fair regeneration at the study site. This disparity in regeneration can be largely attributed to a combination of environmental factors affecting sapling growth. Specifically, the presence of a stony substratum appears to limit the establishment of young trees, while biotic interference from herbivores and competition for sunlight with more mature plants further exacerbate the challenges faced by saplings. These insights underscore the need for targeted conservation efforts to enhance forest regeneration and protect the biodiversity of the Raipur Forest Range.

Keywords: Forest Structure; Altitudinal Gradient; Carbon Stock; Phytosociology; Regeneration; Mussoorie

1. Introduction

Vegetation ecology is an expansive field dedicated to understanding the composition, structure, and dynamics of plant communities and the interactions among plant species within these communities. This discipline examines ecological relationships in diverse habitats, providing insights into how plant species coexist, distribute, and adapt to varying environmental conditions. Mueller-Dombois and Ellenberg (1974) describe vegetation ecology as essential for exploring plant species' sociological and functional interactions within ecological communities, making it foundational to ecological research and management. A key approach within vegetation ecology is phytosociology, the quantitative study of plant communities. Phytosociology focuses on analyzing the relationships between coexisting species, helping to identify patterns of species distribution, abundance, and association. The primary goals of phytosociology are to describe the composition and characteristics of vegetation in different ecosystems, classify plant communities into meaningful categories, and explore the dynamics that influence species distribution over time (Ilorkar and Khatri, 2003).

Forests are invaluable ecosystems that provide a vast array of goods and services essential for human survival and ecological balance. Among the tangible goods derived from forests are timber,

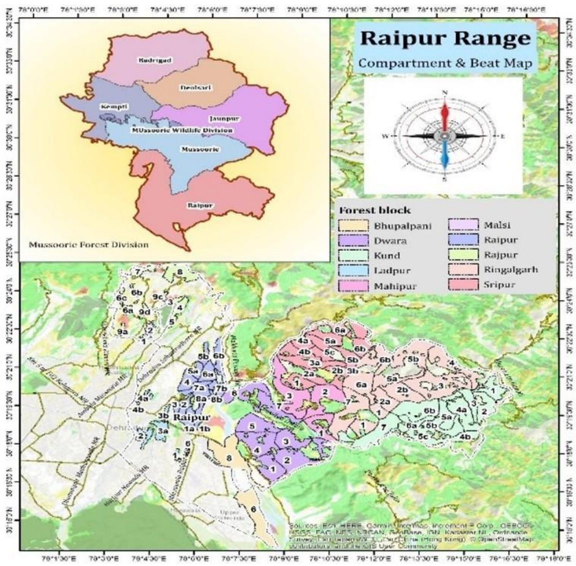

Figure 1. Location map of Raipur Forest Range.

Table 1. Phytosociological attributes of tree species at different study sites.

Site	Elevation (m)	Botanical Name	Frequency (%)	Density tress ha-1	Abundance	IVI	A/F
I	600-800	*Shorea robusta* C.F.Gaertn.	70	25.6	36.57	155.59	0.52
		Ficus benghalensis L.	3.33	0.03	1	82.53	0.3
		Tectona grandis L.f.	10	4.4	44	6.71	3.9
		Cassia fistula L.	6.67	0.17	2.5	4.84	0.3
		Senegalia catechu (L.f.) P.J.H.Hurter & Mabb.	3.33	0.43	13	25.44	4.4
		Bombax ceiba L.	3.33	0.1	3	20.03	0.38
		Moringa oleifera Lam.	3.33	0.03	1	4.86	0.9
II	801-1000	*Shorea robusta* C.F.Gaertn.	83.33	12.27	14.72	183.25	0.5
		Senegalia catechu (L.f.) P.J.H.Hurter & Mabb.	3.33	0.03	1	82.4	0.3
		Mallotus philippensis (Lam.) Müll.Arg.	3.33	0.5	15	19.65	0.18
		Toona ciliata M.Roem.	3.33	0.73	22	9.93	0.3
		Broussonetia papyrifera (L.)	3.33	0.07	2	4.77	6.6
III	1001-1200	*Shorea robusta* C.F.Gaertn.	60	19	38	188.32	0.63
		Pinus roxburghii Sarg.	40	10	30	111.68	0.75

fuelwood, food products, and fodder. In addition to these, forests offer critical ecosystem services, including biodiversity conservation, flood regulation, erosion prevention, and water cycle maintenance. Forests also mitigate the impacts of droughts and avalanches, demonstrating their role as natural shields against environmental hazards. On the socio-economic front, forests contribute significantly to employment generation, the supply of forest products, and the protection of culturally significant sites. Globally, forests are recognized as indispensable in their dual role of supporting human livelihoods and maintaining ecological stability. They act as primary carbon reservoirs, storing more carbon per unit area than any other terrestrial ecosystems (Kuuluvainen and Gauthier, 2018; Liu et al., 2020).

Forest regeneration can occur through two primary mechanisms: natural and artificial. Natural regeneration involves the establishment of forest vegetation through natural processes such as self-sown seeds, suckering, and sprouting. In contrast, artificial regeneration relies on human interventions, including planting seedlings, cuttings, or direct seeding of preferred species in the forest. Mature trees within forests serve as vital seed banks, perpetually producing seeds that lead to the establishment of new individuals, ensuring the continuity of the ecosystem over time and space. These seeds germinate and form seedlings, which must compete for survival under various environmental and ecological conditions (Malik, 2014). The success of natural regeneration is largely determined by the successful establishment of these seedlings. Although forests may produce a substantial number of seedlings, only a fraction survives to maturity due to numerous factors. These include interspecific and intraspecific competition for essential resources such as light, water, and nutrients, as well as anthropogenic pressures and natural environmental factors such as soil aeration, light availability, humus, moisture, and nutrient conditions. Consequently, the survival and growth of seedlings are critical indicators of successful forest regeneration (Good et al., 1972). The regeneration of tree species is contingent on three essential components: the production of new seedlings, the survival of seedlings and saplings, and their ability to grow into mature individuals (Good et al., 1972). The regeneration status of tree species can be assessed through the population's age structure, which provides insights into the distribution of individuals across different life stages (seedling, sapling, and mature tree) (Marks, 1974; Veblen et al., 1979; Pritts and Hancock, 1983; Saxena and Singh, 1984).

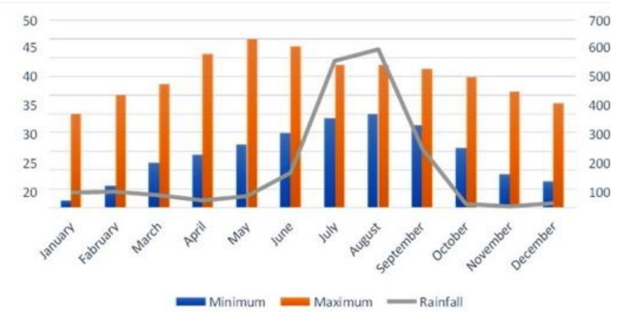

Figure 2. Ombrothermic diagram showing climatological data of the study site.

Temperate forests alone cover approximately 767 million hectares worldwide, accounting for 25% of the total land area and storing around 14% of the planet's total carbon (Pan et al., 2011). In the face of escalating climate change concerns, forests are pivotal in regulating and mitigating climate impacts by reducing atmospheric CO_2 concentrations (Streck and Scholz, 2006; Burman et al., 2021). Accurate quantification of carbon stocks across various forest ecosystems is critical for crafting effective carbon management strategies and achieving international commitments to reduce atmospheric carbon levels (UNFCCC, 2014; Mayer et al., 2020). The biomass within forest ecosystems serves as a direct indicator of the carbon sequestration potential, which is instrumental in meeting emission reduction targets (Brown et al., 1999; Raha et al., 2020).

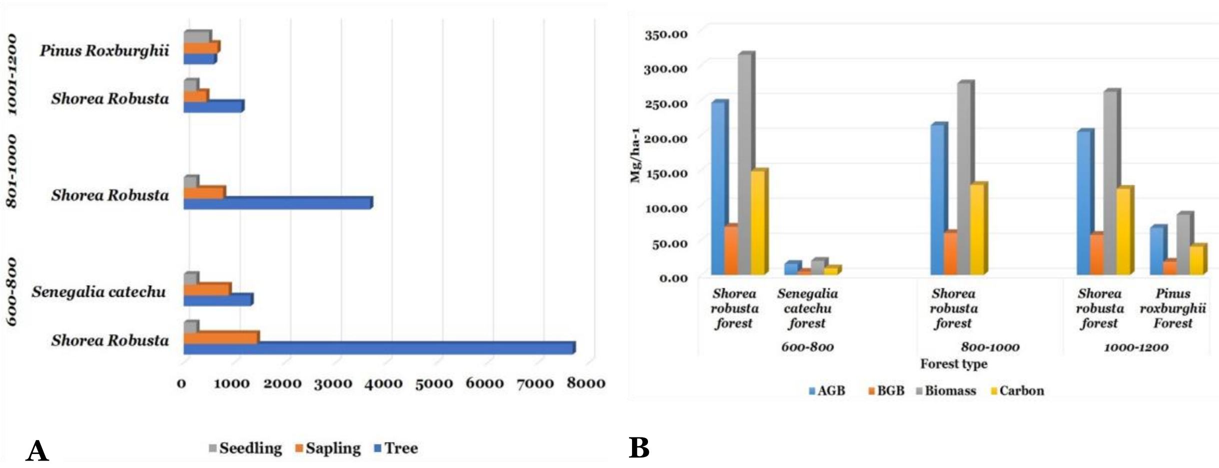

Figure 3. (A) Population structures of dominated forests at different altitudes. (B) Biomass and carbon content in different forest types along altitudinal gradients.

2. Material and method

2.1. Study area

The Raipur range is a section of the Mussoorie Forest Division located in the Dehra Dun district of Uttarakhand, India. It lies within the Lesser Himalayas and has an elevation ranging from 600 – 1900 msl. Geographically, it is situated between 30°14'40" and 30°25'20" North latitude and 78°01'80" to 78°18'00" East longitude. The total area covered by the Raipur Forest Range is 9624.10 hectares, divided into 86 compartments and 10 blocks. Quadrats were laid on seven sites: Dwara, Bhopalpani, Malsi, Raipur, Rajpur, Ringalgarh, and Ladpur. This region represented subtropical and temperate climate, with an annual average rainfall of 1752.28 mm. Approximately 75% of the rainfall is concentrated between mid-July and mid-August. The highest average temperatures are observed in May, while the lowest occur in January.

2.2. Research method

2.2.1. Tree biomass and carbon stock

The study was conducted between November 2022 and March 2024. A non-destructive method was employed to estimate biomass and carbon during the study. Randomly, 30 sample plots of 0.1 he each (31.62m × 31.62 m) were laid out in selected 6 sites (FSI, 2019). The height and diameter at breast height (1.37 m above the ground) of all the trees within the sample plot were measured. Species-specific volume equations/volume tables (FSI, 1996) were used to estimate the volume of individual trees. The estimated volume of each tree was multiplied by its wood density to calculate the stem biomass. To estimate individual tree aboveground biomass, the bole biomass was multiplied by the biomass expansion factor (Haripriya, 2000). The belowground biomass was calculated by multiplying the value of aboveground biomass with the constant factor of 0.26. The total biomass of the individual tree was obtained by adding the aboveground biomass and belowground biomass. To calculate the carbon contents, the total biomass of individual trees was multiplied by the conversion factor of 0.5 (IPCC, 2006). To obtain the total biomass and carbon storage in a sample plot, the total biomass of individual trees and their carbon content were added. The mean total biomass and carbon were calculated by averaging the total biomass and carbon values in all sampling plots.

2.2.2. Tree regeneration status

In each 0.1-ha plot, there were 3x3 m^2 plots for saplings and 1x1 m^2 plots for tree seedlings. According to Saxena and Singh, (1984), a plot was categorized as seedlings if the circumference at breast height (CBH) was less than 10 cm, a sapling if CBH was between 10 cm and 30 cm, and a tree if CBH was more than or equal to 30 cm. The regeneration status of tree species will be determined based on the population sizes of seedlings, saplings, and adults, and the classification will be done as per Shankar (2001).

2.2.3. Phytosociology status

For the analysis, 30 quadrats of 0.1 ha each (measuring 31.62 x 31.62 m^2) were established at each studied site. This sampling strategy provided a robust dataset for examining the composition and distribution of tree species. The vegetation composition was evaluated using established ecological parameters, including frequency, density, abundance, and the Importance Value Index (IVI). These parameters were calculated the methodologies proposed by Misra (1968) and Curtis and McIntosh (1951).

3. Result

3.1. Dominance (Important Value Index)

A total of 11 tree species were recorded in the Raipur Range of Mussoorie Forest Division—the tree phytosociological analysis of vegetation at different altitudinal gradients in the Raipur Range (Table 1). The vegetation of the studied sites was analyzed across different elevations, and all observations were recorded in passive voice. At Site I (600– 800 m), *Shorea robusta* C.F.Gaertn. was recorded with a frequency of 70.00%, a density of 25.60, an abundance of 36.57, and an IVI of 155.59, with the A/F ratio determined to be 0.52. *Ficus benghalensis* L. was observed with a frequency of 3.33%, a density of 0.03, an abundance of 1.00, and an IVI of 82.53, while the A/F ratio was calculated as 0.30. *Tectona grandis* L.f. was recorded with a frequency of 10.00%, a density of 4.40, an abundance of 44.00, an IVI of 6.71, and an A/F ratio of 3.90. *Cassia fistula* L. was noted with a frequency of 6.67%, a density of 0.17, an abundance of 2.50, and an IVI of 4.84, while its A/F ratio was determined to be 0.30. Similarly, *Senegalia catechu* (L.f.) P.J.H.Hurter and Mabb. was observed with a frequency of 3.33%, a density of 0.43, an abundance of 13.00, and an IVI of 25.44, with an A/F ratio of 4.40. *Bombax ceiba* L. was recorded with a frequency of 3.33%, a density of 0.10, an abundance of 3.00, an IVI of 20.03, and an A/F ratio of 0.38. Lastly, *Moringa oleifera* Lam. was noted with a frequency of 3.33%, a density of 0.03, an abundance of 1.00, and an IVI of 4.86, with the A/F ratio being 0.90.

At Site II, situated at 801–1000 m, *Shorea robusta* C.F.Gaertn was again recorded as the dominant species, with a frequency of 83.33%, a density of 12.27 trees per hectare, an abundance of 14.72, an IVI of 183.25, and an A/F ratio of 0.5 was observed at this site.

Table 2. Diversity index of different study site along an altitudinal gradient

Study site	Elevation	H'	CD	1-D	J
I	600-800	0.55	0.71	0.29	0.28
II	800-1000	0.72	0.7	0.3	0.4
III	1000-1200	0.54	0.64	0.36	0.78

Followed by *Senegalia catechu* (L.f.) it had a frequency of 3.33%, a density of 0.03, an abundance of 1, an IVI of 82.4, and an A/F ratio of 0.3, while in the other, the IVI dropped to 7.96, with an A/F ratio of 0.6. *Mallotus philippensis* (Lam.) Müll.Arg. was recorded with a frequency of 3.33%, a density of 0.5, an abundance of 15, an IVI of 11.69, and an A/F ratio of 0.18. *Toona ciliata* M. Roem. was noted with a frequency of 3.33%, a density of 0.73, an abundance of 22, an IVI of 9.93, and an A/F ratio of 0.3. *Broussonetia papyrifera* (L.) L'Hér. ex-Vent. was also recorded with a frequency of 3.33%, a density of 0.07, an abundance of 2, an IVI of 4.77, and the highest A/F ratio at this site, calculated as 6.6.

At Site III (1001–1200 m), *Shorea robusta* C.F.Gaertn. was recorded with a frequency of 60.00%, a density of 19.00, an abundance of 38.00, and an IVI of 188.32, with an A/F ratio being 0.63. *Pinus roxburghii* Sarg. was noted with a frequency of 40.00%, a density of 10.00, an abundance of 30.00, and an IVI of 111.68, while the A/F ratio was determined to be 0.75.

Overall, *Shorea robusta* C.F.Gaertn was the most dominant species across all three study sites, particularly at Sites II and III, where the highest Importance Value Index was exhibited.

3.2. Diversity index

The diversity indices were calculated across different study sites and elevations. At Study Site I, with an elevation of 600–800 m, the Shannon-Weiner Index (H') was recorded at 0.55, while the Concentration of Dominance (CD) was measured at 0.71, the Simpson's Index of Diversity (1-D) was noted at 0.29, and Pielou's Evenness Index (J) was observed at 0.28. At Study Site II, at an elevation of 800–1000 m, the H' increased to 0.72, with CD slightly lower at 0.70, 1-D recorded at 0.30, and J rising to 0.40. At Study Site III, at an elevation of 1000–1200 m, the H dropped to 0.54, CD decreased further to 0.64, 1-D rose to 0.36, and J reached a higher value of 0.78 (Table 2). The range of the Shannon Wiener diversity (H) for the present study was found to be between 0.54 to 0.72, which is comparable to the values reported by Khera et al (2001) in the mixed forest type of Kumaun Himalaya. Moreover, Pande (2001) and Sharma et al (2009) reported diversity value from range 0.91 to 3.0 for the Himalayas. While, reported diversity value from range 1.41-2.04 in Tangmarg Forest division in Kashmir Himalaya, India. In contrast, Sharma and Kant (2014) reported a diversity (H) value 2.48-3.38 in Sub tropical reason of Kandi Siwaliks of Jammu and Kashmir, which could be due to the high-altitude range of their study area.

3.3. Regeneration

At Study Site I, located between 600 and 800 m, we observed two types of forests, *Shorea robusta* and *Senegalia catechu*, both showed poor regeneration. The presence of *Shorea robusta* and *Senegalia catechu* forests with poor regeneration may be attributed to increased human settlements and construction activities such as infrastructure development, often lead to habitat degradation, reduced seedling establishment, and altered forest structure. The proximity of these forests to vehicular roads and picnic spots may further exacerbate the issue. The disturbances caused by vehicular emissions, soil compaction, and human trampling are known to hinder natural regeneration processes, particularly for species like *Shorea robusta* that require specific microclimatic conditions for seed germination and growth. At Study Site II, situated at an altitude of 800 to 1000 m, the *S. robusta* forest exhibited poor regeneration. At Study Site III, ranging from 1000 to 1200 m, we noted two types of forests *S. robusta* and *Pinus roxburghii*. The regeneration status of the *S. robusta* forest was poor, while the *Pinus roxburghii* forest showed fair regeneration (Figure 3.A). This trend aligns with the findings of Rawat et al (2020), who reported that *Pinus roxburghii* is better adapted to the climatic and soil conditions of mid-altitude regions, allowing it to regenerate more effectively than other species. The regeneration of a species is influenced by a variety of factors, both biotic and abiotic. Key influences include environmental conditions, biological interactions, and human activities. Research by Khan et al (1987), Sukumar et al (1994), Barik et al (1996), and Iqbal et al (2012) highlights the complex interplay of these factors in determining species recovery and growth. Anthropogenic effects, such as habitat destruction, pollution, and climate change, can significantly hinder regeneration processes. Conversely, natural phenomena, including climatic variations, seasonal cycles, and ecological relationships, also play a crucial role in shaping regeneration outcomes. Furthermore, studies by Welden et al (1991) emphasize the importance of understanding these dynamics to develop effective conservation strategies and promote the sustainability of species in their natural habitats. Moisture stress and heavy undergrowth is responsible for heavy mortality of Sal seedlings after their recruitments. Recruitment of Sal seedlings is not a problem but establishment of seedlings and their conversion to higher diameter class is more important (Singh et al., 2023).

3.4. Carbon content

The data were gathered across three altitude ranges from 600 to 1200 m, documenting various forest types (Figure 3.B). At altitudes of 600-800 m, *Shorea robusta* forest was measured with Above Ground Biomass (AGB) of 246.14Mgha^{-1}, Below Ground Biomass (BGB) of 68.92Mgha^{-1}, resulting in total biomass of 315.06 Mgha^{-1} and a carbon content of148.08 Mgha^{-1}. At the same altitude, *Senegalia catechu* forest was noted with 15.73 Mgha^{-1} AGB, 4.40 Mgha^{-1} BGB, a total biomass of 20.13 Mgha^{-1}, and a carbon content of 9.46 Mgha^{-1}.This can be attributed to its robust growth and adaptability to warmer, low-altitude conditions, which align with previous studies that identify Shorea robusta as a high biomass accumulator in tropical and subtropical forests (Haripriya, 2000; Pan et al., 2011). In contrast, *Senegalia catechu* forests at the same altitude displayed significantly lower biomass and carbon content, likely due to differences in growth form and ecological requirements.

For the altitude range of 800-1000 m, *Shorea robusta* forest was observed with an AGB of 213.95 Mgha^{-1}, BGB of 59.91 Mgha^{-1}, contributing to a total biomass of 273.86 Mgha^{-1}, and a carbon content of 128.71 Mgha^{-1}. This reduction may reflect the influence of environmental factors such as temperature and soil nutrient availability, which generally decline with elevation (Saxena and Singh, 1984; Streck and Scholz, 2006). Despite this, the carbon content remained substantial (128.71Mg ha^{-1}), underscoring the species' resilience and importance in mid-altitude carbon sequestration.

In the 1000-1200 m range, *Shorea robusta* forest showed values of 204.66 Mgha^{-1} AGB, and 57.31 Mgha^{-1} BGB, with a total biomass of 261.97 Mgha^{-1} and a carbon content of 123.13 Mgha^{-1}. Additionally, *Pinus roxburghii* Forest at this altitude was measured with an AGB of 67.36 Mgha^{-1}, a BGB of 18.86 Mgha^{-1}, a total biomass of 86.22 Mgha^{-1}, and a carbon content of 40.52 Mgha^{-1}. *Shorea robusta* forests continued to exhibit high biomass values (261.97 Mgha^{-1} total biomass), albeit slightly lower than at lower altitudes. The carbon content also declined to 123.13 Mgha^{-1}, which is consistent with observations of reduced growth rates at higher altitudes (Kuuluvainen and Gauthier, 2018). Interestingly, *Pinus roxburghii* forests, which dominate this altitudinal range, showed significantly lower biomass (86.22 Mgha^{-1}) and carbon content (40.52 Mgha^{-1}). This difference can be attributed to the slower growth rate and less dense wood of pines compared to *Shorea robusta* (Veblen et al., 1979; Misra, 1968).

Figure 4. Constructed Road in Sal Forest Providing Vehicle Access to Nearby Picnic spot

Forest structure and carbon dynamics are influenced by altitude, species composition, and site-specific environmental conditions (Pan et al., 2011; Liu et al., 2020). For instance, tropical and subtropical species like *Shorea robusta* tend to have higher biomass productivity than species adapted to montane ecosystems, such as *Pinus roxburghii*. Additionally, the allocation of biomass between aboveground and belowground components reflects species-specific growth strategies and soil characteristics, which are vital for accurate carbon stock estimation (FSI, 2019; UNFCCC, 2014).

4. Conclusion

The investigation conducted in the region revealed three distinct types of forests that vary along the altitudinal gradient. Among these, the *Shorea robusta* forest was the most dominant. However, the regeneration of these forests is significantly influenced by human activities, particularly the establishment of settlements and construction projects near their perimeters. These activities primarily aim to facilitate vehicle access to a nearby picnic spot, which has resulted in increased disturbances within the forest ecosystem. The implications of such human encroachment could negatively affect the long-term health and sustainability of the *Shorea robusta* forest, challenging its natural regeneration processes and biodiversity.

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Authors' contributions

All authors contributed equally to the original idea, its execution, the preparation of the manuscript, and the statistical analysis.

Conflict of interest

The Authors have no conflict of interest.

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