



Research article

Beyond community forests: Carbon variability in Nepal's mixed and pure private forests and its implications for climate policy

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Abstract

Importance of the work: Private forests are a major component of Nepal's landscape and have substantial potential for carbon sequestration, yet their role remains understudied and underutilized in national climate mitigation strategies, such as Reducing Emissions from Deforestation and Forest Degradation (REDD+). A comparative understanding of carbon stocks in different private forest management systems is crucial for developing effective policies and incentives.

Objectives: To quantify and compare the above-ground biomass and carbon stocks in pure and mixed private forests, to analyze the structural attributes (diameter at breast height over bark (DBH), height, density) driving these differences and to identify species preferred by landowners to inform sustainable management and carbon policy.

Materials and Methods: This study was conducted in the Rautahat District of Nepal's Terai region. A systematic sampling design was applied, establishing 14 plots in a pure *Eucalyptus camaldulensis* Dehnh. forest and 4 plots in a mixed-species forest. Tree DBH, height and species were recorded in circular plots (each 250 m²). The above-ground biomass was calculated using a species-specific allometric equation and carbon stock was derived using a 0.47 conversion factor. A one-tailed t test was used to assess the significance of differences between forest types.

Results: Pure eucalypt private forests in Nepal's Terai stored 61% more carbon than mixed-species stands, offering a rapid climate mitigation pathway while balancing livelihood needs. Pure *E. camaldulensis* forests contained significantly higher mean $\pm$ SD carbon stocks (61.15 ± 0.78 t/ha) compared to mixed forests (37.87 ± 2.23 t/ha; $p < 0.05$). This carbon advantage was due to structural superiority as indicated by a larger tree height (16.11 m versus 10.43 m) and a higher stand density (695 trees/ha versus 560 trees/ha) than in pure stands. Beyond carbon, 11 tree species were identified as being managed by landowners primarily for timber, fuelwood and income generation, revealing private forests as socio-ecological systems where climate mitigation and livelihoods intersect.

Main finding: Pure eucalypt private forests sequestered significantly more carbon per hectare than mixed-species forests, demonstrating the high potential of the former for rapid carbon gains. This supports their integration into carbon incentive schemes, such as REDD+, while the diversity of species in mixed forests underscores the need for policies that balance carbon objectives with biodiversity and livelihood benefits. Private forests are no longer climate afterthoughts but strategic assets for Nepal's mitigation targets.

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Introduction

Assessing carbon sequestration potential in forests is essential for understanding their role in climate change mitigation (Pandey et al., 2016; Ravichandran et al., 2024). Forests play a key role in this process by absorbing carbon through photosynthesis and storing it in above- and below-ground biomass (Joshi et al., 2023; Pandey et al., 2024). Globally, forests cover over 4 billion ha and contribute approximately 50% to greenhouse gas mitigation, with about 60% of terrestrial carbon stored in forest ecosystems (Intergovernmental Panel on Climate Change, 2000). In Nepal, forests are estimated to contain 1,054.97 million t of carbon (Department of Forest Research and Survey, 2015). In addition to carbon storage, forests provide a variety of ecological services and wood and non-wood forest products such as firewood, timber, fodder, grazing space and recreational opportunities (Maraseni et al., 2006; Asaminew et al., 2020). In addition, forests support local livelihoods and reduce CO₂ emissions, which helps mitigate climate change impacts (Cadman and Maraseni, 2012; Askar et al., 2018). Beyond biological methods, carbon can be sequestered in long-term reservoirs, such as soils, oceans, living organisms and geological formations, while abiotic methods include saline aquifers, mineral carbonation, deep-ocean CO₂ injection and abandoned mines (Lal, 2008; Maraseni and Pandey, 2014).

Despite the recognized importance of forests, data remains limited on carbon stocks in private forests—those planted and managed by landowners on their own land (Dhakal et al., 2015; Government of Nepal, 2019). While natural forests and community forests have been studied extensively (Joshi et al., 2019; Joshi et al., 2020; Joshi et al., 2021a; Joshi et al., 2021b), carbon storage is poorly documented regarding pure forests versus mixed private forests in Nepal (Pandey et al., 2014a; Pandey et al., 2014b). Therefore, the current study addressed this knowledge gap by quantifying above-ground biomass and carbon stocks in pure and mixed private forests, comparing carbon storage between *E. camaldulensis*-dominated and mixed-species forests and identifying preferred species managed by forest owners to evaluate their contribution to carbon sequestration and Reducing Emissions from Deforestation and Forest Degradation (REDD+) programs. These differences were tested based on the hypothesis that carbon stock differed significantly between pure and mixed private forests. Accurate assessment of biomass and carbon stocks in private forests is essential for understanding their potential in climate mitigation, as demonstrated in other forest management systems (Joshi and Singh, 2020; Joshi et al., 2023). The findings of the current study

should fill the knowledge gap on private forests in Nepal, support forest owners in integrating with REDD+ initiatives and provide guidance for balancing productivity with biodiversity, to achieve both climate and ecological sustainability.

The current study makes three specific contributions to the existing body of knowledge. First, it provides the first comparative assessment of above-ground biomass and carbon stocks between pure and mixed private forests in Nepal's Terai region, addressing a major gap in forest carbon data. Second, it integrates ecological measurements with socioeconomic insights by identifying preferred species and management purposes through interactions with private forest owners, thereby linking carbon sequestration potential with livelihood outcomes. Third, it offers empirical evidence supported by statistical testing showing that *E. camaldulensis*-dominated private forests store significantly higher biomass and carbon than mixed stands, providing valuable guidance for private forest management and REDD+ policy design in Nepal.

Materials and Methods

Study area

This study was conducted in the Rautahat District of Nepal's central Terai region (Fig. 1). The site selection was designed to capture two prevalent private forest management systems: 1) a monoculture plantation; and 2) a mixed-species stand. The specific sites comprised a pure stand (1 ha) of *Eucalyptus camaldulensis* Dehnh. and a mixed-species forest (0.45 ha), both privately owned and managed. The district lies within Madhesh Province (26°50'0"N–27°10'0"N; 85°10'0"E–85°30'0"E), covering approximately 1,130 km². The region experiences a tropical monsoon climate, characterized by distinct seasonal variation: hot, humid summers with temperatures up to 40°C; cool, dry winters with minima around 7°C; and a pronounced monsoon from June to September delivering the bulk of the annual precipitation. This climate supports a landscape dominated by agriculture interspersed with forest patches. The natural and planted forests of the area are typically composed of species such as *Shorea robusta* C.F.Gaertn., *Terminalia alata* B.Heyne ex Roth, *Eucalyptus camaldulensis* Dehnh., *Tectona grandis* L.f. and *Acacia catechu* (L.f.) Willd. The selected forest plots were accessible and representative of the stand structure and species composition found in the privately held land of the Terai, thereby allowing for a robust comparative assessment of dendro-metric properties and carbon stocks.

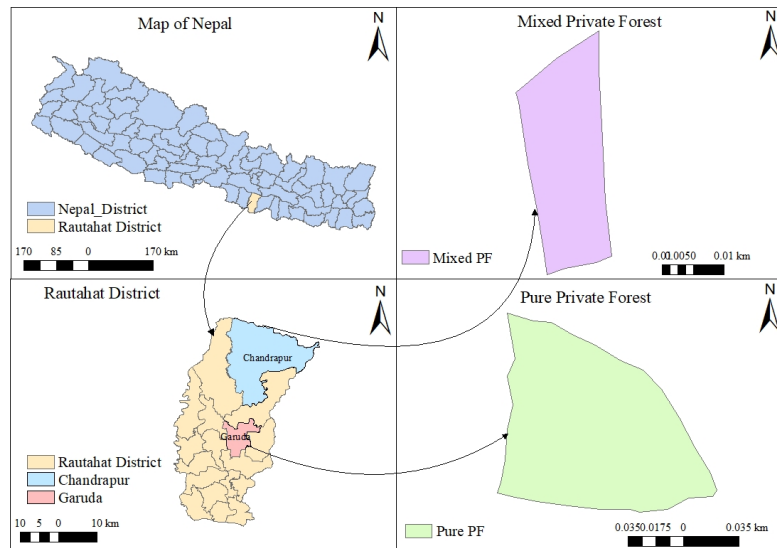


Fig. 1 Map showing study area location in Rautahat district, Nepal, where PF = private forest

Primary data collection

Sample plot layout and biomass sampling

The sampling strategy and plot allocation were designed following the carbon stock measurement inventory guidelines (Subedi et al., 2010). A sampling intensity of 25% was adopted, consistent with Department of Forest Research and Survey (2015) standards for small-scale forest carbon assessments. The total number of sample plots required for the study was estimated based on the carbon stock measurement inventory guidelines (Subedi et al., 2010). This systematic sampling approach aligned with methodologies that have been applied successfully in other forest carbon stock assessments across Nepal (Joshi et al., 2021a; Joshi et al., 2023). Based on the areas of the forests (1 ha pure stand of *E. camaldulensis* and 0.45 ha of the mixed-species stand), the number of plots was determined proportionally, resulting in 14 plots for the pure stand and 4 plots for the mixed stand to ensure adequate representation of each forest type for carbon stock assessment. Although the sampling was limited and may not have captured the full variability of private forests across the Terai region, the selected plots were representative of typical stand structures and species composition in the area. Circular plots were established for tree sampling with a radius of 8.92 m (area = 250 m²). Within each plot, the diameter at breast height over bark (DBH, ≥ 5 cm at 1.3 m height) and the total tree height of all individual trees were measured (Fig. 2).

Secondary data collection

Information regarding Rautahat District was obtained from the Division Forest Office (DFO), Rautahat, Nepal. Published journals and articles were used as references for the literature review. Data regarding species composition, topography and private forest locations were extracted from the DFO. Species identification was based on the records provided by the DFO and verified during field visits. Both scientific and local names were recorded and local names were cross-checked with standard botanical references, including Flora of Nepal (Press et al., 2000), to ensure accuracy. Data related to wood properties, such as specific gravity, were obtained from Sharma et al. (1990).

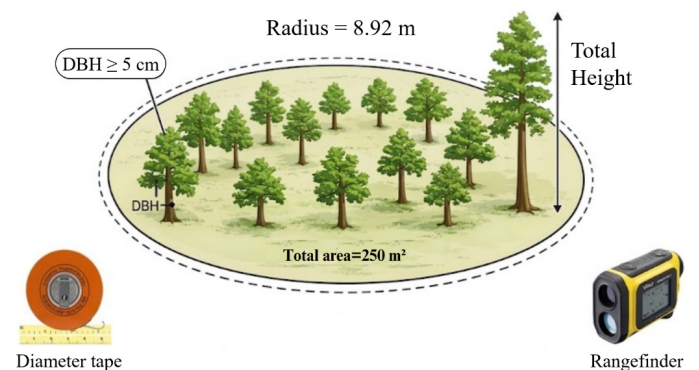


Fig. 2 Schematic diagram illustrating a circular plot used for estimating above-ground tree biomass, where all trees within the plot with a diameter at breast height over bark (DBH) ≥ 5 cm were measured and heighted (Pandey et al., 2014a and 2014b)

Data analysis

The above-ground tree biomass (AGTB) for each individual tree with DBH ≥ 5 cm was calculated using the allometric equation for tropical forests established by Chave et al. (2005), an approach consistently applied in previous studies in the Terai region of Nepal (Joshi et al., 2020; Singh et al., 2023) using Equation 1:

$$\text{AGTB} = 0.0509 \times \rho D^2 H \quad (1)$$

where, AGTB is the above-ground tree biomass (in kilograms), ρ is the wood-specific gravity (in grams per cubic meter), D is the diameter at breast height over bark (in centimeters) and H is the tree height (in meters). For each sampling plot, the biomass of all individual trees was summed and then divided by the plot area (250 m²) to determine the biomass stock density in kilograms per meter. This value was converted to tonnes per hectare by multiplying by 10. To estimate the carbon stock, the biomass stock density was multiplied by the default carbon fraction of 0.47, according to guidelines in Intergovernmental Panel on Climate Change (2006) and Eggleston et al. (2006), using Equation 2:

$$\text{Total above ground carbon} = \text{Total above ground tree biomass} \times 0.47 \quad (2)$$

The Chave et al. (2005) equation was chosen because it is used widely for tropical forests and is suitable for mixed-species and *E. camaldulensis*-dominated forests such as those in Rautahat District. While more region-specific models exist, often they are limited to particular species or forest types. The default carbon fraction of 0.47 represents the accepted average proportion of carbon in woody biomass of tropical forests (Intergovernmental Panel on Climate Change, 2006). Although the carbon content may vary among species, using this standardized fraction allows for consistent and comparable estimates of above-ground carbon, even for small-area studies.

Carbon dioxide Equivalence

The above-ground carbon stock was converted to carbon dioxide equivalents (CO₂-Eq) to quantify the climate mitigation potential of the forests in terms of atmospheric CO₂ removal. The conversion was based on the standardized stoichiometric ratio of 44:12, reflecting the molecular weight ratio of

CO₂ to carbon (Pearson et al., 2007; Eggleston et al., 2006), as shown in Equation 3:

$$\text{Carbon-dioxide equivalent} = \text{Carbon} \times 3.67 \quad (3)$$

Error estimation

Descriptive statistics, including means and standard deviations, were calculated for carbon stocks in each forest type. The standard error (SE) of the mean was computed as $SD/\sqrt{n}$ (where n is the sample size) to quantify the precision of the estimates.

Statistical analysis

To test the hypothesis that carbon stocks were higher in pure forest than in mixed forest, a one-tailed independent samples t test assuming unequal variances was applied. The null hypothesis stated that the mean carbon stock of pure forests was less than or equal to that of mixed forests ($H_0: \mu_{\text{pure}} \leq \mu_{\text{mixed}}$), whereas the alternative hypothesis ($H_1: \mu_{\text{pure}} > \mu_{\text{mixed}}$) stated that pure forests had a higher mean carbon stock than mixed forests. Statistical significance was assessed at $\alpha = 0.05$. All statistical analyses were performed using the R (a language and environment for statistical computing and graphics) software package (R Core Team, 2020).

Results

List of species in private forests with their purposes in Rautahat district

In the mixed private forest, a total of 10 species were recorded, while in the pure forest, only *E. camaldulensis* with various purposes was found (Table 1). The majority of species available in the mixed PF namely *Tectona grandis*, *Dalbergia sissoo*, *Shorea robusta* and *Dalbergia latifolia* were primarily planted for subsistence timber or onfarm use, while some species, such as *Bombax ceiba*, *E. camaldulensis* and *Albizia procera*, were introduced specifically for commercial timber production (i.e., grown for sale in the market).

Table 1 Species on private forests and their purpose in Rautahat District, Nepal

Species	Local Name	Purpose
<i>Shorea robusta</i> C.F.Gaertn.	Sal	Timber
<i>Dalbergia sissoo</i> Roxb. ex DC.	Sissoo	Timber and fuelwood
<i>Tectona grandis</i> L.f.	Teak	Timber and fuelwood
<i>Dalbergia latifolia</i> Roxb.	Satisal	Timber and fuelwood
<i>Mangifera indica</i> L.	Mango	Timber, fruit and fuelwood
<i>Bombax ceiba</i> L.	Simal	Matchstick
<i>Syzigium cumini</i> (L.) Skeels	Jamun	Timber, fruit and fuelwood
<i>Albizia procera</i> (Roxb.) Benth.	Seto siris	Ornamental
<i>Azadirachta indica</i> A.Juss.	Neem	Medicinal
<i>Artocarpus heterophyllus</i> Lam.	Katahar	Fruit and fuelwood
<i>Eucalyptus camaldulensis</i> Dehnh.	Masala	Furniture

Properties of forest stand

In total, 18 plots were established, comprising 4 in the mixed private forest, where DBH in varied widely, with a mean of 15.78 cm, a maximum of 33 cm and a minimum of 5.50 cm. The trees in this forest had a height range of 6–19 m, with a mean height of 10.43 m. The mixed private forest tree density was 560 trees/ha.

The pure private forest was made up of 14 sample plots, again presenting variety, with a mean DBH of 16.60 cm, a maximum of 31 cm and a minimum of 5.30 cm. The trees in this forest had a height range of 9–22 m, with a mean of 16.11 m. The pure private forest tree density was 695 trees/ha (Table 2).

Above ground biomass and carbon stock

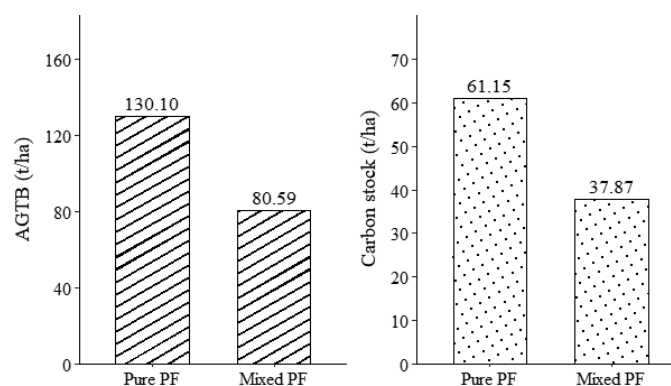
The total above-ground biomass and carbon stock in the trees within the study area were 130.10 t/ha and 61.15 t/ha, respectively, in the pure private forest and 80.59 t/ha and 37.87 t/ha respectively in the mixed private forest (Fig. 3). The number of seedlings was very low, making it difficult to measure accurately in the mixed private forest, while seedlings were completely absent in the pure private forest. Therefore, the biomass and carbon from seedlings were neglected.

Carbon stock distribution within tree species diameter classes

The DBH values of the tree species were categorized into six classes: 5.1–10.0 cm, 10.1–15.0 cm, 15.1–20.0 cm,

20.1–25.0 cm, 25.1–30.0 cm and above 30 cm. In the pure PF, the highest carbon reserve was in the DBH class 20.1–25.0 cm (23.67 t/ha), followed by DBH class 15.1–20.0 cm (18.17 t/ha), DBH class 10.1–15.0 cm (10.02 t/ha), DBH class 25.1–30.0 cm (7.06 t/ha) and DBH class 5.1–10.0 cm (1.20 t/ha), with the DBH class above 30 cm having the lowest carbon reserve (1.01 t/ha), as shown in Fig. 4.

Similarly, in the mixed PF, the highest carbon reserve was in DBH class 15.1–20.0 cm (10.49 t/ha) followed by the DBH class above 30 cm (10.08 t/ha), DBH class 25.1–30.0 cm (8.96 t/ha), DBH class 10.1–15.0 cm (4.00 t/ha), and DBH class 20.1–25.0 cm (3.30 t/ha), with DBH class 5.1–10.0 cm having the lowest carbon store ((1.06 t/ha), as shown in Fig. 4.

**Fig. 3** Total above-ground tree biomass (AGTB) and carbon stock in pure private forest (Pure PF) and mixed private forest (Mixed PF)**Table 2** Forest structure in mixed and pure private forest.

Private forest type	Number of plots	Trees						Stocking (trees/ha)
		Tree DBH (cm)			Tree height (m)			
		Min	Max	Mean	Min	Max	Mean	
Mixed	4	5.50	33.00	15.78	6.00	19.00	10.43	560
Pure	14	5.30	31.00	16.60	9.00	22.00	16.11	695

Min – minimum; Max = maximum.

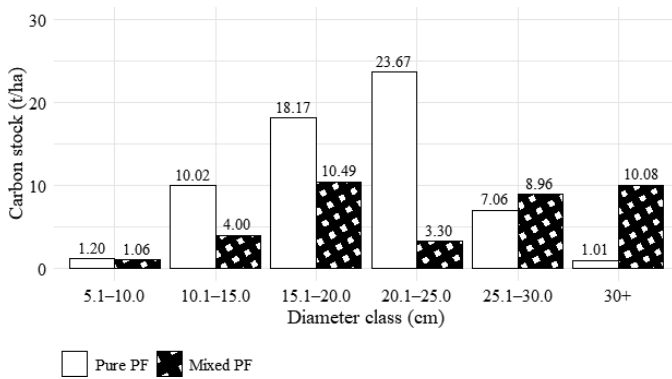


Fig. 4 Carbon stock in different diameter at breast height (DBH) classes in pure private forest (Pure PF) and mixed private forest (Mixed PF).

Carbon stock share within height classes of tree species

In the pure private forest, carbon reserves were distributed across four height classes, with the highest concentration in the 15.1–20.0 m class, accounting for 37.21 t/ha or 60.86% of the total carbon stock. The remaining carbon was distributed as 13.82 t/ha (22.60%) in the 20.1–25.0 m class, 7.81 t/ha (12.78%) in the 10.1–15.0 m class and 2.29 t/ha (3.76%) in the 5.1–10.0 m class.

In the mixed private forest, the highest carbon reserve was in the 10.1–15.0 m height class, which stored 20.35 t/ha, representing 53.73% of the total carbon. The 15.1–20.0 m class contained 9.40 t/ha (24.83%) and the 5.1–10.0 m class contained 8.11 t/ha (21.45%). No trees were present in the 20.1–25.0 m height class, resulting in a carbon stock of zero for this category (Fig. 5).

The results of the one-tailed t-test generated p values of 0.0348 for biomass and 0.0346 for carbon, both of which fall below the 0.05 significance threshold, indicating that the

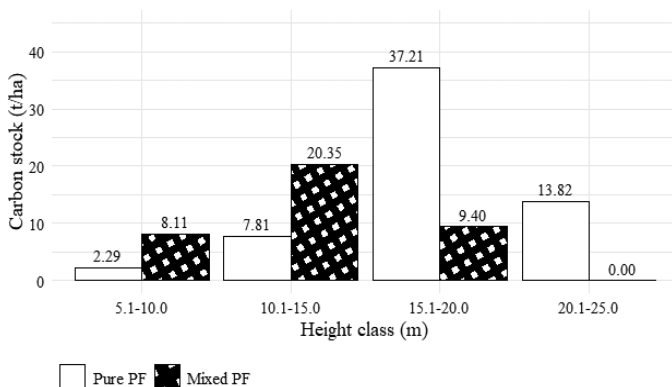


Fig. 5 Carbon stock in different tree height classes in pure private forest (Pure PF) and mixed private forest (Mixed PF).

aboveground tree biomass and carbon content in the pure private forest were significantly higher than in the mixed private forests of Rautahat (Fig. 6).

Carbon dioxide sequestration potential ($\text{CO}_2\text{-Eq}$)

The climate mitigation potential of the forests was quantified based on converting the average carbon stocks to $\text{CO}_2\text{-Eq}$, reflecting the actual amount of CO_2 sequestered from the atmosphere. The pure private forest had a significantly higher CO_2 sequestration capacity, storing an average of 224.42 t/ha $\text{CO}_2\text{-Eq}$. In contrast, the mixed private forest stored 138.98 t/ha $\text{CO}_2\text{-Eq}$. This conversion underscored the substantial role both forest types play in climate change mitigation, with the pure forest having a greater capacity for offsetting atmospheric carbon dioxide due to its higher biomass yield.

Comparison of aboveground biomass and carbon stock between mixed and pure private forest

Both aboveground biomass and carbon stock were higher in pure private forest than in mixed private forest (Table 3). Mean aboveground biomass was 130.25 ± 47.59 t/ha in pure private forest, compared with 80.59 ± 37.18 t/ha in mixed private forest. Similarly, mean carbon stock was 61.15 ± 22.35 t/ha in pure private forest and 37.87 ± 17.47 t/ha in mixed private forest. The one-tailed Welch's t-test indicated that these differences were statistically significant for both aboveground biomass ($t = -2.205$, $df = 6$, $p = 0.035$) and carbon stock ($t = -2.210$, $df = 6$, $p = 0.035$), indicating that pure private forest stored significantly greater biomass and carbon than mixed private forest.

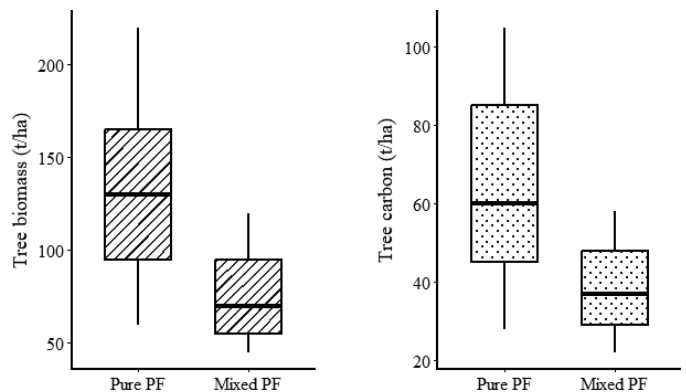


Fig. 6 Boxplots comparing aboveground tree biomass and carbon in pure private forest (Pure PF) and mixed private forest (Mixed PF).

Table 3 Comparison of aboveground biomass and carbon stock between mixed and pure private forests in Rautahat District, Nepal.

Variable	Mixed private forest Mean $\pm$ SD (t/ha)	Pure private forest Mean $\pm$ SD (t/ha)	t	df	p (one-tailed)
Aboveground biomass	80.59 $\pm$ 37.18	130.25 $\pm$ 47.59	2.205	6	0.035
Carbon stock	37.87 $\pm$ 17.47	61.15 $\pm$ 22.35	2.210	6	0.035

Note: Values are expressed as mean $\pm$ SD. Sample sizes were 4 plots for mixed private forest and 14 plots for pure private forest. Statistical comparisons were performed using a one-tailed independent samples t-test assuming unequal variances.

Discussion

The estimated mean carbon stock in the pure private forest was higher than in the mixed forest. This aligned with findings from community-managed Sal forests in the Far-Western Terai, which also showed significant carbon accumulation potential (Joshi et al., 2021b), though the values in the current study were lower, likely due to differences in stand age and management intensity. These results were consistent with Origenes et al. (2021), who reported higher carbon sequestration in pure eucalypt plantations due to their superior tree height and diameter, reflecting the inherent complexity and heterogeneity of forest structures in Nepal, a factor that has been documented across community forests (Joshi et al., 2019) and which significantly influences carbon dynamics (Joshi et al., 2020; Joshi et al., 2023). Similarly, Joshi et al. (2023) found that Terai trees with higher biomass sequestered 2.24 times more carbon than those in the hilly region, supporting the current findings and highlighting the potential of private forests for carbon storage. A study in Banepa Municipality also reported that trees outside forests contributed to significant carbon storage and community socioeconomic advancement (Thapa et al., 2021), indicating the important role of private forests. Oli and Shrestha (2005) emphasized that Nepalese forests contributed substantially to carbon storage through above- and below-ground biomass, litter and soil organic carbon. Furthermore, in the Congo Basin, variations in the above-ground biomass were due largely to fluctuations in the number of large-diameter trees (Djuikouo et al., 2010), which aligned with the current findings. Likewise, in Brazil, fast-growing species such as *Eucalyptus* spp. accumulated biomass more rapidly than slower-growing, mixed-species forests, resulting in higher carbon sequestration (Laclau et al., 2001; Paul et al., 2002).

While pure eucalypt forests have demonstrated higher carbon stocks, notably, there are potential ecological trade-offs associated with these plantations. Eucalypts are fast-growing and sequester carbon efficiently; however, they consume substantial amounts of water, which can affect local hydrology and agricultural activities (Baker et al., 2016).

Often, monoculture plantations support lower biodiversity compared to native or mixed-species forests (Joubert and Dreyer, 2020) and eucalypt leaf litter may alter soil nutrient cycling, potentially reducing long-term soil fertility (Malan et al., 2018). Furthermore, careful consideration is required of the impact of management practices, such as the thinning operations reviewed by Joshi et al. (2023), on long-term carbon stability and ecological balance in monoculture plantations such as those in the current study. Therefore, despite their carbon sequestration benefits, these ecological impacts should be considered in forest management and carbon-focused initiatives, such as REDD+, emphasizing the need for balanced and sustainable plantation planning. In addition, mixed private forests play a crucial role in atmospheric carbon sequestration. Carbon storage in these forests is influenced by species diversity, growth patterns, management strategies and species-specific variations in carbon accumulation rates (Elias et al., 2003). Despite the potential for carbon absorption in both forest types, often, natural forests produce lower amounts of above-ground biomass than plantations due to differences in silvicultural practices (Baishya et al., 2009). In the current study, the reduced carbon stock in the mixed private forest may similarly reflect management effects, such as pruning, thinning, or differences in planting density.

For policymakers considering the integration of private forests into carbon programs, the biological advantages of eucalypts are highly relevant as their rapid growth rate and short rotation cycles enable quicker carbon payback periods, while their drought tolerance and adaptability reduce plantation failure risks, increasing project reliability (Booth, 2013; Puri and Swamy, 2016). Their generally strong coppicing capability is particularly relevant, as it lowers long-term replanting costs for landowners and contributes to carbon stock permanence—a key requirement for carbon markets—by ensuring continuous forest cover after harvest (Laclau et al., 2010). Recognizing these operational advantages is essential for designing feasible incentive mechanisms that can attract private forest owners.

A key limitation of the current study was the small number of plots sampled, which may not have captured fully the ecological variability within pure and mixed private forests.

Factors, such as soil conditions, microclimate, stand age, management practices and planting density, can all influence biomass accumulation and may contribute to observed differences (Baul et al., 2021; Subedi et al., 2022), as seen in studies of soil organic carbon in national parks (Joshi and Bhatta, 2023) and agroforestry systems (Joshi et al., 2024). While modelling tree height and DBH can explain some of the higher carbon stocks in pure forests, additional factors could also play a role, including older stand age, intensive management and planting density. Therefore, the current results should be interpreted with caution and future studies are recommended using larger and more diverse datasets to better understand the drivers of carbon sequestration in private forests. Aryal et al. (2013) reported higher carbon stocks in pine-dominated forests compared to mixed stands in Lalitpur District, Nepal, while Gurung et al. (2023) highlighted the influence of species composition and soil properties on carbon storage in mixed forests of Chandragiri Hills, Nepal. Furthermore, Subedi et al. (2022) and Baul et al. (2021) demonstrated that management practices and species selection significantly affected carbon storage in private forests. Collectively, these findings emphasize the critical roles of species composition, growth characteristics, silvicultural management and ecological variability in determining carbon sequestration potential in private forests.

While the integration of private forests into REDD+ and carbon trading schemes in Nepal faces challenges, such as monitoring costs and ensuring permanence, these are not insurmountable. From a policy perspective, the findings from the current study and others underscore the need to formally recognize and integrate private forests into Nepal's national carbon accounting and REDD+ frameworks. This could be achieved by building upon the institutional lessons learned from community forestry (Joshi et al., 2021a) and by designing incentive mechanisms that are accessible to smallholders, similar to those explored in agroforestry systems (Bhandari et al., 2021; Joshi et al., 2024). Strengthening local institutions, providing technical support and implementing equitable benefit-sharing mechanisms will be critical for improving the feasibility and acceptance of such programs at the private forest level. Often, monitoring, reporting and verification is costly and technically demanding, particularly for small-scale, scattered private forests, which increases the transaction costs relative to the carbon revenue (Shrestha et al., 2014). The permanence of carbon storage is another concern, as private landowners may change land use or management practices in response to short-term economic incentives,

creating risks of carbon reversal (Karky et al., 2012). Similarly, leakage may occur if forest protection in one area drives deforestation or resource extraction elsewhere, undermining net climate benefits (Pandit et al., 2017). Luintel et al. (2013) emphasized that strengthening local institutions, providing technical support and implementing equitable benefit-sharing mechanisms are critical for improving the feasibility and acceptance of REDD+ at the community and private forest level. Therefore, policy frameworks must not only provide financial incentives but also ensure transparent governance and integration of carbon initiatives with livelihood priorities to make participation of private forests in carbon markets sustainable and socially equitable.

Several limitations should be noted. The study's small sample size and restriction to a single district may not have captured fully the ecological variability across private forests in Nepal. Factors, such as stand age, management practices, planting density and local site conditions likely influence carbon stocks and should be addressed in future research. Expanding studies to multiple districts, incorporating below-ground biomass and conducting species-specific carbon assessments would strengthen understanding of private forest carbon dynamics and inform more targeted management strategies.

From a policy perspective, the findings underscore the need to formally recognize and integrate private forests into Nepal's national carbon accounting and REDD+ frameworks. Incentive mechanisms, such as carbon credit payments, low-interest loans, or technical subsidies, should be designed to encourage private landowners to adopt sustainable management practices that balance productivity and biodiversity. *E. camaldulensis*-dominated forests demonstrate strong potential for rapid carbon gains; however, forest policy should promote mixed or multi-species models to mitigate ecological trade-offs and ensure long-term sustainability. Strengthening carbon accounting and monitoring methodology, It will be essential to simplify participation procedures for smallholders and to establish transparent benefit-sharing mechanisms to mobilize private forest contributions toward Nepal's climate mitigation targets and inclusive green growth agenda.

Conclusion

This study demonstrated that pure private forests in Nepal's Terai region sequestered significantly more carbon than mixed-species private forests, with mean $\pm$ SD above-ground carbon

stocks of 61.15 ± 0.78 t/ha and 37.87 ± 2.23 t/ha, respectively. One-tailed t tests confirmed that these differences were significant statistically, highlighting the influence of species composition, tree height and diameter on carbon accumulation. However, both forest types demonstrated substantial carbon storage potential, underscoring the important role of private forests in climate mitigation.

Conflict of Interest

The authors declare no conflicts of interest.

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