

Vertical biomass boundaries: Effects of stump exclusion on aboveground biomass comparability and implications for forest-carbon accounting in Nepal

Santosh Ayer

University of Alberta Department of Renewable Resources <https://orcid.org/0000-0002-3861-4433>

Shiva Khanal

Forest Research and Training Centre, Nepal

Kishor Prasad Bhatta

kishorprasad@uni-goettingen.de

University of Göttingen

Research Article

Keywords: Allometric model, biomass comparability, destructive sampling, forest carbon accounting, pantropical allometry, stump biomass

Posted Date: September 15th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11028012/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: The authors declare no competing interests.

Abstract

Recent national allometric equations developed by Nepal's Forest Research and Training Centre (FRTC) were calibrated using aboveground biomass (AGB) measured above a 30-cm stump, thereby excluding stump biomass from the modelled boundary. However, the magnitude and size dependence of this excluded biomass and its implications for comparability with other AGB approaches have not been quantified. We analysed destructive biomass data for 476 trees representing seven commercially important species. Measured stump biomass was added to reported stump-excluded biomass to reconstruct ground-level AGB, and variation with tree size and species was evaluated using rank correlations and generalized additive models (GAMs). For 328 trees representing five species, pantropical Chave-predicted AGB was calculated using DBH, height, and FRTC-reported wood density, and agreement was compared before and after stump restoration while Chave predictions remained unchanged. Stump biomass averaged 3.61% of ground-level AGB (median 3.09%; range 1.34–11.5%) and declined strongly with DBH both overall (Spearman's $\rho = -0.766$) and within individual species ($\rho = -0.667$ to -0.850 , all Holm-adjusted $p < 0.001$). Species-specific nonlinear relationships explained approximately 75% of deviance, with species means ranging from 3.14% to 4.39%. Boundary harmonization reduced the mean Chave–measured difference by 3.7–5.6 percentage points across species. Across all 328 trees, the mean difference decreased from 20.1% to 15.7%, RMSD decreased from 581.0 to 536.0 kg tree⁻¹ (7.74%; 95% bootstrap CI for the reduction: 36.3–53.8 kg tree⁻¹), and the concordance correlation coefficient increased from 0.963 to 0.969. Although the improvement in agreement was modest, it consistently isolated the effect of biomass-boundary definition from the remaining disagreement, which may reflect differences in model structure, calibration, parameterization, and predictor uncertainty. Biomass boundaries should therefore be explicitly defined and harmonized before national and pantropical estimates are compared or integrated. Further evaluation using representative forest-inventory data is needed to determine whether these modest tree-level differences materially affect stand- and national-scale forest-carbon estimates in Nepal.

1. Introduction

Aboveground biomass (AGB) estimation underpins assessments of forest carbon stocks, carbon dynamics, and responses to forest management and land-use change. Because direct biomass measurement requires destructive harvesting, forest inventories generally rely on allometric equations that convert measurable tree attributes into biomass. This dependence on models introduces substantial uncertainty. Previous studies have identified tree-measurement error, sampling, model selection, tree height, wood density, and extrapolation beyond calibration domains as important sources of variation in AGB estimates (Chave et al., 2004; Molto et al., 2013; Picard et al., 2015). In particular, model choice can represent a major component of biomass-estimation uncertainty (Chave et al., 2004; Picard et al., 2015), while uncertainty and bias associated with height and wood-density information can propagate through tree- and stand-level estimates (Molto et al., 2013; Réjou-Méchain et al., 2017). These concerns have motivated the development of improved pantropical models incorporating diameter at breast height (DBH), height, and wood density (Chave et al., 2014), as well as locally or nationally

calibrated equations intended to better represent regional species composition and tree architecture (Chave et al., 2004).

Despite extensive attention to how AGB is estimated, less attention has been given to whether estimates being compared represent the same biomass quantity. Destructive biomass studies partition trees into components such as the stump, stem, branches, and foliage, and allometric equations consequently depend on which components are included in the response variable (Návar, 2009; Picard et al., 2012). Forest-carbon definitions commonly consider the stump part of aboveground biomass, together with stems, branches, bark, seeds, and foliage (Ashton et al., 2012). Importantly, stump treatment is not merely definitional: Romero et al. (2022) explicitly included stump biomass in total AGB for large Amazonian trees and quantified stumps from the ground to a 30-cm cutting height, demonstrating that this basal component can be separately identified and incorporated into biomass and carbon accounting. Thus, differences among AGB estimates may arise not only from model form, predictors, and parameter uncertainty, but also from differences in the physical biomass domain represented. If one approach includes biomass from ground level while another excludes a basal stem section, estimates carrying the same label of AGB are not strictly equivalent. This issue is distinct from conventional allometric uncertainty, which can propagate from individual-tree estimates to landscape-scale biomass estimates (Vorster et al., 2020). Yet, despite recognition of stump biomass as an AGB component, the consequences of vertical biomass-boundary mismatch itself have rarely been isolated and quantified as a source of disagreement among AGB estimation approaches.

This distinction becomes particularly important when biomass estimates developed under different measurements and modelling frameworks are compared, combined, or scaled for forest-carbon assessment. Forest inventories have historically used operational quantities such as growing stock and merchantable stem volume, whose definitions may depend on stump height, minimum diameter, and other measurement thresholds, whereas carbon accounting requires estimates representing explicitly defined biomass pools (FAO, 2002). Differences in these definitions are not merely terminological: variation in stump height, measurement points, minimum diameters, and included tree components can produce legitimate differences among biomass estimates and conversion factors even when they are applied to the same forest resource (FAO, 2002). This problem has been demonstrated at larger scales in European national forest inventories, where biomass statistics were not directly comparable because countries differed in the tree components included in their biomass pools; subsequent harmonization adopted a common AGB definition that explicitly included the aboveground portion of the stump (Gschwantner et al., 2022). Similar inconsistencies occur among allometric systems: Vorster et al. (2020) found that component definitions differed among equation sets and explicitly adjusted stump biomass before comparing tree-, plot-, and landscape-scale estimates. Thus, an equation based on an above-stump response is not inherently erroneous; rather, it estimates the biomass domain for which it was developed. The problem arises when predictions based on different lower boundaries are treated as equivalent AGB without harmonization. Because differences introduced at the individual-tree level can propagate during aggregation, consistency in biomass definition is relevant not only to model

comparison but also to stand- and landscape-scale biomass estimation and ultimately to forest-carbon assessment and reporting (Vorster et al., 2020).

Nepal provides a particularly relevant setting in which to examine this issue because allometric equations underpin national forest inventory and increasingly support forest-carbon monitoring and reporting. Historically, biomass estimation in Nepal has relied heavily on the equations of Sharma and Pukkala (1990), including their application in the Forest Resource Assessment and forest reference-level framework, while limitations of these older models have motivated development of updated, country-representative equations for major tree species (FRTC, 2025). The Forest Research and Training Centre subsequently developed tree-volume and biomass equations within the same national allometric framework, with AGB defined above a 30-cm stump. This boundary is operationally compatible with the associated volume-estimation framework, but its retention in biomass estimation excludes the basal 0–30 cm portion that would otherwise contribute to ground-level AGB. The magnitude of this excluded component has not been explicitly evaluated, and it remains unknown whether it represents a negligible and approximately constant fraction of AGB or varies systematically with tree size and species. This distinction is particularly relevant because Nepal is strengthening country-specific allometry to improve its national forest monitoring system, forest reference level, and measurement, reporting and verification (MRV) for REDD + and carbon-finance applications (FRTC, 2025). A size- or species-dependent boundary effect could influence comparisons with allometric approaches representing AGB from ground level and cannot necessarily be addressed using a single correction factor. Quantifying this effect is therefore necessary to separate disagreement arising from the definition of the biomass domain from disagreement attributable to the allometric models themselves. More broadly, resolving such boundary inconsistencies is important because tree-level biomass estimates are ultimately aggregated for forest inventories and carbon assessment, allowing systematic definitional differences to propagate across larger spatial scales.

Accordingly, this study used destructive biomass data underlying the FRTC allometric framework to quantify the consequences of the 30-cm lower biomass boundary. Specifically, we aimed to (i) quantify the absolute and proportional contribution of the excluded stump to ground-level AGB, (ii) determine whether proportional stump contribution varies with DBH and among species, and (iii) evaluate how restoring measured stump biomass and thereby harmonizing the biomass boundary alters apparent agreement between destructively measured AGB and AGB predicted using the pantropical equation of Chave et al. (2014). We hypothesized that the excluded stump would constitute a non-negligible proportion of ground-level AGB, that its proportional contribution would decline with increasing tree size and vary among species, and that harmonization to a common ground-level boundary would reduce the apparent difference between Chave-predicted and measured AGB. The Chave comparison was therefore intended as an external comparability assessment, rather than as a validation of either allometric framework.

2. Materials and methods

2.1 Data source and description

This study used tree-level destructive-sampling data generated by Nepal's Forest Research and Training Centre (FRTC) for the development of country-specific allometric equations for seven major tree species (FRTC, 2025). The dataset comprised 476 trees representing *Alnus nepalensis* D. Don, *Castanopsis* spp., *Lagerstroemia parviflora* Roxb., *Pinus roxburghii* Sarg., *Schima wallichii* (DC.) Korth., *Shorea robusta* Gaertn. f., and *Terminalia alata* Heyne ex Roth. Sample trees were selected across diameter classes and destructively sampled following the standardized FRTC field and laboratory protocol. Available tree-level records included species identity, DBH, total tree height, total aboveground biomass (excluding stump), and separately determined stump biomass. In the original sampling, stems, branches, foliage, and other aboveground components were measured separately, with sample-disc volume determined using the xylometric water-displacement method and component-specific measurements used to derive dry biomass (FRTC, 2025). Species-specific sample sizes and ranges of tree dimensions and biomass are provided in Table S1.

Of particular relevance to this study, trees were felled leaving a 30-cm stump, which was measured separately from the above-stump biomass used in development of the FRTC total-biomass equations (FRTC, 2025). Thus, the reported stump-excluded biomass and measured stump biomass represented complementary components of each destructively sampled tree. This allowed ground-level AGB to be reconstructed by adding measured stump biomass to the reported stump-excluded biomass and enabled direct quantification of the effect of changing the lower biomass boundary from 0.30 m to ground level.

For comparison with the Chave et al. (2014) pantropical equation, the analysis was restricted to 328 trees representing five species for which FRTC-recommended wood-density information applicable to total-biomass estimation was available. Tree-level wood-density measurements were not provided in the released dataset; therefore, FRTC-recommended values were assigned following the original report (FRTC, 2025). Species-level values were used for *A. nepalensis*, *L. parviflora*, and *S. wallichii*, whereas DBH-class-specific values were used for *S. robusta* and *T. alata*. *Castanopsis* spp. and *P. roxburghii* were excluded only from the Chave comparison because corresponding recommended total-biomass density values were unavailable; all seven taxa remained in the primary stump-boundary analyses. The wood-density values used in the Chave comparison are provided in Table S2.

2.2 Biomass-boundary reconstruction

The FRTC destructive biomass data distinguish the 30-cm stump from the remaining aboveground tree biomass. To quantify the biomass associated with this boundary, two measured AGB definitions were established for each tree: stump-excluded AGB, representing biomass above the 30-cm stump, and ground-level AGB, reconstructed by restoring the corresponding measured stump biomass. Thus, the reconstruction changed only the lower boundary of measured AGB while retaining the destructively

measured biomass components for each individual tree. Ground-level AGB for tree was calculated using Eq. (1).

$$AGB_{ground, i} = AGB_{excl, i} + B_{stump, i} \dots\dots \text{Eq. (1)}$$

where $AGB_{ground, i}$ is reconstructed ground-level AGB, $AGB_{excl, i}$ is measured AGB excluding the 30-cm stump, and $B_{stump, i}$ is measured stump biomass, all expressed in kg tree^{-1} .

The proportional contribution of the stump to ground-level AGB was then calculated for each tree using Eq. (2).

$$S_i = \frac{B_{stump, i}}{AGB_{ground, i}} \times 100 \dots\dots \text{Eq. (2)}$$

where S_i represents the percentage of ground-level AGB contained in the 30-cm stump. This tree-specific reconstruction was used throughout the analysis rather than applying a constant correction factor, allowing variation in the excluded biomass component among tree sizes and species to be quantified directly.

2.3 Size and species dependence of stump contribution

The relationship between tree size and proportional stump contribution (S_i ; Eq. 2) was evaluated using both rank-based correlation and generalized additive modelling. DBH was used as the measure of tree size. Spearman's rank correlation was first calculated across all 476 trees and then separately for each of the seven species. To account for multiple testing, p -values from the seven species-specific correlations were adjusted using the Holm procedure.

Generalized additive models extend generalized linear models by representing predictor effects through smooth functions, allowing nonlinear relationships to be estimated without specifying their functional form a priori. GAMs were therefore used to characterize the DBH–stump contribution relationship and to determine whether its form differed among species. Because proportional stump contribution was continuous and strictly positive, models were fitted using a Gamma error distribution with a log link. For tree i , the model was specified as Eq. (3) and the expected response was related to the additive predictor through Eq. (4).

$$S_i \mid X_i \sim \text{Gamma}(\mu_i, \phi), \quad E(S_i \mid X_i) = \mu_i, \quad \text{Var}(S_i \mid X_i) = \phi \mu_i^2 \dots\dots \text{Eq. (3)}$$

$$\log(\mu_i) = \eta_i \dots\dots\dots \text{Eq. (4)}$$

Where S_i is proportional stump contribution (%), μ_i is its expected value, ϕ is the Gamma dispersion parameter, X_i denotes the predictor information for tree i , and η_i is the additive predictor. Smooth functions of DBH were estimated using penalized regression splines, with a basis dimension of $k = 10$.

Three candidate GAM formulations were evaluated to determine whether proportional stump contribution followed a common relationship with DBH or whether this relationship differed among species. Model M1 included a single smooth function of DBH and therefore assumed a common size-dependent relationship across all species (Eq. 5). Model M2 added species as a parametric effect, allowing the expected level of stump contribution to differ among species while retaining a common DBH smooth (Eq. 6). Model M3 included species as a parametric effect together with species-specific DBH smooths, allowing both the level and shape of the DBH–stump contribution relationship to vary among species (Eq. 7).

$$M1 : \log(\mu_i) = \beta_0 + f(DBH_i) \dots\dots\dots \text{Eq. (5)}$$

$$M2 : \log(\mu_i) = \beta_0 + \beta_{s(i)} + f(DBH_i) \dots\dots\dots \text{Eq. (6)}$$

$$M3 : \log(\mu_i) = \beta_0 + \beta_{s(i)} + f_{s(i)}(DBH_i) \dots\dots\dots \text{Eq. (7)}$$

where β_0 is the intercept, $\beta_{s(i)}$ denotes the parametric effect associated with the species of tree i , $f(DBH_i)$ is a common smooth function of DBH, and $f_{s(i)}(DBH_i)$ is a species-specific smooth function of DBH.

Candidate models were compared using Akaike's information criterion (AIC), adjusted R^2 , and percentage deviance explained. Relative support among candidate models was assessed using the difference between each model's AIC and the minimum AIC (Eq. 8)

$$\Delta AIC_j = AIC_j - \min_m(AIC_m) \dots\dots\dots \text{Eq. (8)}$$

where AIC_j is the AIC of candidate model j , $\min_m(AIC_m)$ and is the lowest AIC among the candidate models. The model with the lowest AIC was retained for describing the DBH–stump contribution relationship, while adjusted R^2 and deviance explained were reported as complementary measures of model fit. As an additional robustness check, predictive performance of the three candidate GAMs was evaluated using five-fold cross-validation stratified by species. RMSE and mean absolute error (MAE) were calculated from held-out predictions across all folds. Estimated degrees of freedom (edf) were used to characterize the degree of nonlinearity of the fitted smooths. Model adequacy was assessed using residual diagnostics and basis-dimension checks, including the k-index.

2.4 Chave-predicted aboveground biomass

To assess whether harmonization of the measured biomass boundary altered comparability with an established pantropical approach, AGB was independently predicted for each tree using the Chave et al. (2014) pantropical equation. This analysis was restricted to 328 trees representing five species for which the wood-density information required by the equation could be assigned. Because tree-level wood-density measurements were not available in the FRTC dataset, species-level wood-density values reported by FRTC were assigned to the corresponding trees. For tree i , Chave-predicted AGB was calculated using Eq. (9).

$$AGB_{Chave,i} = 0.0673 \left(\rho_i D_i^2 H_i \right)^{0.976} \dots\dots\dots \text{Eq. (9)}$$

Where $AGB_{Chave,i}$ is predicted aboveground biomass (kg tree^{-1}), ρ_i is species-level wood density (g cm^{-3}), is DBH (cm), and H_i is total tree height (m).

For each of the 328 trees, the same Chave-predicted AGB was subsequently compared with two destructively measured AGB references: the original stump-excluded AGB and the reconstructed ground-level AGB defined in Eq. (1). Thus, Chave-predicted AGB, DBH, height, and assigned wood density remained unchanged between comparisons; only the lower boundary of the measured reference biomass differed. This design was used specifically to quantify how restoration of measured stump biomass altered the Chave–measured AGB difference, rather than to provide an independent validation or direct performance comparison between the FRTC and Chave equations.

2.5 Quantification of the biomass-boundary harmonization effect

The effect of biomass-boundary harmonization was quantified by comparing Chave-predicted AGB with destructively measured AGB under the two biomass definitions established in Section 2.2. For each tree, the relative Chave–measured AGB difference was first calculated using the original stump-excluded biomass boundary (Eq. 10). The corresponding difference after harmonizing the measured biomass boundary to ground level was calculated as Eq. (11).

$$D_{excl,i} = \frac{AGB_{Chave,i} - AGB_{excl,i}}{AGB_{excl,i}} \times 100 \dots\dots\dots \text{Eq. (10)}$$

$$D_{ground,i} = \frac{AGB_{Chave,i} - AGB_{ground,i}}{AGB_{ground,i}} \times 100 \dots\dots\dots \text{Eq. (11)}$$

where $D_{excl,i}$ and $D_{ground,i}$ are the relative Chave–measured AGB differences (%) under the stump-excluded and ground-level boundaries, respectively. Positive values indicate that Chave-predicted AGB exceeded the corresponding destructively measured AGB.

The tree-level effect of biomass-boundary harmonization was expressed as the reduction in the Chave–measured AGB difference between the two boundaries (Eq. 12). To determine whether the magnitude of the boundary-harmonization effect varied with tree size, the association between R_i and DBH was evaluated using Spearman’s rank correlation across all 328 trees and separately for each of the five species. Holm adjustment was applied to the five species-specific p -values to account for multiple testing.

$$R_i = D_{excl,i} - D_{ground,i} \dots\dots\dots \text{Eq. (12)}$$

where R_i is the reduction in the Chave–measured AGB difference, expressed in percentage points. A positive R_i indicates that restoring measured stump biomass reduced the difference between Chave-

predicted and measured AGB. The differences under both biomass boundaries and the resulting reductions were summarized across all 328 trees and separately by species.

2.6 Assessment of agreement

Agreement between Chave-predicted and destructively measured AGB was evaluated under both the stump-excluded and reconstructed ground-level biomass boundaries. Two complementary measures were used: root mean square deviation (RMSD) (Eq. 13) and Lin's concordance correlation coefficient (CCC). RMSD quantified the magnitude of the difference between Chave-predicted and measured AGB in the original biomass units (kg tree⁻¹), whereas CCC quantified concordance by accounting for both precision and deviation from the line of perfect agreement. To reduce dependence on biomass scale, RMSD was also expressed relative to the mean measured AGB under each biomass definition. RMSD and CCC were calculated separately using stump-excluded AGB and reconstructed ground-level AGB as the measured reference. The proportional reduction in RMSD following restoration of measured stump biomass was also calculated (Eq. 14). CCC values were reported with 95% confidence intervals. Uncertainty in the change in RMSD following biomass-boundary harmonization was evaluated using a non-parametric paired bootstrap with 5,000 replicates. Trees were resampled with replacement while retaining the stump-excluded and ground-level comparisons for each tree as paired observations, and the 95% confidence interval was obtained from the 2.5th and 97.5th percentiles of the bootstrap distribution.

$$RMSD = \sqrt{\frac{1}{n} \sum_{i=1}^n (AGB_{Chave,i} - AGB_{measured,i})^2} \dots\dots\dots \text{Eq. (13)}$$

$$\Delta RMSD (\%) = \frac{RMSD_{excl} - RMSD_{ground}}{RMSD_{excl}} \times 100 \dots\dots\dots \text{Eq. (14)}$$

where $AGB_{measured,i}$ denotes measured AGB under the respective biomass boundary, and $RMSD_{excl}$ and $RMSD_{ground}$ denote RMSD under the stump-excluded and reconstructed ground-level boundaries, respectively.

3. Results

3.1 Contribution of stump biomass to ground-level AGB

The 30-cm stump constituted a modest but non-negligible component of ground-level AGB across the 476 destructively sampled trees representing seven commercially important species (Table 1). Stump contribution averaged 3.61% of ground-level AGB, but varied considerably among individual trees, ranging from 1.34% to 11.5%. When biomass was pooled across all sampled trees, the stump accounted for 2.57% of ground-level AGB.

Species-level differences were also evident (Table 1). Mean proportional stump contribution was highest in *Schima wallichii* and *Lagerstroemia parviflora* and lowest in *Shorea robusta*. Despite these differences,

stump biomass represented a measurable component of ground-level AGB across all seven species, with substantial variation among individual trees.

Table 1

Tree characteristics, stump biomass, and proportional stump contribution to ground-level AGB for 476 destructively sampled trees representing seven commercially important tree species in Nepal. Values are presented as mean $\pm$ SD.

Species	n	DBH (cm)	Height (m)	Stump biomass (kg)	Stump contribution (%)
<i>A. nepalensis</i>	52	36.0 $\pm$ 18.5	22.5 $\pm$ 7.7	22.7 $\pm$ 21.9	3.46 $\pm$ 1.29
<i>Castanopsis spp.</i>	52	32.0 $\pm$ 16.9	16.3 $\pm$ 5.5	20.0 $\pm$ 21.0	3.34 $\pm$ 1.20
<i>L. parviflora</i>	46	26.2 $\pm$ 13.9	17.9 $\pm$ 6.6	17.6 $\pm$ 19.3	4.35 $\pm$ 1.65
<i>P. roxburghii</i>	96	36.8 $\pm$ 18.5	19.0 $\pm$ 7.7	26.0 $\pm$ 25.7	3.68 $\pm$ 1.94
<i>S. wallichii</i>	47	31.4 $\pm$ 15.4	18.4 $\pm$ 6.8	19.6 $\pm$ 17.5	4.39 $\pm$ 1.85
<i>S. robusta</i>	122	45.4 $\pm$ 22.4	24.5 $\pm$ 7.7	55.4 $\pm$ 56.1	3.14 $\pm$ 1.33
<i>T. alata</i>	61	40.7 $\pm$ 23.0	23.5 $\pm$ 8.3	48.4 $\pm$ 51.1	3.65 $\pm$ 1.89
Overall	476	37.3 $\pm$ 20.2	20.9 $\pm$ 7.9	33.9 $\pm$ 40.8	3.61 $\pm$ 1.66

3.2 Size and species dependence of stump contribution

Proportional stump contribution showed a strong size-dependent pattern, declining with increasing DBH across all 476 trees (Spearman's $\rho = -0.766$, $p < 0.001$; Table S5). This negative relationship was consistent across all seven species ($\rho = -0.667$ to -0.850 ; Holm-adjusted $p < 0.001$), although the shape and magnitude of the decline differed among species (Fig. 2; Table S5). In general, stump biomass represented a larger proportion of ground-level AGB in smaller trees and became progressively less important as tree size increased.

The species-specific GAM provided the strongest support for these size-dependent patterns, with the lowest AIC (1059.76) and 75.1% deviance explained (adjusted $R^2 = 0.743$; Table S3). Five-fold stratified cross-validation yielded RMSE values of 0.935, 0.905, and 0.889 for Model M1, Model M2, and Model M3, respectively. MAE values were 0.671, 0.643, and 0.649, respectively, indicating that M3 retained the lowest RMSE, although predictive differences between M2 and M3 were small. All species-specific DBH smooths were significant ($p < 0.001$) and nonlinear (edf = 3.01–5.02; Table S4). Model diagnostics indicated adequate basis dimensions (k-index = 1.03; $p = 0.75$ – 0.81 ; Table S4; Figure S1).

3.3 Effect of biomass-boundary harmonization

The analysis of Chave-measured AGB differences was based on 328 trees representing five species. Restoring measured stump biomass reduced the Chave-measured AGB difference across all five species (Table 2; Fig. 3). Across the 328 trees, the mean difference decreased from 20.1% to 15.7%, corresponding to a reduction of 4.39 percentage points. Species-level reductions ranged from 3.74 to 5.56 percentage points, with the largest reduction observed for *L. parviflora* and the smallest for *S. robusta* (Fig. 3). The reduction in Chave-measured AGB difference was greater for smaller trees and declined with increasing DBH (Spearman’s $\rho = -0.679, p < 0.001$; Figure S2), This pattern was consistent within all five species (Table S6).

Table 2

Mean difference between Chave-predicted and destructively measured AGB under the stump-excluded and harmonized ground-level biomass boundaries for 328 trees representing five species. Reduction represents the decrease in the Chave-measured AGB difference following restoration of measured stump biomass and is expressed in percentage points.

Species	n	Chave measured difference stump excluded (%)	Chave measured difference ground-level AGB (%)	Reduction (percentage points)
<i>A. nepalensis</i>	52	22.7	18.5	4.2
<i>L. parviflora</i>	46	25.3	19.8	5.56
<i>S. wallichii</i>	47	20.4	15.1	5.34
<i>S. robusta</i>	122	17.7	14	3.74
<i>T. alata</i>	61	18.2	14	4.24
Overall	328	20.1	15.7	4.39

Agreement between Chave-predicted and measured AGB also improved after restoration of measured stump biomass. RMSD decreased from 581.0 to 536.0 kg tree⁻¹, representing a 7.74% reduction (45.0 kg tree⁻¹; 95% bootstrap CI: 36.3–53.8 kg tree⁻¹). Relative RMSD decreased from 40.19% to 36.11%, while CCC increased from 0.963 (95% CI: 0.956–0.968) to 0.969 (95% CI: 0.963–0.974). Species-specific RMSD also decreased after boundary harmonization for all five species, with proportional reductions ranging from 6.2% to 12.0% (Table S7). Species-specific CCC likewise increased under the harmonized boundary for all five species, with increases ranging from 0.005 to 0.011.

4. Discussion

4.1 Stump exclusion creates a distinct aboveground biomass boundary

We found that excluding the 30-cm stump produced a modest but systematic difference between stump-excluded and ground-level AGB, with the stump accounting for approximately 3.6% of ground-level biomass for an average tree. We interpret this finding as more than evidence that the stump contains measurable biomass; it demonstrates that the lower measurement boundary partly determines the biomass quantity represented as AGB. This interpretation is consistent with international forest-reporting definitions, which define aboveground biomass as living biomass above the soil and explicitly include the stump (FAO, 2018). Destructive biomass studies likewise partition trees into components according to the response being modelled (Návar, 2009; Picard et al., 2012). Particularly relevant to our study, Romero et al. (2022) used a 30-cm cutting height for large Amazonian trees but separately estimated the biomass between ground level and the cut and incorporated it into total AGB. We therefore suggest that the cutting height itself is not the principal comparability issue; rather, it is whether biomass below that height is included when the final AGB response is defined.

We consider this boundary effect conceptually distinct from conventional allometric uncertainty. Measurement error, model selection, predictor uncertainty, and equation structure affect estimation of a defined biomass quantity (Chave et al., 2004; Picard et al., 2015; Vorster et al., 2020), whereas the boundary difference examined here changes the quantity being represented before these sources of uncertainty are considered. The importance of consistent biomass definitions has also been demonstrated beyond individual-tree studies. Harmonization of National Forest Inventory data across 26 European countries required adoption of a common AGB definition explicitly including the aboveground stump and other tree components; harmonized biomass estimates differed significantly from national estimates in 14 countries and were approximately 3.8% higher at the European scale (Avitabile & Camia, 2018). More recent European harmonization work similarly reports that national biomass definitions often omit components such as foliage or the aboveground stump, with harmonized and national biomass totals differing by approximately 4% across 26 countries (Avitabile et al., 2024). Our results provide a tree-level example of the same general problem. We therefore do not interpret the stump-excluded FRTC definition as erroneous; rather, the comparability issue arises when estimates representing biomass above 30 cm are treated as equivalent to ground-level AGB. For Nepal, explicitly documenting this lower boundary is consequently important when FRTC estimates are interpreted or compared with other AGB approaches.

Finally, our results caution against interpreting the mean stump contribution as a universal correction factor. Large trees contributed disproportionately to total biomass, whereas we observed that the stump represented a progressively smaller proportion of AGB as tree size increases. The difference between the mean tree-level stump contribution (3.61%) and the pooled contribution (2.57%) reflects this weighting effect, because larger trees contribute more strongly to pooled biomass totals while having lower proportional stump contributions. We therefore hypothesize that the aggregate consequence of stump exclusion will depend on forest diameter structure and potentially species composition, with a greater proportional effect possible where biomass is distributed among smaller stems. This interpretation is consistent with evidence that methodological differences introduced through allometric estimation can propagate from individual trees to plot and landscape biomass estimates (Vorster et al.,

2020). We did not perform such upscaling and therefore do not infer a specific effect on Nepal's forest carbon stocks. Nevertheless, the difference between tree-level and pooled contributions in our data indicates that the effect of stump exclusion cannot be represented adequately by a single percentage across all trees, providing a direct rationale for examining its dependence on tree size.

4.2 The effect of stump exclusion depends on tree size and species

We found that the proportional contribution of the 30-cm stump declined strongly with increasing DBH, both across the complete dataset and within each of the seven species. The observed size-related patterns showed that stump exclusion had a proportionally greater effect among smaller trees and progressively less influence toward larger diameter classes. This pattern is consistent with changes in tree geometry and biomass allocation during tree development: although absolute stump biomass may increase with tree size, the excluded vertical section remains fixed at 30 cm while biomass accumulates throughout an increasingly larger stem and crown. Previous studies have similarly shown that the proportional allocation of biomass among aboveground components changes with tree size rather than remaining constant (Návar, 2009; Picard et al., 2012; Poorter et al., 2015). Tree diameter has been identified as a major determinant of proportional biomass allocation, with allocation patterns also influenced by functional traits and species identity (Mensah et al., 2016). More generally, biomass allocation changes systematically with tree size, and such size-dependent allocation patterns are well established across woody species (Poorter et al., 2015). Our results extend this principle to biomass-boundary definition and demonstrate an important methodological point: a fixed physical boundary does not necessarily produce a fixed proportional biomass difference.

We also observed differences in the strength and shape of the DBH relationship among species. Most notably, *Pinus roxburghii* showed the strongest monotonic decline in proportional stump contribution ($\rho = -0.850$), although significant negative relationships occurred in all seven species. Allowing the DBH smooth to vary among species also improved the GAM representation, suggesting that tree size accounted for much, but not all, of the observed variation. We hypothesize that differences in basal stem form, taper, architecture, and wood properties may contribute to these species-specific patterns, consistent with evidence that biomass allocation varies with species identity and functional traits in addition to tree size (Mensah et al., 2016). However, this interpretation remains tentative because the species differed in their sampled DBH ranges and geographic and environmental settings, which can also influence tree allometry and biomass allocation (Forrester et al., 2017). The present analysis was not designed to distinguish these environmental influences from intrinsic species characteristics or to identify the mechanisms underlying the observed patterns. The GAMs were intended to characterize nonlinear size dependence rather than establish causality. Although diagnostic tests indicated adequate basis dimensions, the fitted smooths remain conditional on the available sample sizes and DBH ranges and should not be extrapolated beyond the observed data (Wood, 2017). The strong size dependence is particularly relevant to application of the FRTC framework (FRTC, 2025) because the proportional consequence of the 30-cm boundary will depend on the diameter structure of the population to which

the equations are applied. Large trees contribute disproportionately to tropical forest AGB; Slik et al. (2013), for example, showed that variation in the abundance of large trees was a major determinant of AGB variation across tropical forests. We therefore hypothesize that forests dominated by smaller stems could exhibit a greater proportional boundary effect than forests in which biomass is concentrated in larger trees. Differences in species composition and diameter structure among Nepalese forests could consequently produce different aggregate effects (DFRS, 2015). We did not perform stand- or landscape-scale upscaling, so this implication remains to be tested using representative forest-inventory distributions of DBH and species. Nevertheless, our tree-level results demonstrate that stump exclusion is not a constant proportional effect and therefore caution against applying a universal percentage correction irrespective of forest structure.

4.3 Biomass-boundary harmonization improves comparability with Chave-predicted AGB

Bringing the destructively measured AGB to the same ground-level boundary as the Chave prediction consistently improved their apparent agreement. This improvement was not driven by a single species: RMSD decreased and CCC increased after harmonization for all five species. Because the Chave equation and its inputs remained unchanged, the approximately 4.4-percentage-point reduction in the pooled Chave–measured difference was attributable specifically to restoring the measured stump biomass. Thus, an identifiable component of the original disagreement arose from a mismatch in biomass definitions rather than from predictive-model behaviour. This distinction is important because differences among allometric estimates are commonly attributed to model selection and structure, calibration data, measurement uncertainty, wood density, tree height, and model transferability (Chave et al., 2004; Molto et al., 2013; Chave et al., 2014; Picard et al., 2015; Vorster et al., 2020). Those factors remain important, and the difference that persisted after harmonization may reflect several of them. Our findings show, however, that the biomass boundary should be checked before the remaining difference is interpreted. Two estimates can appear to disagree even though part of that difference comes from the quantities being defined differently. In this case, changing the reference boundary alone improved agreement with an otherwise unchanged prediction.

The harmonization effect was present in all five species and was greater among smaller trees. It declined as DBH increased, which is consistent with the observed size dependence of proportional stump contribution. This has particular relevance in Nepal because the FRTC reference biomass excludes the 30-cm stump (FRTC, 2025), while the Chave equation represents ground-level AGB (Chave et al., 2014). Comparisons between them can therefore combine differences arising from the allometric frameworks with differences created by the biomass boundary. Restoring the measured stump biomass allowed us to remove the latter component before examining what remained. The improvement does not establish that Chave is intrinsically more accurate, and it should not be read as evidence that the FRTC framework is incorrect. It simply makes the comparison more consistent.

Similar concerns about definitions, measurement protocols, and reference datasets have been raised in forest-inventory harmonization and biomass assessment because such inconsistencies can limit comparisons across data sources (Vidal et al., 2016; Avitabile & Camia, 2018; Papucci et al., 2026). Our analysis illustrates this issue at the individual-tree level using measured stump biomass, without relying on an assumed percentage correction. The practical message is straightforward: the biomass domains represented by the reference observations and model predictions should be confirmed before their difference is attributed to model performance.

4.4 Remaining differences reflect factors beyond biomass-boundary definition

Although restoring stump biomass improved agreement with Chave-predicted AGB, a substantial difference remained. This was expected. Aligning the lower biomass boundary makes the measured and predicted quantities more comparable, but it does not remove differences between the pantropical Chave model and the population represented by the FRTC destructive sample. Chave et al. (2014) developed their equation using 4,004 destructively sampled trees from 58 tropical sites, while the FRTC dataset represents a more geographically and taxonomically specific sample. Generalized equations do not perform uniformly across all application settings. Ngomanda et al. (2014), for example, found substantial differences between site-specific and some pantropical equations in a Central African forest. In southeastern Cameroon, Fayolle et al. (2013) found that a pantropical multispecies equation performed nearly as well as a locally fitted model. Such contrasting results are not unexpected because biomass relationships can vary with species composition, forest structure, tree architecture, and diameter–height relationships (Fayolle et al., 2013; Ngomanda et al., 2014; Khanal et al., 2024). Khanal et al. (2024) also showed that allometry, species composition, and forest structure can make separate contributions to variation in AGB. The remaining Chave–measured difference in our study is likely to reflect several of these influences. The biomass boundary explains one measurable part of the disagreement, but clearly not all of it.

The Chave comparison also has limitations. It included five of the seven species because suitable FRTC-recommended wood-density values were unavailable for *Castanopsis* spp. and *P. roxburghii*. The agreement results consequently apply only to the five-species subset. Tree-level wood-density measurements were not available in the released dataset, so Chave AGB was calculated using the density information reported by FRTC, including DBH-class-specific values where available. This introduces another source of uncertainty because wood density enters directly into the Chave equation (Chave et al., 2014). Errors or uncertainty in wood density and tree height can propagate into tropical biomass estimates, together with uncertainty associated with the allometric model itself (Molto et al., 2013; Réjou-Méchain et al., 2017). The released data also lacked an explicit plot or site identifier, preventing us from accounting for possible dependence among trees sampled from the same location. Given these limitations, the residual difference cannot be assigned specifically to wood density, model structure, calibration domain, forest composition, or any other single source. Nor can it be used to

determine whether Chave or the FRTC framework is intrinsically more accurate. Such an assessment would require independent validation data, including predictor measurements collected for that purpose.

These unresolved factors do not, however, explain the improvement produced by stump restoration. For each tree, DBH, height, assigned wood density, and the resulting Chave prediction were identical in both comparisons. Only the boundary of the measured biomass changed. The paired, within-tree comparison therefore isolates the effect of stump restoration, even though it cannot explain the difference that remained afterward. Our conclusion is intentionally limited: harmonizing the biomass boundary removes an identifiable definitional component of apparent disagreement, while the residual difference reflects a combination of unresolved allometric, predictor, calibration, and data-related factors. The observed improvement supports the need for consistent biomass boundaries. It should not be interpreted as validation or correction of either allometric framework.

4.5 Implications for AGB comparability and forest-carbon accounting

A central implication of this study concerns the explicit reporting of the biomass boundary represented by an allometric estimate. The 30-cm stump boundary is an integral part of the FRTC biomass definition and should be documented whenever these equations are applied. International reporting frameworks generally define aboveground biomass as all living biomass above the soil, including the stump, stem, branches, bark, seeds, and foliage (FAO, 2018). Consequently, an estimate based on the FRTC boundary and one representing ground-level AGB do not describe exactly the same quantity, even though both may be reported as aboveground biomass. Previous harmonization studies have shown that differences in the components included in national biomass estimates can limit comparison and integration across datasets (Avitabile & Camia, 2018). Explicit reporting of the lower boundary would help prevent such definitional differences from being interpreted as ecological variation or model error.

The issue has particular relevance in Nepal, where nationally developed allometric equations support forest-resource assessment and increasingly intersect with forest-carbon monitoring, reference-level reporting, REDD+ implementation, and emerging carbon-finance applications (FRTC, 2025; MoFSC, 2017; MoFE, 2018; World Bank, 2021). Our results do not suggest that the FRTC equations require replacement or that a ground-level definition is intrinsically preferable. The appropriate treatment depends on how the estimates will be used. Biomass estimates may remain on their original stump-excluded boundary when they are produced and interpreted consistently within the FRTC framework. Where FRTC estimates are compared or integrated with approaches representing ground-level AGB, however, the biomass definitions should first be made compatible. Recording the lower boundary and included biomass components as part of the accompanying metadata would improve transparency and reduce ambiguity in subsequent analyses.

The mean stump contribution of 3.61% should not be applied directly as a universal correction to existing biomass totals. Proportional stump contribution declined with DBH and varied among species, so its aggregate effect will depend on the diameter distribution and species composition of the forest

population. Large trees contribute disproportionately to tropical forest biomass (Slik et al., 2013), yet their proportional stump contribution was lower in our dataset. A tree-level arithmetic mean may therefore differ from the biomass-weighted effect at stand or national scale. Because we did not upscale these relationships using representative forest-inventory data, no specific bias in Nepal's reported carbon stocks or carbon-credit calculations can be inferred. Applying the observed size- and species-dependent relationships to national inventory data would establish whether the modest tree-level effect remains small after aggregation or materially influences stand- and national-level estimates.

Conclusions

This study quantified the previously undocumented consequences of the 30-cm stump boundary in Nepal's FRTC allometric framework. Although the excluded stump biomass was modest on average, it represented a systematic and identifiable component of AGB and reached a considerably higher proportion in some individual trees. Its contribution also varied with tree size and species, indicating that the boundary effect cannot be adequately represented by a single universal correction factor. Harmonizing the measured biomass boundary to ground level reduced the Chave–measured difference by 3.7–5.6 percentage points across species and improved agreement consistently across all five evaluated species, while also modestly improving overall agreement without altering the Chave predictions. Thus, biomass-boundary inconsistency explained part but not most of the apparent disagreement between the two approaches. The remaining differences likely reflect model structure, calibration data, parameterization, and other sources of uncertainty; consequently, boundary harmonization should not be interpreted as validation or correction of either the FRTC or Chave framework. Biomass boundaries should be explicitly documented and harmonized before estimates from different allometric systems are compared or integrated. Further evaluation using representative forest-inventory data is needed to determine whether these modest but systematic, size- and species-dependent tree-level effects materially influence stand- and national-scale biomass and carbon estimates in Nepal.

Declarations

CRedit author statement

Santosh Ayer: Conceptualization, Methodology, Formal analysis, Writing – original draft; **Shiva Khanal:** Writing – review & editing; **Kishor Prasad Bhatta:** Writing – review & editing.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Data availability statement

The data used in this study were extracted from a publicly available report published by the Forest Research and Training Centre (FRTC), Government of Nepal (FRTC, 2025). The source report is cited in the manuscript and can be accessed through the original publication.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Acknowledgements

The authors acknowledge the Forest Research and Training Centre (FRTC), Government of Nepal, for making the national allometric data used in this study publicly available (FRTC, 2025). The authors would like to thank Open Access Fund of University of Göttingen for this publication.

Declaration of generative AI and AI-assisted technologies

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) to assist with language editing and improving the clarity and readability of the manuscript. The authors reviewed and edited the output and take full responsibility for the content of the published article.

References

1. Ashton MS, Tyrrell ML, Spalding D, Gentry B (eds) (2012) Managing forest carbon in a changing climate. Springer. <https://doi.org/10.1007/978-94-007-2232-3>
2. Avitabile V, Camia A (2018) An assessment of forest biomass maps in Europe using harmonized national statistics and inventory plots. *For Ecol Manag* 409:489–498. <https://doi.org/10.1016/j.foreco.2017.11.047>
3. Avitabile V, Pilli R, Migliavacca M, Duveiller G, Camia A, Blujdea V, Adolt R, Alberdi I, Barreiro S, Bender S, Borota D, Bosela M, Bouriaud O, Breidenbach J, Cañellas I, Čavlović J, Colin A, Di Cosmo L, Donis J, Fischer C, Mubareka S (2024) Harmonised statistics and maps of forest biomass and increment in Europe. *Sci data* 11(1):274. <https://doi.org/10.1038/s41597-023-02868-8>
4. Chave J, Condit R, Aguilar S, Hernandez A, Lao S, Perez R (2004) Error propagation and scaling for tropical forest biomass estimates. *Philos Trans R Soc Lond B Biol Sci* 359(1443):409–420. <https://doi.org/10.1098/rstb.2003.1425>
5. Department of Forest Research and Survey (2015) State of Nepal's forests. Forest Resource Assessment Nepal, Ministry of Forests and Soil Conservation, Government of Nepal
6. FAO (2018). *Terms and definitions. FRA 2020*. Food and Agriculture Organization of the United Nations. <https://openknowledge.fao.org/server/api/core/bitstreams/531a9e1b-596d-4b07-b9fd-3103fb4d0e72>

7. Fayolle A, Doucet J-L, Gillet J-F, Bourland N, Lejeune P (2013) Tree allometry in Central Africa: Testing the validity of pantropical multi-species allometric equations for estimating biomass and carbon stocks. *Forest Ecology and Management*, 305, 29–37. Molto, Q., Rossi, V., & Blanc, L. (2013). Error propagation in biomass estimation in tropical forests. *Methods in Ecology and Evolution*, 4(2), 175–183. <https://doi.org/10.1111/j.2041-210x.2012.00266.x>
8. Food and Agriculture Organization of the United Nations (2002) *Proceedings: Expert meeting on harmonizing forest-related definitions for use by various stakeholders, Rome, 23–25 January 2002*. FAO
9. Forest Research and Training Centre (FRTC) (2025) Allometric equations for seven major tree species of Nepal. Government of Nepal, Ministry of Forests and Environment. <http://frtc.gov.np/en/sources/21/25542290>
10. Forrester DI, Tachauer IHH, Annighoefer P, Barbeito I, Pretzsch H, Ruiz-Peinado R, Stark H, Vacchiano G, Zlatanov T, Chakraborty T, Saha S, Sileshi GW (2017) Generalized biomass and leaf area allometric equations for European tree species incorporating stand structure, tree age and climate. *For Ecol Manag* 396:160–175. <https://doi.org/10.1016/j.foreco.2017.04.011>
11. Gschwantner T, Alberdi I, Bauwens S, Bender S, Borota D, Bosela M, Bouriaud O, Breidenbach J, Donis J, Fischer C, Gasparini P, Heffernan L, Hervé J-C, Kolozs L, Korhonen KT, Koutsias N, Kovácsévics P, Kučera M, Kulbokas G et al (2022) Growing stock monitoring by European National Forest Inventories: Historical origins, current methods and harmonisation. *For Ecol Manag* 505:119868. <https://doi.org/10.1016/j.foreco.2021.119868>
12. Khanal S, Nolan RH, Medlyn BE, Boer MM (2024) Disentangling contributions of allometry, species composition and structure to high aboveground biomass density of high-elevation forests. *For Ecol Manag* 554:121679. <https://doi.org/10.1016/j.foreco.2023.121679>
13. Lin LI-K (1989) A concordance correlation coefficient to evaluate reproducibility. *Biometrics* 45(1):255–268. <https://doi.org/10.2307/2532051>
14. Mensah S, Glèlè Kakai R, Seifert T (2016) Patterns of biomass allocation between foliage and woody structure: The effects of tree size and specific functional traits. *Annals For Res* 59(1):49–60. <https://doi.org/10.15287/afr.2016.458>
15. Ministry of Forests and Environment (MoFE) (2018) Nepal National REDD+ Strategy (2018–2022). REDD Implementation Centre, Government of Nepal, Kathmandu, Nepal
16. Ministry of Forests and Soil Conservation (MoFSC) (2017) Nepal's National Forest Reference Level (2000–2010). REDD Implementation Centre, Government of Nepal, Kathmandu, Nepal
17. Návar J (2009) Biomass component equations for Latin American species and groups of species. *Ann For Sci* 66:208. <https://doi.org/10.1051/forest/2009001>
18. Ngomanda A, Engone Obiang NL, Lebamba J, Moundounga Mavouroulou Q, Gomat H, Mankou GS, Loumeto JJ, Iponga M, Ditsouga D, Koumba FKZ, Botsika Bobé R, Okouyi KH, Nyangadouma CM, Lépengué R, Mbatchi N, B., Picard N (2014) Site-specific versus pantropical allometric equations: Which option to estimate the biomass of a moist central African forest? *For Ecol Manag* 312:1–9

19. Papucci E, Valbuena R, Roberge C, Mensah AA, Ståhl G (2026) A review of forest biomass assessments based on remote sensing reveals progress in methodological quality—but major challenges remain. *Forestry: Int J For Res* 99(2):cpag007. <https://doi.org/10.1093/forestry/cpag007>
20. Picard N, Saint-André L, Henry M (2012) Manual for building tree volume and biomass allometric equations: From field measurement to prediction. Food and Agriculture Organization of the United Nations & Centre de Coopération Internationale en Recherche Agronomique pour le Développement
21. Poorter H, Jagodzinski AM, Ruiz-Peinado R, Kuyah S, Luo Y, Oleksyn J, Usoltsev VA, Buckley TN, Reich PB, Sack L (2015) How does biomass distribution change with size and differ among species? An analysis for 1200 plant species from five continents. *New Phytol* 208(3):736–749. <https://doi.org/10.1111/nph.13571>
22. Réjou-Méchain M, Tanguy A, Piponiot C, Chave J, Hérault B (2017) Biomass: An R package for estimating above-ground biomass and its uncertainty in tropical forests. *Methods Ecol Evol* 8(9):1163–1167. <https://doi.org/10.1111/2041-210X.12753>
23. Romero FMB, Jacovine LAG, Torres CMME, Ribeiro SC, Rocha SJSS, Novais TNO, Gaspar RO, Silva LF, Vidal E, Leite HG, Staudhammer CL, Fearnside PM (2022) Aboveground biomass allometric models for large trees in southwestern Amazonia. *Trees Forests People* 9:100317. <https://doi.org/10.1016/j.tfp.2022.100317>
24. Sharma ER, Pukkala T (1990) *Volume equations and biomass prediction of forest trees of Nepal* (Publication No. 47). Forest Survey and Statistics Division, Ministry of Forests and Soil Conservation, Kathmandu, Nepal
25. Slik JWF, Paoli G, McGuire K, Amaral I, Barroso J, Bastian M, Blanc L, Bongers F, Boundja P, Clark C, Collins M, Dauby G, Ding Y, Doucet J-L, Eler E, Ferreira L, Forshed O, Fredriksson G, Gillet J-F, Harris D, Leal M, Laumonier Y, Malhi Y, Mansor A, Martin E, Miyamoto K, Araujo-Murakami A, Nagamasu H, Nilus R, Nurtjahya E, Oliveira Á, Onrizal, Parada-Gutierrez A, Permana A, Poorter L, Poulsen J, Ramirez-Angulo H, Reitsma J, Rovero F, Rozak A, Sheil D, Silva-Espejo J, Silveira M, Spironelo W, ter, Steege H, Stevart T, Navarro-Aguilar GE, Sunderland T, Suzuki E, Tang J, Theilade I, van der Heijden G, van Valkenburg J, Van Do T, Vilanova E, Vos V, Wich S, Wöll H, Yoneda T, Zang R, Zhang M-G, Zweifel N (2013) Large trees and tropical forest biomass. *Global Ecology and Biogeography*, 22(12), 1261–1271. <https://doi.org/10.1111/geb.12092>
26. Vidal C, Alberdi IA, Mateo LH, Redmond JJ (eds) (2016) National Forest Inventories: assessment of wood availability and use, vol 845. Springer International Publishing, Cham
27. Vorster AG, Evangelista PH, Stohlgren TJ, Kumar S (2020) Variability and uncertainty in forest biomass estimates from the tree to landscape scale: The role of allometric equations. *Carbon Balance Manag* 15:8. <https://doi.org/10.1186/s13021-020-00143-6>
28. Wood SN (2017) Generalized additive models: An introduction with R, 2nd edn. Chapman and Hall/CRC. <https://doi.org/10.1201/9781315370279>
29. World Bank (2021) Nepal signs landmark agreement with World Bank to reduce carbon emissions from forests. World Bank, 26 February 2021. <https://www.worldbank.org/en/news/press->

Figures

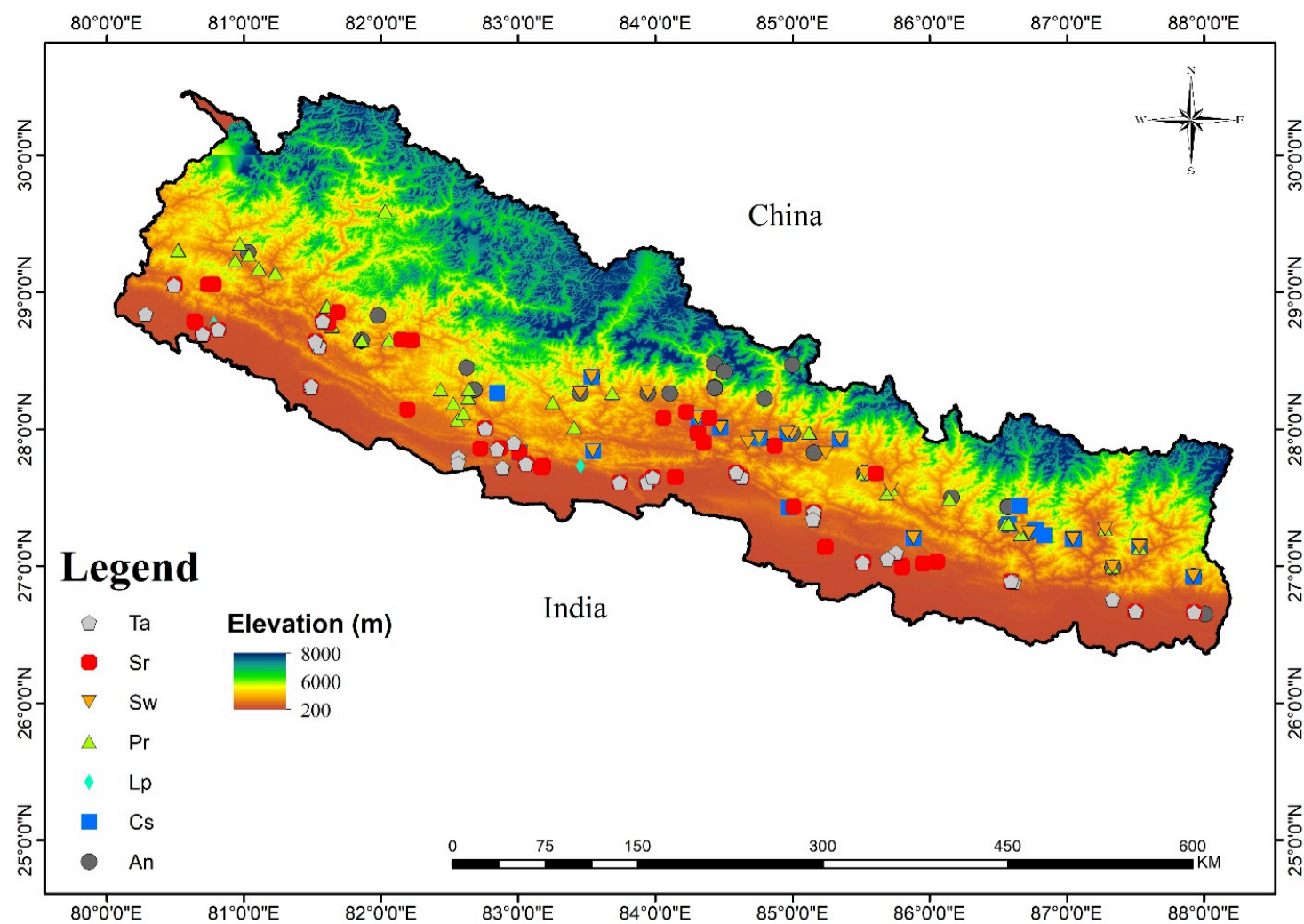


Figure 1

Spatial distribution of the 476 destructively sampled trees used in this study across Nepal. Sampling locations are shown over elevation, with symbols indicating the seven taxa: An = *Alnus nepalensis*, Cs = *Castanopsis* spp., Lp = *Lagerstroemia parviflora*, Pr = *Pinus roxburghii*, Sw = *Schima wallichii*, Sr = *Shorea robusta*, and Ta = *Terminalia alata*. Elevation is expressed in metres above sea level. Source: FRTC (2025).

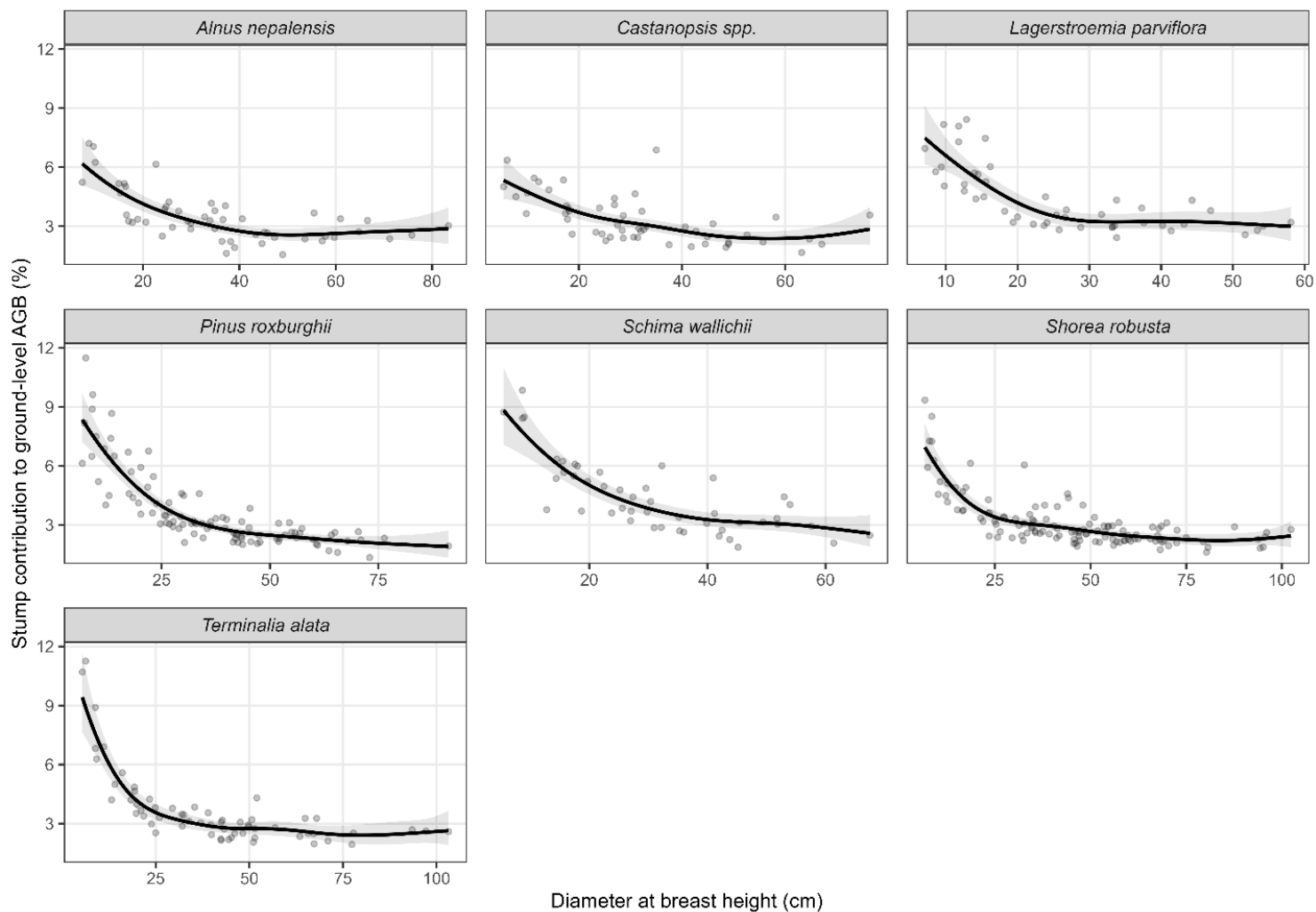


Figure 2

Size-dependent variation in proportional stump contribution to ground-level AGB across seven commercially important tree species in Nepal. Points represent individual destructively sampled trees, solid lines show species-specific predictions from the selected Gamma GAM, and shaded bands represent approximate 95% confidence intervals. Species panels are displayed over their observed DBH ranges.

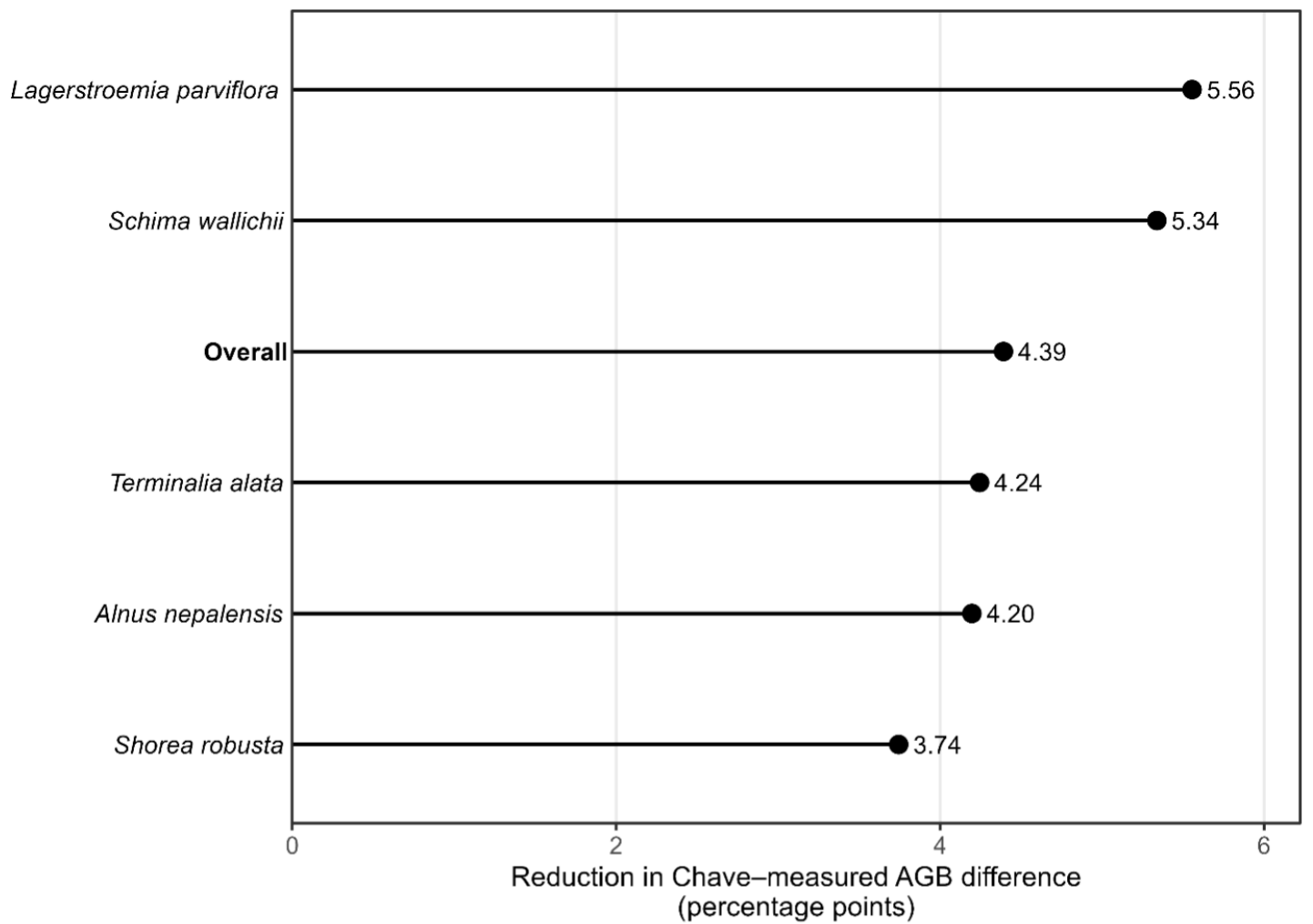


Figure 3

Reduction in the mean Chave-measured aboveground biomass (AGB) difference following harmonization of the measured biomass boundary from the stump-excluded to the ground-level definition. Values show the reduction in percentage points for each of the five species and across all 328 trees.